Pediatric Trauma

Pathophysiology, Diagnosis, and Treatment

SECOND EDITION

Edited by

David E. Wesson • Bindi Naik-Mathuria

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Preface

Injury continues to be the leading cause of death and disability in children older than one year in the United States and in older children and adolescents worldwide. The spectrum of causes varies with age, but blunt forces cause the overwhelming majority of injuries. The common adage "children are not just small adults" certainly holds true in pediatric trauma, as many of the differences in behavior, risk, exposure, anatomy, and physiology between children and adults have a direct bearing on trauma care. In recent years, this reality has been widely accepted in the field. The Committee on Trauma of the American College of Surgeons has specifically addressed the needs of injured children in its resources document and in the curriculum of its Advanced Trauma Life Support® course. In many countries around the world, children's hospitals, pediatric surgical subspecialists, pediatric emergency physicians, and prehospital providers have focused on the needs of injured children and have established pediatric-specific benchmarks in the management of trauma care. But there is a problem. There are simply not enough children's hospitals or pediatric trauma specialists to meet the needs of all the injured children. Much, if not most, of pediatric trauma care is provided in general hospitals by nonpediatric specialists.

This book is intended for everyone who treats injured children. The primary target audience includes pediatric surgeons, general surgeons, trauma surgeons, emergency physicians, and surgical subspecialists. Trainees and mid-level providers in any of these fields, as well as providers in low-resource countries, may also find this book useful as it provides a broad overview of the key topics in pediatric trauma care. The content not only relates primarily to direct patient care, but also includes topics such as disaster planning, injury prevention, and long-term outcomes.

The book is divided into four parts. Part I deals with trauma systems for children, including epidemiology and organization of pediatric trauma care. Part II covers general principles of resuscitation and supportive care relevant to all pediatric trauma patients, including management of burns and child abuse, and pediatric-specific imaging and transfusion recommendations. Part III covers the management of specific injuries, including brain, truncal, skeletal, and vascular injuries. Finally, Part IV deals with outcomes, rehabilitation, and effective communication with families of injured children. The chapters from the first edition have been revised and updated to reflect the most contemporary practices within the field.

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PART I

Trauma systems for children

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Epidemiology of pediatric trauma

DAVID E. WESSON

Introduction

Epidemiology is the study of the distribution of diseases in groups or populations. One of its aims is to define the occurrence of disease by place and time in the general population and in specific subpopulations. The overarching goal is to reduce the incidence and severity of specific diseases. Injury epidemiology involves the collection of data on the time, place, mechanism, and victim of injury. Studies of pediatric injury epidemiology have had a major impact on our understanding of pediatric trauma. Injury epidemiology has allowed us to identify and quantify specific injury risks, develop prevention and treatment strategies, and monitor their effectiveness. The study of injury epidemiology has produced one fundamental fact: Injuries are the leading threat to the health and well-being of young people in our society today [1,2]. This is of major importance to public health officials and health care providers alike.

Epidemiology can help clinicians by identifying common causes, mechanisms, and patterns of injury. This is best done in defined populations of children at the local, regional, national, or international level. Epidemiology tells us that motor vehicle crashes and falls from a great height cause more life-threatening injuries than sports and recreational activities. We know that blunt injuries far outnumber penetrating injuries and that children are prone to develop intracranial hypertension from cerebral edema after a closed head injury. The astute trauma surgeon will learn to suspect and recognize these patterns based on the age of the child and the mechanism of injury. As in most areas of surgical practice, the history of events before presentation aids significantly in diagnosis and treatment.

Historical perspective

One hundred years ago, infections were the great scourge of children in our society. Today the problem is injury or trauma. Changing social conditions, better housing and nutrition, immunization, and quarantine of infectious cases all helped reduce the threat from infectious diseases. Over the same time period, new environmental factors, notably the introduction of the automobile, increased the risk of injury.

Trauma systems for children

Our present understanding of the epidemiology of trauma in our society began in the 1960s with the publication of a monograph entitled *Accidental Death and Disability: The Neglected Disease of Modern Society* by the Committees on Trauma and Shock of the National Academy of Sciences [3]. This report pointed out that accidental injuries were the nation's most important environmental health problem. This was followed by another important publication *Injury in America* that documented in much greater detail the impact of injuries on American society and suggested a broad approach to the problem encompassing epidemiology, prevention, biomechanics, acute treatment, and rehabilitation [4].

Since these two important publications appeared, much progress has been made both in prevention and treatment of injuries. During the 1980s and 1990s, the mortality rate from pediatric trauma in the United States fell by about 50%. This trend has continued. The mortality rate from unintentional injuries among children 1–19 years of age in the United States fell from 15.0 per 100,000 in 2000 to 8.3 per

100,000 in 2013 [1,2]. No doubt this resulted from improvements in both prevention and treatment. But there are many reasons why we will have to increase our prevention efforts if we hope to see another 50% reduction in the next 20 years.

The costs of treating trauma victims and the pain and suffering they endure are very high, even when the final outcome is excellent. Prevention would eliminate these effects. About 50% of pediatric trauma deaths occur in the field before the victim even reaches a trauma center. Here too, prevention is the answer. Most trauma systems now have very low preventable death rates. There is always room for improvement, but the curve is flattening out. It is unlikely that substantial reductions in the overall trauma mortality rate in the United States could be achieved by better care of the injured.

We lack effective treatments for primary brain injuries, the most common cause of death in pediatric trauma. Here too, prevention is the solution. A report from the National Pediatric Trauma Registry showed that about 70% of pediatric injury deaths are caused by central nervous system (CNS) injury [5]. Only prevention can significantly reduce these deaths.

Injury facts

More than half of all childhood deaths in the United States result from injuries. In 2013, among children 1–19 years old, unintentional injuries (accidents), suicide (self-harm), and homicide (assault) were the first, second, and third leading causes of death, respectively [1]. Together they account for >56% of all deaths among children 1–19 years of age. Unintentional injuries are the number one childhood killer in all age brackets—1–4, 5–9, 10–14, and 15–19 [1]. In 2013, unintentional injuries of all types, including suffocation, drowning, burns and scalds, as well as blunt and penetrating trauma, caused 6489 deaths among children 1–19 years of age in the United States. This represents 34% of all pediatric deaths and a mortality rate of 8.3 injury deaths per 100,000 per year. There has been considerable improvement in these numbers since 2000. In that year, there were 11,232 deaths accounting for 44% of all deaths at a rate of 15.0 per 100,000 children from 1 to 19 years of age [2].

Also in 2013 suicide, the second leading cause of death, resulted in 2143 deaths or 11% overall. Homicide contributed 2021, also around 11% of all deaths. The incidence of homicide plotted against age creates a U-shaped curve with peaks among infants and adolescents. Among infants, the most common mechanism is abusive head trauma (AHT) or "shaken baby syndrome" that peaks at 2–3 months of age. This is the age at which colic is most prevalent suggesting that infant crying may trigger at least some cases of AHT. At our Level I pediatric trauma center, we admit 60–80 children each year with injuries caused by physical abuse. Most of them are infants less than 6 months of age. Child abuse accounts for more than one-third of all trauma deaths at our center. It is the single most common cause of fatal injury.

In Texas, injuries are the leading cause of death among children from 1 to 17 [6]. Motor vehicle–related injuries are the most common cause. Most were passengers, followed by pedestrians struck by a motor vehicle and drivers. In Texas, almost two-thirds of pediatric homicides are committed with a firearm, usually a handgun. Gunshot wounds are also the most common mechanism of child suicide.

For every injured child who dies dozens more are hospitalized and hundreds are treated in emergency centers.

Risk factors

The risk of most types of injury varies with age. Homicide is the leading cause of injury death for infants from 1 month to 1 year of age in the United States. The homicide rate for boys is almost three times higher than for girls. It is also much higher among African Americans than Caucasians. Child abuse causes the majority of homicides in the first year of life; gunshot wounds predominate among teenagers. A person known to the victim, most commonly a parent, perpetrates the vast majority of homicides.

Suffocation is the number one cause of unintentional injury death in infants, but is rare in other groups. Drowning and submersion are the leading cause of death in children 1–4 years of age. Toddlers have a much higher death rate for burns and scalds than older children do. The risk of injury for school-aged boys is far greater than for girls. Motor vehicle occupant injuries predominate among teenagers 15–19 years old.

The likelihood of a child being fatally injured is associated with single parentage, low maternal education, young maternal age at birth, poor housing, large family size, and parental abuse of alcohol and other drugs. A study from Newcastle, England, of fatal head injuries revealed that children from poorer neighborhoods were at greater risk than were those from more affluent areas [7]. The authors concluded that the lack of proper playgrounds, which forced poor children to play in the streets, accounted for the difference. Children living in trailer homes in the United States have twice the risk of dying in house fires than children living in other types of housing. Children who live in rural counties have a higher incidence of motor vehicle–related injury and a higher risk of dying compared to urban children. There is also a strong correlation between per capita income and mortality from motor vehicle crashes among all the counties in the lower 48 states. Racial and ethnic factors correlate with other socioeconomic determinants, but even when these are controlled for, American Indians have the highest rates of injury mortality in the country.

Costs

It is difficult to accurately determine all of the costs of pediatric trauma but it is clear that injuries are the leading cause of medical costs. Most estimates suggest that these costs are enormous. Hospital costs represent only one slice of the pie. Other costs include medical services, lost productivity, indirect costs to families for lost income, and so on. Rice and Mackenzie estimate that the cost of injury to children from birth to 14 years of age in the United States in 1985 was $13.8 billion [8]. A recent report entitled "Unintentional Injuries in Childhood" in the Future of Children series published by the David and Lucile Packard Foundation provides a lot of data on this subject [9]:

- For school-aged children and teenagers, injuries are almost as frequent as the common cold.
- In 1996, injuries—mostly to the brain, spinal cord, and limbs—and burns left an estimated 150,000 children permanently disabled.
- Injuries to children resulted in the loss of 2.7 million quality adjusted life years.

This publication also attempted to express the impact of childhood injuries in financial terms. It estimated the total financial burden of childhood injury in America for 1996 as $81 billion:

- Direct spending for medical services over the lifetime of the victim amounted to $14 billion.
- Other resource costs including emergency medical services totaled $1 billion.
- Lifetime productivity losses amounted to $66 billion.

Trends

We have made substantial progress in the fight against childhood injury. The death rate has declined significantly in one generation. Unintentional injury mortality fell by 50% from 1970 to 1995 in the Organization for Economic Cooperation and Development (OECD) nations (the 26 richest nations in the world) [10]. During the same period, the proportion of all childhood deaths caused by injuries rose from 25% to 37%.

Improved highway and vehicle design, smoke detectors and alarms, car seats, and seat belts have all played a part in reducing childhood injury mortality. Even the homicide rate has declined. This trend continues [1,2].

In the province of Ontario, Canada, the number of children seriously injured while bicycling fell sharply during the 1990s [11]. This was due in part to legislation making helmets mandatory for children riding a bicycle on public roads. Across Canada, there is a clear association between bike helmet legislation and the risk of head injury. Provinces with helmet laws had a 25% lower head injury risk.

Comparisons with other countries

Injuries are the principal cause of death for children 1–14 years of age in all nations in the OECD, the wealthiest countries [10]. Injuries account for 40% of all deaths in children 1–14 years of age. Together they take the lives of more than 20,000 children each year in the OECD nations. Traffic accidents account for 41% of the deaths. For every death, there are 160 hospital admissions and 2000 emergency department visits. Injuries account for almost 30% of the total burden of childhood disease measured by disability adjusted life years.

The Swedish, British, Italian, and Dutch child injury death rates are among the lowest; the United States rate is among the highest along with Poland, New Zealand, Portugal, and Mexico. The United States accounts for almost one-third of all child injury deaths in the developed nations. More than 12,000 child injury deaths a year could be prevented if all countries had the same child injury death rate as Sweden. Bringing the United States rate down to that of Sweden would save 4700 American children each year.

Common clinical scenarios and patterns of injury

Astute clinicians learn to recognize common clinical scenarios and patterns of injury. Thus, knowledge of the circumstances can help identify patients with certain types of injury. For example, restrained children in side-impact crashes are much more likely to sustain injuries from compartment intrusion than children in frontal crashes. Side-impact crashes also cause more severe injuries (Injury Severity Score >15; Glasgow Coma Scale <9) and more injuries to the head, cervical spine, and chest to restrained children [11]. In contrast to this, restrained children in frontal crashes are more likely to suffer injuries to the abdomen and lumbar spine.

The following is a partial list of common pediatric trauma clinical scenarios:

- The infant brought in with a vague history (e.g., a fall at home), altered mental status, and severe neurotrauma from child abuse
- The properly restrained toddler involved in a high-speed motor vehicle crash brought in by ambulance who proves to have no significant injury
- The school-aged child struck by a motor vehicle who presents with a lower limb fracture, intra-abdominal or thoracic visceral trauma, and a closed head injury
- The preteen who suffers a high-grade hepatic or splenic injury from an off-road all-terrain vehicle (ATV) crash
- The child with an acute epidural hematoma following a seemingly minor direct blow to the head
- The rear seat passenger with a transverse abdominal bruise and occult small bowel and lumbar spine and/or spinal cord injuries from a lap belt
- The child with a duodenal hematoma or pancreatic laceration from a direct blow to the abdomen from a hockey stick or bike handlebar

Emergency physicians and trauma surgeons should be on the alert for children with these typical clinical presentations.

Role of the trauma center

The primary role of the trauma center is, of course, to care for patients with life- and limb-threatening injuries. Trauma centers can also make important contributions to injury control through education and prevention. Education efforts can target health care providers and the greater community. Education is a necessary component of all injury prevention programs and is usually a necessary first step before new legislation mandating injury prevention measures such as seat belts, child restraints, bike helmets, and so on. Trauma centers can also help identify specific causes of injury and associations or patterns of injury. Data from the trauma registry showing a significant number of fatal bicycling injuries motivated the trauma program staff at the Hospital for Sick Children, Toronto, to start a bike helmet campaign. The first phase of the campaign was intended to educate the public, health care workers, government officials, and politicians of the risk of bike-related head trauma and of the benefits of bike helmets. This eventually lead to a bike helmet law in the province of Ontario, which contributed significantly to a 26% reduction in bicycling-related head injuries among children 1–19 years of age [12]. The rate of fatal injuries ultimately fell by more than 50% [13]. A national population-based study across Canada confirmed that parts of the country with helmet laws had lower head injury rates.

SUMMARY

Injuries are the leading risk to the lives and limbs of children from infancy through adolescence in our modern world. The mechanisms and the numbers vary with age, gender, race, parental education, social class, and economic status. Awareness of these variations can assist clinicians in the management of pediatric trauma victims. Analysis of these variations can also help us develop ways of preventing childhood injuries from occurring in the first place.

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Organizing the community for pediatric trauma

ERIC H. ROSENFELD and ARTHUR COOPER

Introduction

Modern pediatric trauma care, like adult trauma care, has undergone constant evolution during the past generation, since the care of injured children first emerged as a distinct discipline. In part, this was driven by the widespread recognition among pediatric surgeons—initially led by Dr. Jacob Alexander Haller, Jr., of The Johns Hopkins University in Baltimore—that pediatric trauma care constituted a key component of the subspecialty of pediatric surgery [1], and in part by the ultimate recognition by the Federal government that emergency medical services (EMS) for children had been neglected during the development of EMS systems nationwide [2]. Since their inception, pediatric trauma programs have stressed the need for full integration with their affiliated adult trauma programs and their regional EMS systems, to ensure seamless care and cost-effective use of scarce human and financial resources [3]. They have also recognized the need for all who care for pediatric patients to ensure that the special needs of injured children are met at every level of trauma and EMS system organization [4].

To this end, this chapter describes the current state of the art with respect to pediatric trauma system design. Consistent with this purpose, the public health approach to trauma and EMS systems will be emphasized. Additionally, the literature supporting the need for and components of pediatric-capable trauma and EMS systems will be reviewed. Finally, critical elements of prehospital care for the pediatric trauma patient will be delineated, to arm not only pediatric-capable trauma professionals, but also adult-oriented trauma professionals—who, of necessity, provide the majority of pediatric trauma care in the United States—with a working knowledge of pediatric trauma system design and function, to ensure, insofar as is possible, that every child in every community has the benefit of optimal pediatric trauma prevention and treatment, hence the greatest possible opportunity for relief, recovery, and rehabilitation.

Trauma and EMS for children (EMSC)

Modern EMS systems evolved because of the recognition that trauma and sudden cardiac emergencies were the leading causes of death in the United States, and that the largely volunteer, fire company–based rescue squads that historically comprised most EMS were not optimally prepared to meet this challenge. The physicians who first created the EMS systems were trained chiefly in the adult-oriented specialties of surgery, internal medicine, cardiology, and anesthesiology [5]. Infants and children were cared for in these EMS systems, but their needs were not specifically addressed, and deficiencies in their care were not recognized, based on the false notion that children could be treated as little adults. Hence, none of the key legislative initiatives that resulted in the creation of modern EMS—the Highway Safety Act of 1966, the Emergency Medical Service Systems Act of 1973, and the Preventive Health and Health Services Block Grant Program of 1982 that ultimately replaced the EMS Systems Act—made special mention of the unique needs of infants and children in the emergency care system, even though neonatal care had previously been regionalized under the EMS Systems Act.

The development of pediatric surgery and pediatric emergency medicine as distinct disciplines, each with approved residency and fellowship training programs and recognized board certification, fostered the development of emergency medical services for children (EMSC) in many parts of this country. It was recognized that pediatric patients comprised some 5%–10% of prehospital transports, 30% of emergency department visits, 21% of all prehospital trauma care, and 12% of all in hospital trauma care [6,7]. Seminal reports described the unique epidemiology of pediatric prehospital care, and documented deficiencies in the way trauma systems provided access for children and in the way they educated, equipped, and provided medical control of prehospital personnel [6,8–10]. These led, in turn, to major federal initiatives in EMSC, including legislation and funding, systematic analysis of the nation's strengths and weaknesses in EMSC by the Institute of Medicine (IOM), and development of specific plans to remedy the weaknesses it identified, which have continued to be updated on a regular basis [11,12].

The current Federal EMSC Program is administered by the Maternal and Child Health Bureau (MCHB) of the Health Resources and Services Administration (HRSA) in collaboration with the Office of EMS (OEMS) of the National Highway Traffic Safety Administration (NHTSA), with the assistance of the EMSC Innovation and Improvement Center (EIIC) at the Baylor College of Medicine and Texas Children's Hospital in Houston, TX, and the National EMSC Data Analysis and Research Center (NEDARC) at the Primary Children's Hospital in Salt Lake City, UT. EMSC consists of six phases of care and contains several of the elements addressed in the EMS Systems Act of 1973. It encompasses the entire spectrum of care for the child requiring emergency services and exists within the established EMS system. These phases of care may reside in one or more of the multiple agencies that comprise the EMS system. The program has long enjoyed generous Congressional support and has been progressively expanded over the years to embrace a wide variety of projects designed and selected through competition to enhance the efficacy of each of these six phases of emergency care, as delineated in Tables 2.1 and 2.2.

Numerous professional organizations have also contributed to the development of EMSC. These efforts have led to the promulgation of national guidelines defining minimum standards of pediatric equipment and protocols for ambulances, pediatric equipment and care for hospital emergency departments and trauma centers, and postgraduate training and continuing education requirements in pediatric emergency and trauma care [13–20]. Experiments with voluntary consensus standards for pediatric emergency and trauma care have also been successful in many locales, particularly southern California's Emergency Departments Approved for Pediatrics (EDAP) Program and New York City,s 911 Ambulance Destination System [21,22]. The depth and breadth of resources now provided by regional and national EMSC programs are truly expansive—an EMSC program now exists in virtually every state and territory. They provide both the foundation and the framework on which and within which to build a pediatric trauma system for every region with the United States.

Table 2.1 EMS system components and EMSC system phases

EMS component	EMSC phase
Manpower	Prevention
Training	System access
Communications	Field treatment
Transportation	Emergency department treatment
Facilities	Inpatient treatment
Critical care units	Rehabilitation
Public safety agencies	–
Consumer participation	–
Access to care	–
Patient transfer	–
Coordinated patient record keeping	–
Public information and education	–
Review and evaluation	–
Disaster plan	–
Mutual aid	–

Table 2.2 Projects supported by Federal EMSC program

EMSC Innovation and Improvement Center (EIIC)
National EMSC Data Analysis and Resource Center (NEDARC)
Partnership grants with all interested states and territories
Partnership grants with stakeholder organizations in EMSC
Targeted issues and grants addressing specific issues in EMSC
Research network grants supporting multicenter trials in EMSC (PECARN)

The public health approach to pediatric trauma

Trauma is the leading cause of death and disability for Americans between 1 and 44 years of age [23]. It kills and maims more children between 1 and 14 years of age than all other diseases combined [23]. Despite these grim statistics, and the facts that (1) the estimated cost to American society of a single childhood injury death likely exceeds $600,000, when the best historical data are corrected for inflation

[24]; (2) the Centers for Disease Control and Prevention (CDC) estimated in 2010 that fatal unintentional injuries resulted in $1.8 billion in medical costs and $112 billion in lost productivity in the United States [25]; and (3) the World Health Organization (WHO) reported in 2004 that motor vehicle collisions were the second leading cause of death worldwide for children and young adults ages 5–29 years old while the estimated cost from motor vehicle collisions alone is $518 billion [26], trauma unequivocally remains in 2016 "the neglected disease of modern society" as it was in 1966 when the National Academy of Sciences published its now famous white paper, *Accidental Death and Disability: The Neglected Disease of Modern Society* [27]. Afflicting as they do the youngest and ablest members of our society, it is evident that injury and trauma are the leading public health problems of our age.

No doubt, much has changed over the last 50 years. In 1966, there were few trauma hospitals in America, trauma education of surgical residents was inconsistent at best, emergency medicine had yet to emerge as a distinct specialty in all but a few centers, pediatric surgery was a young specialty focused chiefly on congenital anomalies and childhood cancer, pediatric emergency medicine had not yet been conceived as an organized specialty with a distinct body of knowledge, prehospital care was rudimentary in most localities throughout the nation, few—if any—states had organized systems for trauma care, and injury fatalities were considered accidental events and accepted as inevitable occurrences of everyday life. In 2016, all states have designated Level I trauma centers, and all graduates of surgery and emergency medicine residencies have advanced trauma life support (ATLS) certification and specific education and experience in operative and nonoperative trauma care. Emergency medicine is an established and essential discipline, pediatric surgery and pediatric emergency medicine are recognized and robust subspecialties, and prehospital care is both readily accessible and relatively sophisticated. All states have recognized trauma care hospitals, most states have organized trauma care systems, and injuries are no longer considered accidents, but are viewed as predictable events that can be modified through the application of harm reduction strategies directed at the host, agent, and environment before, during, and after the traumatic event. Despite these impressive advances in the structure and process of trauma care, trauma remains the leading killer of our most productive citizens, and those who will soon become our most productive citizens—our children.

These facts led the leadership of American trauma surgery—in partnership with the NHTSA, OEMS, as well as the HRSA EMSC Program—to ask why, despite the obvious investment in trauma and EMS throughout the past 50 years, there remains such a gap between expectations and reality. The conclusion these experts have reached, neatly outlined in two documents produced by these two agencies, the *Trauma System Agenda for the Future* [28], published in 2002, and the *Trauma Systems Planning and Evaluation: A Model Approach to a Major Public Health Problem* [29], published in 2004—reinforced soon thereafter by the IOM in a tripartite series by its Committee on the Future of Emergency Care in the United States Health System, *Hospital Based Emergency Care: At the Breaking Point* [30], *Emergency Medical Services at the Crossroads* [31], *Emergency Medical Services for Children: Growing Pains* [32], published in 2006, with the support of the Josiah Macy, Jr., Foundation, the Department of Health and Human Services Agency for Healthcare Research and Quality, HRSA, CDC, and the Department of Transportation (DOT) NHTSA—is startling in its simplicity, but imposing in its implications: We have had the tools needed to solve this problem for nearly as long as it has been recognized, but have failed to make use of them in a coherent and consistent manner. Specifically, through lack of public education and the necessary appropriation of funds, we have failed to harness the resources required to mount a comprehensive injury control strategy—one that links the expertise of our public health system in disease prevention and control with the expertise of our health care system in diagnosis and treatment, as underscored by the IOM in its 2012 report, entitled *Investing in a Healthier Future*, which highlighted the dysfunction in how public health infrastructure is funded and organized and called for collaboration of states and the federal government [33]. This problem is illustrated vividly in Figure 2.1, which depicts the disconnect between the primary and secondary prevention emphasis of the public health system and the tertiary prevention capabilities of the health care system—but in so doing, also suggests the obvious solution, namely, the collaboration of all parties through public–private partnerships to develop a coordinated and organized approach to injury prevention and control.

The fundamental concepts of public health are not new to trauma professionals. Indeed, the core elements of trauma system design enumerated in the *Trauma System Agenda for the Future* are fundamentally congruent with the 10 essential services provided by the public health system, as defined by the Public Health Functions Steering Committee of the United States Public Health Service in its 1994 report, *Public Health in America* [34], and reiterated in *Trauma Systems Planning and Evaluation: A Model Approach to a Major Public Health Problem* delineated in Table 2.3, while the three core functions of the public health system described by the IOM of the National Academy of Sciences in its 1988 and 2002 reports, *The Future of Public Health* [35] and *The Future of the Public's Health in the 21st Century* [36], namely assessment, policy development, and assurance, which are the framework through which each of the 10 essential public health services are managed, are strikingly reminiscent of the performance improvement processes well known to most health care professionals, as demonstrated in Table 2.4. Thus, there exists a natural affinity between public health professionals and trauma care professionals in their approach to problem solving. What remains is for regional leaders in public health and trauma care to form collaboratives that set goals and objectives for the public health system and the trauma care system within

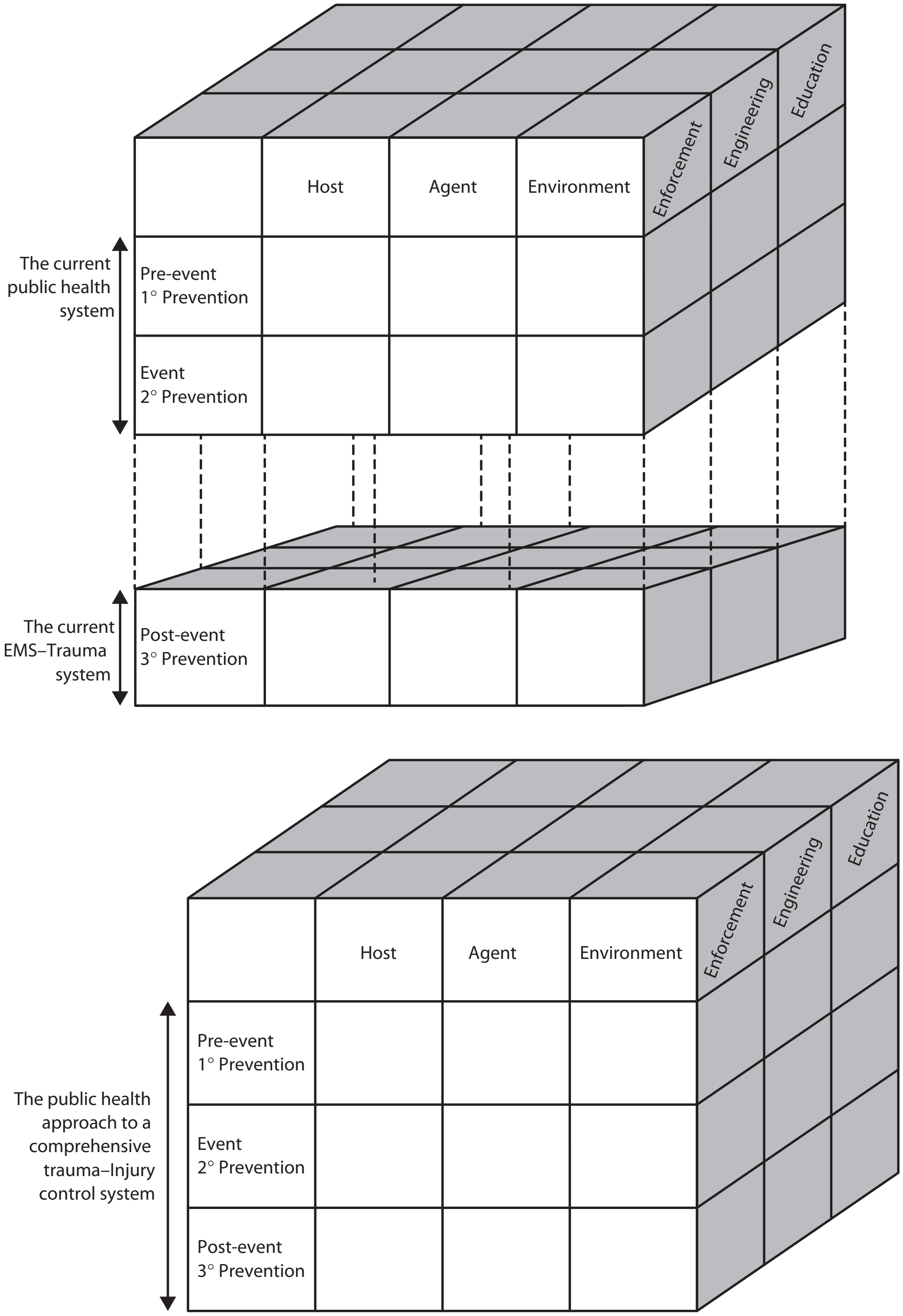

Figure 2.1 The Haddon Runyan cube of injury prevention and control. The comprehensive public health approach integrates all phases of injury control into a single system. The current system maintains an artificial separation between the three phases of injury control.

a given region with respect to injury prevention and control, which allow each component of these public–private partnerships to focus upon what each does best—the public health system on regional data collection, processing, and analysis, as well as primary and secondary prevention efforts, the trauma care system on trauma patient care, including tertiary prevention efforts such as prehospital emergency care, in hospital acute care, and posthospital and rehabilitative care—while each keeps an eye on what the other is doing, to ensure full coordination in regional

Table 2.3 The 10 essential services of the public health system are fully congruent with the fundamental components and key infrastructure elements of the trauma system

Essential public health services[a]	**Trauma system components and elements**[b]
Monitor health	Information management
Diagnose and investigate	Information management
Inform, educate, and empower	Education and advocacy
Mobilize community partnerships	Education and advocacy
Develop policies	Education and advocacy
Enforce laws	Injury prevention
Links to/provides care	Prehospital care, acute care facilities, posthospital care
Ensure competent workforce	Professional resources
Evaluate	Information management
Research	Research
[System infrastructure]	Leadership information management finances technology

Sources: National Highway Traffic Safety Administration, *Trauma System Agenda for the Future*, National Highway Traffic Safety Administration, Washington, DC, 2002; Peden M et al., *World Report on Road Traffic Injury Prevention*, World Health Organization, Geneva, 2004.

[a] Public Health in America.

[b] Trauma System Agenda for the Future.

Table 2.4 The three core functions of the public health system are fully compatible with the five steps of performance improvement

Core public health functions[a]	**Steps in performance improvement**[b]
Assessment	Plan Design Measure Analyze
Policy development	Improve
Assurance	Cycle continues

Source: Cooper G et al., *Trauma Systems Planning and Evaluation: A Model Approach to a Major Public Health Problem*, Health Resources and Services Administration, Rockville, MD, 2004.

[a] The Future of Public Health.

[b] The Joint Commission.

injury prevention and control efforts, to the benefit of both the public at large and patients as individuals.

The benefits of such collaboration are most obvious in primary and secondary injury prevention, but they can also accrue through tertiary prevention by improvements in EMS. For example, through a population-based study of the epidemiology of pediatric trauma care in 1992 that compared vital statistics and hospital discharge data abstracts from a single state for a single year, Cooper et al. [7] reported that while total pediatric trauma and burn deaths occurred at a rate of 11.8 per 100,000 population, in-hospital pediatric trauma and burn deaths occurred at a rate of only 2.6 per 100,000 population. Since only 22% of trauma and burn deaths occurred after hospital admission, these authors concluded that only through effective injury prevention programs and improved EMS were pediatric injury deaths likely to decrease. Thus, to be effective, the children's trauma surgeon must be prepared not only to operate upon the patient, but also to "operate" within the community, bringing the resources of the pediatric-capable trauma center to adjoining neighborhoods to keep them safe for children at play, and to neighboring EMS to ensure they have the knowledge, skills, and attitudes necessary not only to treat pediatric injuries after they occur, but also to prevent them.

Effective injury prevention programs are community based and require extensive collaboration with civic leaders, governmental agencies, commercial entities, and neighborhood coalitions. Programs such as the Injury Free Coalition for Kids® (www.injuryfree.org) [37–42] and the New York Safe Routes to School program [43] have been highly successful in creating substantial reductions in the burden of childhood injury in more than 40 communities throughout the nation. Such programs require ongoing collaboration between regional and area trauma centers and local public health entities, so the incidence of injury can be tracked locality by locality using population-based databases, and specific plans made to target injuries endemic to the community, based on what have been described as the "ABCDEs" of injury prevention [44]. They require major institutional commitment on the part of trauma systems and centers in prevention of injuries, including commitment of the necessary staff, equipment, and resources.

Evidence in support of specialized hospital care for pediatric trauma

Variations in clinical practice patterns have raised concerns about the efficacy, effectiveness, and efficiency of the care provided. As such, the establishment of outcome benchmarks has become a priority in trauma, while national databases are making this information increasingly available to the public. Components that help define quality of care include infrastructure, process, and outcome. Certain key elements will be highlighted in this section.

Improved outcomes from tertiary centers of pediatric intensive care were first noted by Pollack et al. in 1991 in a statewide comparison of tertiary and nontertiary facilities [45]. To conduct this analysis, these authors compared illness-adjusted mortality rates in pediatric intensive care units in a single state using PRISM scores to calibrate risk. They found that illness-adjusted mortality rates were significantly higher (odds ratios [ORs] 1.1, 2.3, 8 for mortality risk groups <5%, 5%–30%, >30%) among patients in nontertiary facilities, mostly for patients with severe traumatic brain injury. Thus, they concluded that critically ill children were best cared for in tertiary care pediatric intensive care units.

The severity and mortality associated with pediatric blunt injuries in hospitals with pediatric intensive care units versus other hospitals was also reviewed by Farrell et al. in 2004 [46]. They compared these outcomes in 8180 seriously injured (Injury Severity Score [ISS] ≥ 8) pediatric patients (age ≤ 12) enrolled in a population-based statewide trauma registry, finding that (1) injury severity of patients treated in hospitals with pediatric intensive care units and regional trauma centers without pediatric intensive care units was significantly higher than at other hospitals; (2) the risk-adjusted mortality rates were lower at hospitals with pediatric intensive care units than at other hospitals, except for nontrauma hospitals without pediatric intensive care units whose patients were considerably less severely injured; and (3) there is significant triaging of the most seriously injured pediatric blunt trauma patients to hospitals with pediatric intensive care units, and evidence that this policy is effective. A follow-up study by Odetola et al. in 2005 confirmed this finding [47]. They analyzed 18,337 deaths from data from the National Center for Health Statistics mortality data file and found that the presence of pediatric intensive care units was associated with a lower mortality from trauma incidence rate ratio (IRR) = 0.72; 95% CI 0.67–0.78.

Differences in pediatric trauma care between pediatric and nonpediatric trauma centers were reviewed by Nakayama et al. in 1993 in a comparison of outcomes between pediatric and nonpediatric trauma centers from a single state using a statewide trauma registry [48]. They found that the mortality was highest in rural nonpediatric trauma centers. They also found that mortality was similar in urban pediatric and nonpediatric trauma centers, although the probability of survival was slightly, but not significantly, higher for patients with moderately severe injuries in pediatric trauma centers (PTCs), using the TRauma score, Injury Severity Score, age combination index, more commonly known as the TRauma and Injury Severity Score (TRISS), for analysis. They concluded that children fared better in hospitals that made special provisions for the care of injured children.

The question of whether PTC designation impacts favorably upon the care of injured children was addressed by Hall et al. in 1993 [49]. They reviewed medical examiner records from a large urban metropolis for a 5-year period. They documented clear improvement in outcome following designation of adult trauma centers (ATCs), and further improvement upon designation of PTCs. They concluded that PTC designation saved many lives.

The efficacy of pediatric trauma care was reaffirmed in a population-based study by Cooper et al. in 1993 [50]. They compared the frequency and mortality of pediatric trauma hospitalizations, based upon hospital discharge data abstracts from a single state in a single year, versus those reported to the National Pediatric Trauma Registry during a similar epoch. They found evidence both of triage of more seriously injured patients to pediatric trauma hospitals, and an overall 10-fold increase in survival in PTCs for patients with moderately severe (ISS, 15–19) brain, visceral, and musculoskeletal injuries. They concluded that PTC care was efficacious for those patients who need it the most, namely those with injuries serious enough to carry a significant mortality risk, yet not so serious as to pose a potentially insurmountable threat.

The outcome of pediatric patients with blunt injuries was also found to be best at a PTC by Hall et al. in 1996 [51]. They reviewed the fatality rates of 1797 children admitted to PTCs, using TRISS analysis to stratify risk. While the Z scores did not differ statistically between pediatric and ATCs for penetrating injuries, it was significantly better in PTCs for blunt injuries. They also found a lower incidence of surgical intervention for liver and spleen injuries in PTCs compared to ATCs (4% vs. 37%–58% and 21% vs. 43%–53%, respectively).

The influence of a statewide trauma system on pediatric hospitalization and outcome was studied by Hulka et al. in 1997 [52]. They compared the frequency and mortality of pediatric trauma hospitalizations, based upon hospital discharge data abstracts, from two adjacent states with similar geography and demographics, one with and one without a statewide trauma system. They found the risk-adjusted mortality rate to be significantly lower in the state with the trauma system 6 months after its implementation. They concluded that triage to trauma centers saved many young lives.

An evidence-based review of all pediatric trauma system research reported to date was also prepared by Hulka for the Academic Symposium to Evaluate Evidence Regarding the Efficacy of Trauma Systems held in Stevenson, Washington, in 1998, also known as the Skamania Conference, and published the following year [53]. Hulka found that of the studies reviewed only two population-based studies evaluated the impact of trauma centers or trauma systems on children. One found that a trauma center did not improve the injured child's risk of death, while the other found that a statewide trauma system improved the risk of death in seriously injured children, although a third population-based study found a lower risk of death if the child was treated in an urban trauma center. It was concluded that since only two published studies had evaluated the care of injured children treated at trauma centers versus nontrauma centers and only one had examined the impact of a trauma system on pediatric outcome, further analysis was necessary to demonstrate that trauma systems make a difference in pediatric outcome, although all three studies had found that injured children had a reduced risk of death if treated at an urban trauma center [50–52].

The impact of PTCs on mortality in a statewide system was extensively studied by Potoka et al. in 2000 [54]. They performed a retrospective analysis of 13,351 children reported to a statewide trauma registry over a 5-year period, stratifying patients by mechanism of injury, ISS, specific organ injury, and type of trauma center. They found that most injured children were being treated at PTCs or ATCs with added pediatric qualifications, and that this improved survival rates. Moreover, the outcome for head, liver, and spleen injuries was better while laparotomy and splenectomy rates were lower at PTCs versus other types of centers.

Improved functional outcome for severely injured children treated at PTCs was also documented by Potoka et al. in 2001 [55]. They performed a retrospective analysis of 14,284 children reported to the same statewide trauma registry over the same 5-year period, stratifying patients both by type of trauma center and functional outcome. They found an overall trend toward better functional outcome at PTCs versus ATCs with added pediatric qualifications and large ATCs, but not versus small ATCs to which pediatric patients were rarely triaged. Moreover, significantly improved functional outcome was documented at discharge for head-injured patients treated at PTCs versus ATCs with added pediatric qualifications and large ATCs, but, once again, not versus small ATCs to which pediatric patients were rarely triaged.

The question of whether PTCs have better survival rates than ATCs was also studied by Osler et al. in 2001 [56]. They performed a retrospective analysis of the experience of trauma centers participating in the National Pediatric Trauma Registry over a 10-year period from 1985 to 1996, during which 53,113 cases were enrolled. While the overall mortality was lower at PTCs versus ATCs (1.8% vs. 3.9%), there was no difference in risk-adjusted mortality rate. Overall mortality was also lower at trauma centers verified by the American College of Surgeons Committee on Trauma as appropriate for pediatric trauma care.

Despite 10 years of progressively increasing evidence in favor of specialized pediatric trauma care, a survey conducted by Segui-Gomez et al. evaluating pediatric trauma care in 18 states demonstrated that 47% of pediatric trauma care was provided in nontrauma centers, while only 13% of injured children were treated in PTCs [57]. Remarkably, whether pediatric centers deliver better care than ATCs continues to be a subject of debate, although the evidence gleaned from recent studies continues to support the advantage of specialized pediatric trauma care. For example, Densmore et al. in 2006 analyzed 79,673 pediatric admissions from the KID database (a national database consisting of 27-state inpatient data). They found that while 89% of children were triaged to adult centers or adult centers with pediatric units, adult hospitals had in-hospital mortality rates and lengths of stay that were significantly higher than in children,s hospitals, especially for younger and more seriously injured children [58].

A more recent study by Amini et al. in 2011 reviewed the records of 11,053 injured children in Quebec, Canada between 1998 and 2005 [59]. They compared the mortality rates of children treated at ATCs versus those treated at PTCs, finding the risk of mortality, expressed as adjusted OR, to be greater for children treated at all other ATC levels (Level I OR = 3.1 [95% confidence interval [CI]: 1.3–7.5] Level II OR = 2.5 [95% CI: 1.3–5.0], Level III OR = 5.2 [95% CI: 2.1–13.1], Level IV OR = 9.9 [95% CI: 2.4–41.3]). Similar findings were observed among the subsamples of children who were more severely injured (ISS > 15) and who sustained head injuries.

Wang et al. in 2011 similarly examined the efficacy of the pediatric trauma system in California [60], investigating the outcomes of 77,874 children with nontrivial trauma. Trauma centers cared for 67% of patients with a mortality rate of 6.1%, nontrauma centers for 33% of patients with a mortality rate of 3.8%, owing to the higher percentage of proportionally more severely injured patients in trauma centers, 31.2%, versus nontrauma centers, 23.8%. However, of the 52,214 children cared for in a trauma center, PTCs cared for 38,836, or approximately three-fourths, with a mortality rate of 5.8%, while ATCs had a mortality rate of 6.3%. The Trauma Mortality Prediction Model was used to adjust for trauma severity, while regression analysis demonstrated a 0.79 percentage point (95% CI −0.80 to −0.30; $p = 0.044$) decrease in mortality for children cared for in trauma centers. No decrease in mortality was demonstrated for children cared for in PTCs versus ATCs.

The specific question of whether pediatric trauma patients can be optimally treated by adult trauma surgeons has been investigated by a number of authors. Knudson et al. and Fortune et al. in 1992 [61,62], Rhodes et al. in 1993 [63], Bensard et al. in 1994 [64], and D'Amelio et al. in 1995 [65], in comparing, respectively, 353, 303, 1115, 410, and 427 pediatric patients with the Multiple Trauma Outcome Study database regarding demographics, mechanism of injury, Revised Trauma Score, surgical procedures, intensive care, ISS, and outcome, found that overall fatality rates, respectively, of 6%, 8.9% (mean ISS 15.6), 2.5% (mean ISS 11.1), 2%, and 4.2% (mean ISS 11.5) compared favorably with national standards—while Partrick et al. in 2000 [66] and Sherman et al. [67] in 2002 found similar results with respect not only to mortality outcomes, but also to the management and outcomes of injuries to two specific body regions, the head and abdomen. Taken together, these studies provide strong evidence that adult trauma surgeons can provide appropriate care for pediatric trauma patients. However, what is not mentioned in any of these reports is that all institutions involved in these studies had the benefit of comprehensive pediatric inpatient facilities, including pediatric emergency care, pediatric intensive care, pediatric acute care, and perhaps most important yet most frequently overlooked, pediatric nursing care—indirectly supporting the notion that what is most critical in pediatric trauma care is proper emphasis on the special needs of pediatric patients throughout all phases of care, and validating the observation that when such provision is made, pediatric trauma patients can be expected to have optimal outcomes.

In summary, there now exists a substantial body of scientific evidence in support of the need for specialized pediatric trauma care. As with adult trauma care, such evidence has been difficult to obtain and substantiate, and has been limited by a number of confounding variables unique to pediatric patients—the relative infrequency of major pediatric trauma (despite the fact that it remains the leading public health problem of childhood), the sharply lower mortality rate of major pediatric trauma (about one-third the rate of major adult trauma fatalities), and the lack of statistically valid, reliable, risk-adjusted, population-based models to predict outcome after major pediatric trauma. While it is clear that trauma systems and trauma centers that make special provisions for the needs of injured children are likely to achieve better outcomes than those that do not, it is not known who or what is specifically responsible for this survival advantage. Although studies to date have lacked the statistical power to address these questions, the development and maintenance of a national trauma registry for children that is representative of the pediatric population as a whole—the ultimate goal of the American College of Surgeons National Trauma Data Bank®—will permit and promote the performance of such studies, and will allow further refinement of existing systems of pediatric trauma care to better suit the needs of the United States' injured children.

In conclusion, the implications of these research findings are clear. Trauma systems must ensure that the special needs of pediatric patients are met throughout the entire continuum of trauma care—from prevention through access, ambulance care, emergency care, operative and intensive care, acute care, recovery, and rehabilitation. To ensure that these goals are met at the system level, regional trauma advisory committees should invite representatives from the pediatric trauma care community to participate in all their activities on a permanent basis. To ensure these goals are met at the hospital level, all trauma center medical directors should assume personal responsibility to invite the participation of pediatric capable trauma professionals to the care of the pediatric trauma patient. To this end, reliance on the latest editions of the American College of Surgeons' *Consultation for Trauma Systems* [68] and *Resources for Optimal Care of the Injured Patient* [18] will ensure the needs of injured children are met in the system and the hospital alike, the principles of which are described in the section "Elements of Contemporary Pediatric Trauma System Design" with respect to the care of the pediatric trauma patient.

Elements of contemporary pediatric trauma system design

Pediatric trauma system

The pediatric trauma system is part of the fully inclusive regional trauma system, each component of which is pediatric capable. The regional trauma center and, ideally, the regional PTC are at the hub of the system. Area trauma centers may be needed in localities distant from the regional trauma center and must be capable of surgical management of pediatric trauma. All other hospitals in the region should participate as they are able, but must at least be capable of initial resuscitation, stabilization, and transfer of pediatric trauma patients. Finally, there must be a regional trauma advisory committee that includes pediatric representation, with the authority to develop and implement guidelines for triage of pediatric trauma patients within the system. The regional trauma system should also collaborate with the public health system in injury prevention, and with local public health, public safety, and emergency management agencies in disaster planning.

Pediatric trauma center

The PTC should be located in a trauma hospital with comprehensive pediatric services, such as a full service general, university, or children's hospital. This hospital must demonstrate an institutional commitment to pediatric trauma care, as evidenced by the provision of appropriate staff, equipment, and other resources necessary to care for the most seriously injured pediatric trauma patients. Pediatric medical and surgical subspecialty services and units must be present and should include pediatric trauma surgery, pediatric emergency medicine, pediatric critical care, pediatric neurosurgery, pediatric orthopaedics, pediatric radiology, and pediatric anesthesiology. Pediatric nursing and allied health professionals must also be present, and advanced life support training in trauma and pediatrics must be current for all staff who care for pediatric trauma patients. Finally, there must be an organized pediatric trauma service within the regional PTC, with separate medical leadership, nursing coordination, social services, and performance improvement. Regional PTCs must also support education and research in pediatric trauma and provide leadership in pediatric trauma system coordination, including pediatric disaster management.

Evidence in support of specialized prehospital care for pediatric trauma

Resuscitation

There is scant literature on prehospital pediatric trauma resuscitation. Those studies that exist focus chiefly on airway management, volume resuscitation, and cervical spine stabilization, and, collectively, suggest that less is more, that a "scoop and run" philosophy remains preferable to a "stay and play" approach for pediatric trauma patients, as is also true for adult trauma patients—especially since pediatric resuscitation skills are infrequently used in pediatric trauma patients [69,70]. Specifically, it appears that neither endotracheal intubation (ETI), nor medical antishock trousers (MAST), nor intravenous (IV) fluid improves the survival of pediatric trauma patients in the field, and that even under circumstances where volume resuscitation is utilized, the small volumes infused would be unlikely to have significant physiologic benefit. Furthermore, it appears that while cervical spine stabilization is critical for seriously head and brain injured patients, current methods are neither risk free nor optimally designed to achieve proper neutral positioning in the majority of pediatric trauma patients.

The first clue that prehospital pediatric ETI was potentially harmful came in a retrospective analysis of 496 injured patients of all ages published in 2000 by Eckstein et al. [71], who found that adjusted survival for major trauma patients aged 0–91 years of age requiring bag-valve-mask (BVM) ventilation was 5.3 times more likely than for those who underwent ETI (95% CI, 2.3–14.2, $p = 0.00$). The specific effect of out-of-hospital pediatric ETI on survival and neurological outcome was definitively studied by Gausche et al. and reported in 2000. These authors conducted a prospective randomized trial of consecutive pediatric patients less than 13 years of age [72], and found that mortality rates were similar between the two groups (26% vs. 31%, respectively), as was good neurological outcome (20% vs. 23%, respectively), including multiply injured and head-injured patients. However, while procedural complications were identical between the two groups (51% vs. 53%, respectively), scene times were longer for patients who were ventilated via tube rather than bag and mask (11 vs. 9 min).

In view of the relatively small numbers of head-injured patients in the above study—the very patients who might be expected to benefit most from definitive airway control—prehospital ETI for severe head injury in children was reviewed by Cooper et al. [73] in 2001. They performed a retrospective analysis of all 578 severely (Abbreviated Injury Scale [AIS] ≥ 4) head-injured patients reported to the National Pediatric Trauma Registry during its last 5 years of operation who required prehospital airway management (ETI in 83% vs. bag and mask in 17%), finding that mortality rates were identical between the two groups (48% vs. 48%, respectively), intubated patients being older, more often transported by helicopter, and more often resuscitated with fluid. As before, procedure or equipment failure or complications were identical between the two groups—as were functional outcomes—but injury complications occurred less often in intubated patients than in masked patients (58% vs. 71%, respectively), for reasons that could not be explained. Extending on the previous study, DiRusso et al. [74] looked at 5460 children in the National Pediatric Trauma Registry between 1994 and 2002 who were intubated in the field for any indication, finding that the actual (observed) death rate, based on a logistic regression model, was significantly higher than predicted among those intubated in the field regardless of injury severity.

The absence of survival benefit and the high rate of complications associated with prehospital pediatric ETI have led most EMS systems and agencies to allow these only in cases when airway control is needed but cannot be achieved by other means. Carlson et al. [75] recently confirmed the unacceptably high failure rate of 26% for this procedure in looking at 3049 pediatric intubation attempts in children less than 18 years of age reported to the National Emergency Medical Services Information System. The proliferation of supraglottic airway devices, such as the laryngeal mask airway (LMA) and the King laryngeal tube-disposable (LT-D), which require less training and are less challenging than ETI, have shown promising results. In a pilot study of simulated prehospital pediatric cardiopulmonary arrest by Chen and Hsaio [76] in 2008, paramedics achieved effective ventilation in 23 seconds via LMA versus 46 seconds via ETI with fewer attempts and fewer complications, while in a similar study of simulated pediatric respiratory arrest by Ritter and Guyette in 2011, 41 of 45 paramedics (95.5%) successfully placed the King LT-D on the first attempt with a mean time to placement of 34 seconds [77].

The efficacy of MAST use in injured children who present in hypotensive shock was examined by Cooper et al. [78] in 1992. They reviewed the experience of the National Pediatric Trauma Registry over a 4-year period in 179 hypotensive (systolic blood pressure [SBP] ≤ 80 mmHg) children (age ≥ 5 years), of whom 48 (27%) were treated with MAST. The MAST patients were somewhat older (12.6 vs. 10.3 years) and more severely injured (pediatric trauma score [PTS] 1.9 vs. 3.8, ISS 35.3 vs. 25.8), but were otherwise similar to controls. However, survival was dramatically lower in patients treated with MAST (25% vs. 48%). Those with severe injuries (PTS ≤ 4, ISS ≥ 20) or who were severely hypotensive (SBP ≤ 50 mmHg), were neither helped nor hurt by MAST use, presumably because their injuries were of such great severity that survival was uncommon.

The efficacy of prehospital volume resuscitation in injured children who present in hypotensive shock was examined by the same group [79] in 1993. They reviewed the experience of the National Pediatric Trauma Registry over a 5-year period in 1727 hypotensive children (SBP ≤ 80 mmHg < 5 years of age, SBP ≤ 90 mmHg ≥ 5 years of age), of whom 386 (22%) were treated with IV fluid in the field. The fluid patients were significantly older (8.9 vs. 3.7 years) and more severely injured (PTS 4.1 vs. 7.3, ISS 26 vs. 10), more severely head injured (Glasgow Coma Scale [GCS] 8 vs. 10), more hypotensive (SBP 62 vs. 79), and more often victims of motor vehicle crashes and gunshot wounds but less often victims of falls. Once again, survival was significantly lower in patients treated with fluid (52% vs. 89%), a finding that was independent of age, injury severity, and SBP, except among patients with severe injuries (ISS ≥ 20) or profound hypotension (SBP ≤ 50 mmHg), most of whom died.

The efficacy of intraosseous (IO) fluid infusion either in the field or in the emergency department in injured children who present in hypotensive shock was also examined by this group [80] in 1993. They reviewed the experience of the National Pediatric Trauma Registry over a 5-year period in 405 hypotensive (SBP ≤ 80 mmHg) children (age < 5 years), of whom 33 (8%) were treated with IO fluid. The IO patients were far more severely injured (PTS −0.1 vs. 5.6, ISS 33 vs. 16), far more severely head injured (GCS 4 vs. 11), far more hypotensive (SBP 29 vs. 67), but were similar in age and sex. Survival was dramatically lower in patients treated with fluid versus unmatched controls (12% vs. 80%); survival was also significantly lower in patients treated with fluid versus controls matched by severity of injury.

The effectiveness of prehospital fluid therapy in pediatric trauma patients was also reviewed by Teach et al. [81] in 1995. They reviewed the ambulance trip and emergency department records of 50 pediatric patients less than 18 years of age (average age 9.6 years) who received IV fluid in the prehospital setting. They found that the combined total prehospital time (scene time plus transport time) did not differ whether the IV catheter was placed at the scene or in the ambulance (25.6 vs. 25.5 minutes, respectively), while the average prehospital infusion volume was only 4.4 mL/kg (range 0–17 mL/kg), or less than 25% of the dose prescribed in regional advanced life support protocols. They also determined that of the 50 patients reviewed, the intervention was possibly beneficial in two, possibly detrimental in one, and inconsequential in the remainder.

Owing to the different injury patterns typically sustained by children (1) who mostly sustain blunt trauma, (2) among whom hemodynamic instability is relatively infrequent [82], and (3) for whom IV access is more difficult as a result of smaller, collapsible vessels and increased subcutaneous fat, many have questioned the role of prehospital volume resuscitation in injured children. A retrospective review by Vella et al. [83] in 2006 revealed that only 50% of children received two peripheral IV lines and that only 10% of children required more than a single fluid bolus. The only predictor for the need of fluids was ISS. Although this study was conducted after patient arrival in the PTC, it does suggest that the time and effort needed to establish a second IV line in the field may not be needed, and may detract from other priorities.

While the preceding investigations, taken together, suggest that prehospital volume resuscitation, whether via the IV or IO route, may add limited value to the care of the injured child in the field, recent evidence compiled by the Joint Theater Trauma Registry of the American military medical services during the Middle Eastern conflicts suggests that the use of commercially available arterial tourniquets is no less effective in children than in adults. Kragh et al. [84] in a retrospective review of the use of such tourniquets in 88 pediatric casualties reported over a 6 ½-year period from 2003 to 2009 documented a survival rate in this cohort of 93%. Survivors and nonsurvivors were similar in all independent variables except duration of hospital stay, which was 5 days for survivors and 1 day for nonsurvivors. Although no civilian data have yet been published on tourniquet use in children with otherwise uncontrollable extremity bleeding, the military experience with these devices was deemed sufficient by an expert panel for the American College of Surgeons Committee on Trauma to promulgate an Evidence-Based Prehospital Guideline for External Hemorrhage Control that supported tourniquet use in children [85].

Emergency transport and positioning in young children who have an injury of the cervical spine were investigated by Herzenberg et al. in 1989 [86]. They found that in 10 children less than 7 years old, an unstable injury of the cervical spine had anterior angulation or translation, or both, on initial lateral radiographs that were made with the child supine on a standard backboard. Supine and lateral radiographs of 72 children who did not have a fracture also demonstrated more relative cervical kyphosis in younger children when they were in the supine position. They concluded that to prevent undesirable cervical flexion in young children during emergency transport and radiography, a standard backboard should be modified to provide safer alignment of the cervical spine, either through use of a recess for the occiput or a double mattress pad.

The respiratory effects of spinal immobilization in children were studied by Schafermeyer et al. in 1991 [87]. They performed a prospective study of the restrictive effects of two spinal immobilization strapping techniques on the respiratory capacity of 51 normal, healthy children (age 6–15 years) by measuring forced vital capacity in the standing, supine, and fully immobilized positions. They found a 20% (range 4%–59%) reduction in forced vital capacity regardless of strapping technique. They concluded that spinal immobilization significantly reduced respiratory capacity in children.

Neutral cervical spine positioning was further researched by Nypaver and Treolar [88] in 1994. They measured the height of back elevation required to place the cervical spine in a neutral position in a convenience sample of children less than 8 years old, finding that (1) all children required elevation of the back for correct neutral position (mean height 25.5 mm, range 5–41 mm), and (2) children less than 4 years old required more elevation than older children (27 vs. 22 mm). Extending their investigations in 1997, Treolar and Nypayer [89] prospectively evaluated semirigid cervical collars in eliminating cervical spine flexion in children on backboards. They used C-spine radiographs on 18 children less than 8 years of age by measuring the C2–C6 lateral Cobb angles before and after the semirigid collar was removed. In finding 3.4 ± 9.9 versus 5.6 ± 6.8 degrees of cervical flexion ($p < .05$), they showed that extrication collars then in use failed to fully eliminate cervical flexion.

Achieving neutral position with pediatric cervical spine immobilization was also examined by Curran et al. in 1995 [90]. They conducted a prospective evaluation of current spine immobilization devices in achieving radiographic neutral positioning of the cervical spine in 118 pediatric trauma patients by obtaining lateral cervical spine radiographs while these patients remained fully immobilized. They found that 60% of patients had excessive kyphosis or lordosis, 50% were in excessive flexion, and that no single device or technique (collar, backboard, and towels and collar, backboard, and blocks were most frequently used) appeared to provide superior protection from angulation. No single method or combination of methods consistently achieved a neutral position.

The question of whether prehospital cervical spine immobilization can be safely avoided in pediatric patients with minor injuries has not been answered definitively. Attempts were made by Jaffe et al. [91] and Rachesky et al. [92] in 1987 to develop clinical prediction rules that would reliably determine which of these patients had sufficiently low risk of cervical spine injury to justify omission of cervical spine stabilization in the prehospital setting but neither was sufficiently accurate. However, the National Emergency X-Radiography Utilization Study (NEXUS) criteria for clinical prediction of cervical spine injury established by Hoffman et al. [93] in 2000 were applied to pediatric trauma patients by Viccellio et al. [94] in 2001, and appeared to perform well, with 100% sensitivity and negative predictive value (95% CIs of 88%–100% and 99%–100%, respectively). Even so, the authors urged caution in applying the results due to the small size of the study, certainly a wise recommendation in view of the known risks of spinal cord injury without radiographic abnormality and atlantoaxial instability, especially in patients with Down syndrome [95,96].

Ehrlich et al. [97] in 2009 also examined the application of the NEXUS criteria, as well as those of the Canadian C-spine rule (CCR), by retrospective analysis of age-matched trauma patients 10 years of age and younger. They formed two groups, in one of which imaging of the cervical spine was performed, while in the other no such imaging was performed. They then applied the NEXUS and the low-risk CCR criteria to each group, finding that the NEXUS criteria had a sensitivity of 43% and a specificity of 96%, while the CCR had a sensitivity of 86% and a specificity of 94%. As such, they concluded that neither rule is sensitive nor specific enough to be used in children younger than 10 years old.

Another retrospective study of the need for cervical spine clearance—and by extrapolation, the need for prehospital cervical spine stabilization—in children younger than 3 years of age was conducted by Pieretti-Vanmarcke et al. [98] on behalf of the American Association for the Surgery of Trauma. Based on a review of the experience in 22 trauma centers throughout America, they developed a score that assigned points as follows: GCS < 14 (3 points), GCS eye opening = 1 (2 points), motor vehicle accident (2 points), and age > 2 years (1 point). A score <2 had a negative predictive value of 99%, a sensitivity of 93%, and a specificity of 70%, while only five patients (0.06%) with a score <2 had a cervical spine injury. Owing to the difficulty of establishing easy-to-use clinical prediction rules for cervical spine clearance—and, again, by extrapolation, the need for prehospital cervical spine stabilization—the federally supported Pediatric Emergency Care Applied Research Network (PECARN) also conducted a study to determine factors associated with cervical spine injury in children after blunt injury [99]. Based on a study involving 540 children compared with 1060, 1012, and 760 random, mechanism of injury, and EMS controls, they identified a number of factors associated with cervical spine injury in children after blunt trauma: altered mental status, focal neurologic findings, neck pain, torticollis, substantial torso injury, and conditions predisposing to cervical spine injury (e.g., diving and high-risk motor vehicle crashes). One of the aspects limiting the ability to devise accurate clinical prediction rules, of course, is relative rarity of cervical spine injuries in young children, which in a recent systematic review of the problem by Schöneberg et al. was found to be only 1.4% [100]. While, in contrast to the conclusions reached by Treolar and Nypaver cited above [89], they stated that the cervical spine in children can be cleared by a combination of NEXUS low-risk criteria and the CCR, they also advised caution in applying these rules, especially to nonverbal and/or unconscious children, the very patients in whom the diagnosis of cervical spine injury is most likely to be missed—not unlike the caution Viccellio et al. [94] recommended in their comments regarding the application of NEXUS to the pediatric population.

Triage

Most regional pediatric prehospital trauma triage criteria are based upon the original American College of Surgeons Field Trauma Triage Decision Scheme, which includes anatomic, physiologic, mechanistic, and comorbid criteria including age less than 5, and which have been twice revised since this monograph was first published [101,102]. The PTS was also developed as a field triage tool that correlates closely with ISS as a predictor of mortality [103]. However, the Revised Trauma Score performs nearly as well as the PTS—despite the fact that it is based upon adult vital signs—presumably because abnormalities in respiratory rate (RR) and GCS score tend to correlate in seriously injured pediatric patients, most of whom have serious traumatic brain injury, thereby giving “double weight” to those components of the score most likely to be abnormal following head injury [104]. Yet, both scores require calculation in the busy prehospital setting, calling for simpler tools requiring no added calculations that would minimize both undesirable overtriage and unacceptable undertriage.

To assess patterns of pediatric trauma triage and patient transfer to regional PTCs and proximate ATCs based upon use of the anatomic, physiologic, and mechanistic criteria delineated in the American College of Surgeons Field Triage Decision Scheme, a review of 1307 pediatric trauma cases was conducted by Jubelirer et al. [105] in 1990. The study was performed in eight Level II trauma centers surrounding a major metropolitan statistical area that contained two regional PTCs. They found that while 43 patients were transferred to the regional PTCs based on local criteria, the remaining 1264 patients were treated in the Level II trauma centers, with outcomes that compared favorably to those in other published reports. They concluded that patients with moderate but not severe injuries (PTS > 8) could be successfully managed by Level II trauma centers—although the observed mortality rate of 1.8% suggests that at least some patients who died, all of whom clearly had serious injuries (PTS ≤ 8), might have fared better at a PTC.

The need for pediatric-specific triage criteria was reinforced following publication of the results of a statewide trauma triage study by Phillips et al. [106] in 1996. They performed a retrospective analysis of state trauma registry data and state hospital discharge data in a nine-county region to determine if use of the state trauma triage "scorecard" based upon the American College of Surgeons Field Triage Decision Scheme resulted in appropriate categorization as "major" or "minor" trauma according to standardized protocols developed by an expert medical panel. They found that of the 1505 pediatric cases available for analysis, which accounted for 9% of the total study population, 6% of all hospitalized cases, and 7% of all trauma deaths, there was a 15% overtriage rate and a 33% undertriage rate, well above the 5% target rates for acceptable overtriage and undertriage. They concluded that new pediatric triage instruments were needed to avoid unacceptable undertriage.

To this end, a better alternative for predicting inpatient mortality for pediatric trauma patients with blunt injuries was reported by Hannan et al. [107] in 2000. They performed a retrospective review of 2923 seriously injured (ISS ≥ 8) pediatric patients (age ≤ 12 years) reported to a single state's trauma registry over a 2-year period. They tested all variables from the PTS and the Revised Trauma Score, as well as the individual components of the GCS Score, the Alert, Voice, Pain, Unresponsive (AVPU) Score, the ISS, the International Classification of Disease (ICD)-9 based Injury Severity Score (ICISS), and age-specific SBP, finding that the only significant independent predictors of mortality were ICISS, a best motor response of 1 from the GCS Score, and the unresponsive category from the AVPU Score—the latter two being readily available to prehospital personnel. Moreover, the sensitivity and specificity of both measures exceeded 90%.

Prehospital triage in the injured pediatric patient was also studied by Engum et al. [108] in 2000. They performed a prospective analysis of 1295 pediatric trauma patients versus 1326 adult trauma patients who died in the emergency department, underwent operation, or were admitted to the intensive care unit, as indicators of the need for specialized trauma care. They found that the most accurate criteria for prediction of major injury were SBP ≤ 90 mmHg, burn ≥ 15% of total body surface area, GCS ≤ 12, RR ≥ 29 breaths per minute, and paralysis, while less accurate criteria for major injury were fall > 20 feet, penetrating trauma, vehicle ejection, paramedic judgment, vehicle rollover, and need for vehicle extrication. Using these criteria, they found an overtriage rate of 71% but an undertriage rate of 0%, with the Revised Trauma Score and PTS missing 30% and 45% of major trauma patients, respectively.

The specific question of whether specialized tools for pediatric trauma team activation and for pediatric helicopter triage could improve pediatric trauma staff utilization and pediatric trauma survival rates without excessive overtriage rates has also been investigated. Sola et al. [109] in 1994, in a study of 952 children treated at a regional PTC over a 1-year period, found that pediatric trauma triage criteria had a sensitivity of 86% in predicting which trauma patients would require either an operation or pediatric intensive care, while maintaining a specificity of 98%. Moront et al. [110] in 1996, in a study of 3861 injured children treated at a regional PTC over a 4-year period, found that helicopter transport was associated with better survival rates than ground transport, and that pediatric helicopter triage criteria based on GCS score and heart rate improved helicopter resource utilization without compromising care, although substantial overtriage rates were observed. However, Kotch and Burgess [111] in 2002, in a study of 969 patients transported to a regional trauma center by helicopter over a 5-year period, of whom 143 patients were children, found no differences in triage scores, injury severity, or survival probability in children versus adults, although pediatric lengths of stay were slightly shorter.

Recognizing that the American College of Surgeons Field Triage Decision Scheme likely required significant revision based upon new evidence, the CDC in 2005 convened an expert panel to review this evidence and recommend changes to the triage algorithm. The revised algorithm was published in 2006 as *Guidelines for Field Triage of Injured Patients* [101]. These *Guidelines* were modified for children versus adults in only two ways: (1) under "Step One," the physiologic component, the lower limit of acceptable RR was increased from <10 breaths per minute to <20 breaths per minute for infants aged less than 1 year, and (2) under "Step Three," the mechanistic component, the upper limit of acceptable fall height was decreased from >20 to >10 feet or two to three times the height of the child. It was also stated, under the final "Step Four" of the *Guidelines*, that children should be triaged preferentially to pediatric-capable trauma centers.

Recognizing the paucity of reliable data upon which to base triage recommendations in children, Newgard et al. [112] in 2007 reported the results of their evaluation of the predictive value and appropriate ranges of prehospital physiologic parameters in 3877 high-risk injured children less than 14 years of age from Oregon State Trauma Registry, finding prehospital GCS to be the variable of greatest importance in identifying high-risk children, followed by airway intervention, RR, heart rate, SBP, and shock index, and that there was a linear relationship between GCS and outcome that was consistent across all groups through age 14. Specific age-based ranges of other physiological measures were also identified for high-risk children. Extending their previous work, Newgard et al. [113] later conducted a multisite assessment of the 2006 *Guidelines* in identifying seriously injured children and adults, finding that the 2006 *Guidelines* appeared to have lower sensitivity but higher specificity in both groups than the previous American College of Surgeons Field Triage Decision Scheme, particularly among elders ≥55 years.

The most recent edition of the *Guidelines for Field Triage of Injured Patients* was published in 2012 by the CDC, again based on the recommendations of a National Expert Panel on Field Triage meeting in 2011. The revised algorithm is shown in Figure 2.2 [102]. The *Guidelines* were again

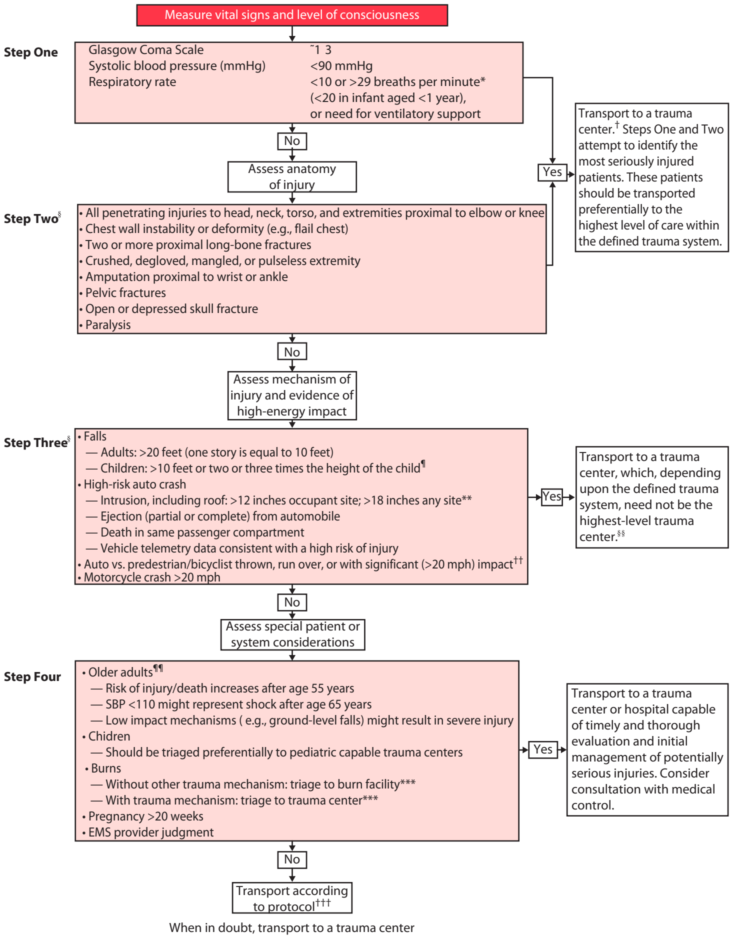

Figure 2.2 Guidelines for field triage of injured patients—United States, 2011. The figure shows the revised field triage guidelines (previously termed the "field triage decision scheme") developed in 2011 for use by emergency medical services (EMS) providers to determine the most appropriate destination hospital for injured patients. The guidelines have four steps: (1) assessing physiologic criteria, (2) assessing anatomic criteria, (3) assessing mechanism-of-injury criteria, and (4) special considerations. Steps One and Two attempt to identify the most seriously injured patients. These patients should be transported preferentially to the highest level of care within the defined trauma system. For Step Three, persons meeting these criteria should be transported to a trauma center, which, depending upon the defined trauma system, need not be the highest level trauma center. Those meeting Step Four criteria should be transported to a trauma center or hospital capable of timely and thorough evaluation and initial management of potentially serious injuries, and consultation with EMS medical control should be considered.

*The upper limit of respiratory rate in infants is >29 breaths per minute to maintain a higher level of overtriage for infants.

†Trauma centers are designated Levels I–IV. A Level I center has the greatest amount of resources and personnel for care of the injured patient and provides regional leadership in education, research, and prevention programs. A Level II facility offers similar resources to a Level I facility, possibly differing only in continuous availability of certain subspecialties or sufficient prevention, education, and research activities for Level I designation; Level II facilities are not required to be resident or fellow education centers. A Level III center is capable of assessment, resuscitation, and emergency surgery, with severely injured patients being transferred to a Level I or II facility. A Level IV trauma center is capable of providing 24-hour physician coverage, resuscitation, and stabilization to injured patients before transfer to a facility that provides a higher level of trauma care.

§Any injury noted in Step Two or mechanism identified in Step Three triggers a "yes" response.

¶Age <15 years.

**Intrusion refers to interior compartment intrusion, as opposed to deformation which refers to exterior damage.

††Includes pedestrians or bicyclists thrown or run over by a motor vehicle or those with estimated impact >20 mph with a motor vehicle.

§§Local or regional protocols should be used to determine the most appropriate level of trauma center within the defined trauma system; need not be the highest level trauma center.

¶¶Age >55 years.

***Patients with both burns and concomitant trauma for whom the burn injury poses the greatest risk for morbidity and mortality should be transferred to a burn center. If the nonburn trauma presents a greater immediate risk, the patient may be stabilized in a trauma center and then transferred to a burn center.

†††Patients who do not meet any of the triage criteria in Steps One through Four should be transported to the most appropriate medical facility as outlined in local EMS protocols.

modified for children in only two ways: (1) under the first step, the physiologic component, now entitled "measure vital signs and level of consciousness," the lower limit of acceptable RR still remained increased from <10 to <20 breaths per minute for infants; and (2) under the third step, the mechanistic component, now entitled "assess mechanism of injury and evidence of high-energy impact," the upper limit of acceptable fall height again remained decreased from >20 to >10 feet or two to three times the height of the child. Moreover, it again stated, under the final step of the *Guidelines*, entitled "assess special patient or system considerations," that children should be triaged preferentially to pediatric-capable trauma centers.

The appropriateness of the 2011 *Guidelines* with respect to pediatric patients is currently being studied by a research group based at the Medical College of Wisconsin with support from the federal EMSC Program. *The evaluation of the accuracy of the first step of the Guidelines*, the physiologic component, has recently been accepted for publication. Similar analysis of the second step, the anatomic component, has recently been completed, and is expected to be published soon thereafter. However, to most accurately relate pediatric trauma triage guidelines to the need for specialty pediatric trauma care, and provide a more uniform approach to future research efforts in pediatric trauma triage, the group has also developed a consensus-based criterion standard definition for the evaluation of pediatric trauma patients who needed the highest level trauma team activation [114].

Elements of contemporary pediatric prehospital trauma care

Pediatric trauma resuscitation should begin as soon as possible after the injury occurs, ideally through pediatric-capable emergency medical dispatchers who provide prearrival instructions to lay rescuers at the scene. It continues with the arrival of prehospital professionals, including first responders, emergency medical technicians (EMTs), and paramedics. Prehospital treatment protocols utilized by these emergency medical personnel should be conservative yet permissive, emphasizing basic life support modalities such as supplemental oxygen and assisted ventilation via bag and mask, only providing advanced life support interventions such as ETI and volume resuscitation when appropriate [115]. Pediatric prehospital trauma care emphasizes aggressive support of vital functions during what has been called the "platinum half hour" of early pediatric trauma care [116].

Pediatric trauma protocols utilized by emergency medical personnel begin with an analysis of scene safety, including a survey for hazardous materials—and, if the scene is safe, continue with formation of a general impression of the urgency of the patient's condition, utilizing the "Pediatric Assessment Triangle" to obtain a rapid evaluation of the patient's *A*ppearance, work of *B*reathing, and *C*irculation to skin [117,118]. Prehospital trauma professionals next proceed to the primary survey, or initial assessment, of the airway, breathing, circulation, and disabilities, with an emphasis on detection and management of neuroventilatory rather than hemodynamic abnormalities, the former being some five times more common than the latter [82] in pediatric trauma patients. The secondary survey, or focused history and detailed physical examination, is performed next—but is omitted entirely, or performed en route, if the patient is less than fully stable. Because of the need for specialized pediatric trauma care, injured children should be transported to the nearest pediatric-capable trauma center, keeping the child warm.

Prehospital professionals are our "prehospital pediatric trauma surgeons" and must be fully trained in all aspects of prehospital pediatric trauma resuscitation if they are to be effective in this role. The National EMS Scope of Practice Model currently recognizes four prehospital professional levels: (1) emergency medical responders (EMRs) currently receive 40–50 hours of training in oxygen administration, use of airway adjuncts, assisted ventilation via bag and mask, bleeding control, splinting, and immobilization, only 6 of which hours are in pediatric care [119]; (2) EMTs currently receive 110–120 hours of training, including all of the above, plus additional training in lifts, carries, and ambulance transport, only 10 of which hours are in pediatric care [120]; (3) advanced EMTs currently receive 180–200 hours of training, including all of the above, plus additional training in administration of medications deemed vital to advanced life support [121]; and (4) paramedics currently receive 1000–1200 hours of training, including all of the above, plus additional training in ETI, needle cricothyroidotomy, needle decompression of probable tension pneumothorax, and IV and IO access for volume resuscitation, only 20 of which hours are in pediatrics [122].

Prehospital professionals, previously taught utilizing National Standard Curricula developed for each level of practice, which were periodically revised on an ad hoc basis, are currently being taught in accordance with the *Instructional Guidelines* cited in the preceding paragraph, based upon *National Emergency Medical Services Education Standards* [123], consistent with the recently updated *EMS Education Agenda for the Future* [124]. An "andragogical" versus a "pedagogical" approach is taken to teaching, based upon modern principles of adult education, and the "need to know" versus what might be "nice to know." The curricula are, for the most part, "assessment based" rather than "diagnosis based," and thereby focus on presenting problems rather than underlying illnesses and injuries. Pediatric educational modules follow upon adult educational modules, to allow the limited pediatric curricular hours to be used most efficiently, and should be regularly and generously supplemented by up-to-date continuing trauma education programs such as the *Prehospital Trauma Life Support (PHTLS) Course* of the

National Association of Emergency Medical Technicians and the American College of Surgeons, as well as up-to-date continuing pediatric education programs such as the *Pediatric Emergencies for Prehospital Professionals (PEPP) Course* of the American Academy of Pediatrics [125,126].

Pediatric equipment is mandatory for the successful resuscitation of critically injured children in the prehospital setting. Minimum standards for pediatric equipment in ambulances at both the basic life support and advanced life support levels have been published by the American Academy of Pediatrics, the American College of Emergency Physicians, the American College of Surgeons Committee on Trauma, the Federal Emergency Medical Services for Children Program, the Emergency Nurses Association, the National Association of EMS Physicians, and the National Association of State EMS Officials, as summarized in Table 2.5 [13]. Although medications required by children differ little from those needed by adults, drug dosages, for the most part, are determined on the basis of size. The use of color-coded tapes that key drug doses and equipment selection to body length has proved effective in the field and is now standard equipment in most agencies [127], although their accuracy has recently been questioned [128,129] and alternative methods proposed [130–132].

Table 2.5 Minimum standards for pediatric equipment in ambulances

Minimum standards for pediatric equipment in basic life support (BLS) ambulances
Pediatric stethoscope, infant/child attachments
Pediatric blood pressure cuffs, infant/child sizes
Disposable humidifier(s)
Pediatric simple/nonrebreathing oxygen masks, all sizes
Pediatric face masks, all sizes
Pediatric bag-valve devices, infant/child sizes
Pediatric airway adjuncts, all sizes
Pediatric suction catheters, all sizes
Pediatric Yankauer device
Pediatric extrication collars, all sizes
Pediatric extrication equipment (including infant car seat)
Pediatric limb splints, all sizes
Minimum standards for pediatric equipment in advanced life support (ALS) ambulances
All of the above, plus . . .
Pediatric endotracheal tubes, all sizes
Pediatric stylets, all sizes
Pediatric laryngoscope blades, all sizes
Pediatric Magill (Rovenstein) forceps
Pediatric intravenous catheters, all sizes
Pediatric intraosseous needles, all sizes
Pediatric nasogastric tubes, all sizes
Pediatric ECG electrodes
Pediatric defibrillator paddles, infant/child sizes
Pediatric dosage-packed medications/fluids
Pediatric dosage/volume wall chart
Mini-drip intravenous infusion sets

Pediatric interfacility transport is a key component of pediatric trauma care, and many pediatric comprehensive care centers have established specialized teams for interfacility transport of critically ill and injured patients for this purpose. However, pediatric interfacility transport is not risk free, as adverse events such as plugged endotracheal tubes and loss of vascular access occur at nearly twice the rate during interfacility transport as in the pediatric intensive care unit, and 10 times more frequently with nonspecialized teams than with specialized teams [133,134]. At a minimum, transport providers must be capable of critical pediatric assessment and monitoring, and must be highly skilled in the techniques of pediatric ETI and vascular access, as well as fluid and drug administration in critically ill and injured children [135,136]. Whenever possible, interfacility transport of such patients should be conducted by specialized pediatric transport teams staffed by physicians and nurses with special training in pediatric critical care treatment and transport [137,138].

Pediatric ambulance patient transport involves both a different purpose and a different environment than pediatric automobile passenger transport. The ambulance patient compartment is open and large, contains numerous heavy pieces of equipment, and carries restrained patients and passengers and unrestrained providers in a wide variety of places and positions. However, in contrast to automobile passenger safety, formal standards are not yet developed regarding ambulance occupant protection. This unfortunate situation obtains despite the documented lethal hazards of ambulance crashes, which are 10 times more common per passenger mile than automobile crashes [139].

Pediatric ambulance patient transport, though inherently unsafe, can be made less hazardous through use of safe driving practices and effective restraint of patients, passengers, providers, and equipment. Unfortunately, many commercially available restraint devices are ineffective, but are not known to be so because they have been subjected only to static testing at the laboratory bench rather than dynamic testing in a moving ambulance [140]. Fortunately, recent evidence suggests that safe restraint of a child occupant can be achieved through the use of a child safety seat when secured to the ambulance stretcher using two standard ambulance gurney belts [141]. Yet, the most important step in ensuring safe transport of ill or injured pediatric patients is to ensure that all personnel, most especially ambulance drivers, regularly follow the Do's and Don'ts recently issued by the NHTSA and the EMSC, as shown in Table 2.6 [142].

Table 2.6 The Do's and Don'ts of transporting children in an ambulance

Do's

DO drive cautiously at safe speeds observing traffic laws.
DO tightly secure all monitoring devices and other equipment.
DO ensure available restraint systems are used by EMTs and other occupants, including the patient.
DO transport children who are not patients, properly restrained, in an alternate passenger vehicle, whenever possible.
DO encourage utilization of the DOT NHTSA Emergency Vehicle Operator Course (EVOC), National Standard Curriculum.

Don'ts

DO NOT drive at unsafe high speeds with rapid acceleration, decelerations, and turns.
DO NOT leave monitoring devices and other equipment unsecured in moving EMS vehicles.
DO NOT allow parents, caregivers, EMTs, or other passengers to be unrestrained during transport.
DO NOT have the child/infant held in the parent's, caregiver's, or EMT's arms or lap during transport.
DO NOT allow emergency vehicles to be operated by persons who have not completed the DOT EVOC or equivalent.

SUMMARY

Organizing the community for pediatric trauma not only specialized knowledge of the evaluation and management of childhood injury, including pediatric injury prevention and EMS for children, but also unwavering commitment to ensure that the specialized needs of injured children are met at every level of system organization. Mature understanding of the trauma system as a public good and practiced application of the interpersonal and organizational skills necessary to lead and manage complex undertakings are also mandatory for the trauma professional who seeks to influence the provision of care in a given region. While the principles of pediatric trauma and EMS system design may be simple, they are not always easy to implement without a clear understanding that pediatric trauma care is a truly collaborative venture which requires the coordination of numerous professionals and services from many different disciplines and agencies, all of which have a stake in the care of the injured child.

The benefits to the community that chooses to organize itself for pediatric trauma care are self-evident, even—perhaps especially—to those with whom the system itself may not interact or interface on a regular basis. For example, civic and business leaders have a major stake in the development and support of the community pediatric trauma system. Childhood injuries cost time and money, not only from the involved families, but also from their employers and their insurance companies. There is ample ground to make common cause with such community partners, for whom the well-being of children is clearly no less important than to public health and trauma care professionals. Indeed, it is the one health care benefit on which all agree—the need for systems and services that keep children healthy.

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3

Disaster planning and mass casualties

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Introduction

Recent disasters and mass casualty events, both natural and man-made, have highlighted the need for both hospitals and communities to prepare for a surge in casualties. The unpredictability of many crises and the subsequent stress on the system make disaster planning difficult and expensive. Although emergency planning agencies and strategies are in place to respond to mass casualties across the United States, problems are usually local or regional and the specific needs of children are often overlooked. Children add variability to all plans because they present a variety of ages, physiology, psychology, and disabilities that are challenging to account for in most plans. In recent crises, children presented unique vulnerabilities that caused many leaders to pause and consider children in broader emergency planning strategies and tactics. In this chapter, we focus on the changing demographics of disasters, unique challenges for pediatric patients, and the ongoing needs for children before, during, and after the catastrophic event.

Recent events highlight need for planning

Man-made and natural disasters are difficult to predict and large in scope. They often overwhelm the capacity of the response system despite previous planning. It is common for jurisdictions to determine their hazard vulnerability and use this analysis as a guide for system-wide emergency planning. Recent global mass casualty events such as the Indian Ocean tsunami (2004), Hurricane Katrina (2005), the earthquakes in China (2008) and Haiti (2010), and Superstorm Sandy (2012); man-made events including the 9/11 terrorist attacks (2001), the wars in Iraq, Afghanistan, and the civil war in Syria, multiple mass shootings in the United States as well as the terrorist attacks in Paris (2015); and disease pandemics such as the H1N1 influenza (2009) and Ebola outbreaks (2014) provide ample evidence for how vulnerable modern and less developed societies are and why systems need to be fortified for such mass impact events that will eventually impact your region. Each of these disasters has involved significant numbers of pediatric survivors and highlights the need for special consideration for pediatric disaster preparedness.

We and others have shown in recent publications that outcomes are improved when disaster planning incorporates the needs of the pediatric population [1–3]. Children are a vulnerable population during disasters due to a multitude of factors, encompassing the entire timeline from preparation pre-event to recovery after the disaster [4]. Children may not be able to seek shelter or evacuate from an area of danger before the onset of the disaster, or to identify themselves or their caregivers. They may be unable to communicate verbally because of their young age or developmental delay. They may show regression behaviors due to confusion from chaos and may suffer severe anxiety and posttraumatic stress due to the trauma. The incorporation of behavioral health professionals, such as psychologists, psychiatrists, and child life specialists, can help address the psychosocial needs of children and their families during pandemics. Recent mass casualties such as Hurricane Katrina and Superstorm Sandy, where many children were displaced or separated from their families, to school shootings such as Sandy Hook have highlighted the importance of pediatric disaster behavioral health needs [5]. Although the recommendations from national organizations are varied, five guiding principles set forth by the authors of Reference [5] should be considered in facilitating a behavioral health response for children and families during a disaster: (1) employ the language of resilience to prevent adverse outcomes when an individual's capacity to cope has been overwhelmed and functional impairment is evident; (2) describe responses, roles, and responsibilities for behavioral health professionals in context of the type of disaster, and develop, nurture, and maintain relationships with public health professionals as part of disaster preparedness; (3) promote interdisciplinary coordination and collaboration during planning; (4) provide focused guidance on pediatric preparedness and response; and (5) facilitate professional awareness and knowledge through evidence-informed practices for effective psychosocial assessment, prevention, and intervention. Efforts to collaborate among behavioral health professionals and emergency responders and a focus on building resilience and ensuring consistency in planning and education will improve behavioral disaster response and minimize persistent negative outcomes.

From an anatomic and physiologic standpoint, children are often shorter, placing them closer to the ground where many noxious inhalational substances settle; their increased metabolism leads to an increased respiratory rate and distribution of toxic substances to their tissues. Their surface-to-volume ratio is increased thus putting them at risk for greater exposure to chemicals and radiation as well as dehydration due to exposure and fluid loss such as diarrhea. Body temperature regulation is also difficult due to the larger surface area. Finally, the close proximity of internal organs anatomically leads to increased multisystem organ involvement during a blast or penetrating injury [4,6–12]. Being aware of the specific needs of the child instead of the expectation that children should receive the same care as adults will allow systems to effectively triage and manage resource utilization [13–16].

Changing demographics

Children make up approximately 25% of the U.S. population [6,17]. Overseas, especially in developing countries, this percentage is even higher [18,19]. Southeast Asia, in particular, is home to 600 million inhabitants. It is characterized by diverse political, religious, ethnic, racial, and economic nations. Children are often at increased risk of exposure to both man-made and natural disasters [20]. As a geographic area familiar with extreme weather, some estimate that there are now 63.8 million people at risk of exposure to flooding in Southeast Asia, a figure that has more than doubled in the past 40 years. Geographic areas projected to be affected by the sea-level rise and storm surge include Bangkok, Jakarta, Manila, Yangon, and Ho Chi Minh City. To compound the situation, 44% of the region's population, or 221 million people, live below the $2 per day poverty line. Many of these inhabitants at risk are children [21].

In the 2010 earthquake that devastated Haiti, 53% of patients from tent camps in Port-Au-Prince were younger than 20 years old [22]. In a country where 45% of the population is in the pediatric age group, a comprehensive response including pediatric-specific care was paramount. However, many developing countries are plagued with inadequate infrastructure, therefore making state-of-the-art trauma care virtually impossible [20,21,23–25]. The establishment of a national trauma system has been at the forefront for Haiti postearthquake in order to address one of its most critical public health problems [26,27].

In the United States, children have been involved in recent mass casualty events, and some, such as school shootings, have specifically targeted children. Of the 168 casualties suffered in the 1995 Oklahoma City bombing, 11.3% were children [11]. In the Boston Marathon bombings, there were 10 children under 15 years old transported to Level I trauma centers, and one child mortality [28]. Boston, a city with four pediatric Level 1 trauma centers, was able to efficiently triage and transport children to appropriate centers. However, if a natural disaster such as a high-magnitude earthquake struck Los Angeles, resources would be stretched. Los Angeles County is a vast metropolitan area that includes the city of Los Angeles and 87 other incorporated cities, with an estimated pediatric population of 2.5 million [29]. A consortium of state and federal agencies sponsored a volunteer earthquake drill entitled *The Great California ShakeOut*, which simulated a 7.8-magnitude earthquake that occurred on November 13, 2008 at 10 AM. Simulated in this scenario were 1800 deaths, 50,000 injuries, and $200 billion in damages. The drill put the 14 disaster resource centers in Los Angeles County to the test. Balasuriya et al. specifically examined the integration of pediatric disaster preparation at these disaster resource centers and found that few centers included children as mock victims, and little or no attention was focused on pediatric triage, clinical, psychosocial, or resource issues [29]. Furthermore, although data are limited, pediatric trauma centers (PTC) have more resuscitation, treatment, and bed resources dedicated to pediatric survivors and are more familiar with the psychological and developmental needs of children [2]. One can infer that outcomes would be improved if children were triaged to a PTC during a mass casualty event; therefore, the presence and availability of a PTC in a disaster surge should be included in the preparation for such events.

Importance of pediatric disaster preparedness

There are many anatomic, physiologic, psychological, and developmental differences in children compared with adults that make them more vulnerable during a disaster [30–32]. Furthermore, most trauma systems are designed for adults, with limited pediatric-specific personnel and equipment [2].

Anatomy and physiology

Children have proportionately larger organs that are less protected and more exposed to external forces than in adults. The developing child's cartilaginous ribs do not confer the same degree of protection to thoracic and upper abdominal viscera as they do in the adult thorax. In the trauma literature, it is reported that children are more likely to suffer from multiorgan injury than adults due to this anatomic difference [33,34]. Additionally, children have proportionately larger heads, which puts them at increased risk for head injury and increased mortality [35]. Physiologically, children are at increased risk for a multitude of reasons. In younger children, there is an increased surface-to-volume ratio that not only makes it difficult to maintain body temperature and fluid status during times of exposure, but also contributes to an impaired barrier defense. The immature skin barrier of the child increases permeability, putting the child at risk for greater absorbance of chemical and biologic toxins [6,36]. Furthermore, the increased metabolic rate leads to an increased respiratory rate, allowing for a more rapid inhalation of toxins and faster body distribution due to the increased heart rate [4]. Drug metabolism is altered, so knowledge of how to administer lifesaving fluid resuscitation and medication is essential. Since younger children are smaller, the availability of and knowledge of how to choose appropriately sized equipment are necessary. Previous studies have demonstrated that many emergency personnel are unfamiliar with pediatric equipment availability and lack of knowledge required for its proper use [12,37,38]. Emergency and hospital personnel should incorporate mass pediatric casualty care and equipment in preparing for future events.

Maturational development

Child health care includes neonates to teenagers, with a wide variability in size, physiology, and psychology at each developmental stage. For instance, young children are often nonverbal during a crisis, thus making them poor communicators of vital information such as their identity, caregiver's identity, or the location of their injuries [39]. Children may also be non- or minimally verbal due to developmental delay or fear, increasing the communication gaps with patients. Children and families with limited English proficiency are at increased vulnerability due to the challenges they face trying to communicate identification or needs during a disaster [40]. Furthermore, children may be unable to recognize disaster, lack the cognitive ability to escape, and may even move toward areas of danger due to curiosity [4]. Even after the resolution of the immediate threat, young children must rely on others for hydration, nutrition, and navigation toward a safe environment and reunification with their families. The involvement of behavioral health professionals is important in coordinating reunification efforts as well as addressing the emotional and behavioral needs of the child during a disaster [5,41]. During Hurricane Katrina, families were evacuated and subsequently separated urgently and over great distances across state lines [41]. Efforts at better organization and guidelines to expedite and streamline the process have been subsequently put forth [39,41–43].

Children with special health care needs

Children with disabilities and special needs are particularly vulnerable, as they require greater emotional, behavioral, or physical assistance in surviving during a disaster. It is estimated that 15%–20% of American households have a child with special health care needs, which calculates to over 11 million children [44]. Children with special health care needs are defined by the American Academy of Pediatrics as "those who have or are at increased risk for a chronic physical, developmental, behavioral, or emotional condition and who also require health and related services of a type or amount beyond that required by children generally" [40]. Families of children with special needs feel they are underprepared to meet the child's needs during a disaster and require greater education and outreach [44–46]. In a survey and focus group involving parents of children who are followed in an Intestinal Rehabilitation Clinic, it was found that none of the families had a communication plan in place in the event of a disaster; 69% lacked an emergency supply kit; and 93% did not have a clinician-completed emergency information form. However, 71% had a backup electricity source and 79% had backup nutrition for their child, although concerns were raised for parenteral nutrition, which is specially formulated and typically has a refrigerated shelf life of 9 days. This is shortened to 24 hours, once supplementation is injected into the bag [47]. It appears families of children with special health care needs are generally unprepared for disaster, and physicians caring for these chronic patients should educate their families about disaster preparedness and develop support programs to assist in their preparation.

Value of PTCs during mass casualty incidents

Where children should be transported to during a mass casualty or disaster situation remains debated. PTCs have a range of pediatric subspecialty personnel and equipment readily available; however, they are fewer and more regionalized than adult trauma centers [2,3,48]. Although previous publications have shown that children who are brought to adult trauma centers have acceptable survival outcomes, especially if they are triaged to a Level I or II trauma center, other studies have shown that pediatric patients who have suffered blunt trauma do better at a PTC [49–53].

Ochoa et al. [54] reviewed the current evidence comparing outcomes for pediatric trauma treated at adult versus children's hospitals. Although their review was unable to conclude whether injured children should be treated at a children's hospital or an adult hospital with a dedicated pediatric unit, it suggested that there might be disparities in current pediatric trauma care. They found that most injured children are treated at adult hospitals; injured children who are treated at a children's hospital had improved overall outcomes and survival, including some studies which showed this in severely injured children. Children treated at a trauma center did better than those treated at a nontrauma center or a nonverified PTC, and injured children treated at a PTC may have improved survival and functional outcome [54]. However, they point to the smaller number of PTCs and reinforce previous recommendations on the importance of educating adult trauma surgeons on the nuances of pediatric trauma care. Ongoing studies and prospective data banks should continue to shed light on this topic.

The role of a PTC can vary depending on the scale and location of the disaster. When the attack or disaster occurs in the area of the PTC, PTC personnel may be called on to triage and treat the patients, working closely with adult trauma centers in the area to transport critically ill children to the PTC. In theory, PTC physicians would need to transfer out less critically ill patients to regional or community hospitals to accommodate the surge in critically injured victims [2]. However, in an event that the disaster strikes far from the PTC, clinicians and emergency planners at the PTC may be involved in transport coordination, accepting both victims of the disaster as well as other inpatients, or providing pediatric-specific expertise remotely. It is possible that resources near the disaster may be devastated, as would be the case in a large-scale earthquake, hurricane, or in war zones. This would require transport of severely injured children to the closest trauma center, adult or pediatric.

Technology is a valuable tool that a PTC with disaster assist capabilities may use to help those at the disaster epicenter. In a systematic review, Burke et al. suggested that since most hospitals in the United States have wireless capabilities they could be functional for a disaster medical response, including portable handheld devices such as cellular phones. Cell phones are not only valuable for communication, but also provide opportunities for situational awareness with their built-in geopositioning capabilities [55]. Furthermore, digital technology can be a valuable tool to capture images of the disaster environment or to track children at triage points or as they enter hospitals. Rapid identification of children will facilitate rapid reunification with families [39]. Finally, informatics can be utilized to distribute disaster preparation information, either via text or video, and aid in simulation such as predicting a surge using geospatial technology [4,56]. Maximizing these resources will greatly enhance care for children during a disaster.

In a pilot study, Barthel et al. [2] described a population kinetics approach that personnel at a PTC may use to estimate the effect of availability on admission and discharge rates. In this process model, the first important rate affecting the ability for a PTC to treat pediatric patients is the rate of discharging previously admitted patients, as well as those who are not critically injured and can be triaged elsewhere [3]. To accommodate the entire surge population, it is imperative that the clinicians at the PTC efficiently admit and discharge patients until the PTC is full. The authors found that the availability of a PTC decreased the time needed to triage or admit the entire pediatric surge population. Using data from the Israeli Defense Forces field hospital that responded to the Haiti earthquake of 2010, the authors calculated that the presence of a PTC would allow for a significant increase in overall admission rate, reduce the time to treatment in half, and decrease the time to completely treat all children by more than a third. Importantly, according to their model, the availability of a PTC was calculated to result in a relative mortality risk reduction of 37%. The inclusion of PTCs in disaster planning will have significantly positive effects on triage, treatment, and outcomes.

Because hospital capacities may become critically insufficient during surge situations, the system of "reverse triage" to transfer or discharge noncritically ill patients has been developed in adult hospitals. However, its application in pediatric surge capacity has not been studied. During Superstorm Sandy, the Neonatal Intensive Care Unit at New York University Langone Medical Center required evacuation due to a power outage secondary to the storm. They were able to safely transport 21 neonates to surrounding receiving hospitals over a 4.5-hour period; however, they retrospectively reviewed their experience and found that there were several challenges with the transport of vulnerable neonates [57]. They report that establishment of a command structure, backup personnel, methods of communication, medical information, and equipment including neonatal transport resources, situational awareness, regional coordination, flexibility, and special attention to the needs of families were of utmost importance. Kelen et al. used a modified-Delphi consensus model to agree upon a five-category risk-based disposition classification system for reverse triage and identification of patients deemed safe for early discharge during surge events [58]. Further research is needed in this area of disaster science.

Preparation for responders and hospitals

Although most disasters are difficult to predict and to prepare for, responder education and regular drills are necessary to minimize the postdisaster impact on a health care system and the local population. Because many providers will be asked to respond outside their normal scope of practice, such as adult surgeons or hospitals treating children and general pediatricians triaging critically ill patients, education must be at the forefront of disaster preparedness. Tegtmeyer et al. described two approaches to education for pediatric emergency mass critical care events: training in advance and just-in-time training [59]. Training in advance is typically given to a preselected or self-selected group of providers who may be called on to respond to a mass casualty disaster. It is more detailed, allowing for more discussion, and covers more comprehensive, broad subjects. There is typically ample time for simulation or other hands-on training including the acquirement of new procedural skill sets. An example is the annual Disaster Olympix at Children's Hospital Los Angeles, where a full-day education and team competition event targets six areas of disaster preparedness through disaster simulation: (1) disease identification, (2) human-waste management, (3) alternate care, (4) decontamination, (5) patient evacuation, and (6) Disaster Jeopardy! [60]. Such an exercise targets regular hospital workers from multidisciplinary backgrounds, coordinates with emergency response personnel such as firefighters from the surrounding community, and incorporates local elementary school students as simulation participants, but also educates the children on disaster preparedness. The main weakness of training in advance is the inability to reach a wider audience due to time and space constraints.

Since many crises are not predictable, just-in-time training may be a realistic alternative for many centers. Just-in-time training takes place immediately prior to an event or as needed as a crisis is unfolding. The training targets personnel who have an acute need for mass casualty knowledge for care or management purposes [59]. It is typically delivered in a concise fashion and often by web- or computer-based, self-directed learning. Although this technique is efficient in reaching those who are responding to the disaster event, its disadvantages are many. It requires affected providers to have some basic knowledge. The training is less interactive because it is focused on the problem at hand with obvious time constraints since the staff must attend to the immediate needs of their patients and new casualties. Neither approach is adequate when practiced alone.

Training in advance can cover more material due to more time, but many practitioners forget the material and fail to retain all the information due to the lack of perceived immediate need for the information. Just-in-time training is often hurried, superficial, and requires prior planning and access to educational resources. The two approaches in conjunction with a disaster simulation may be ideal for educating providers taking part in an exercise, since real-time evaluation of the organization's response to a disaster is a direct test of the training [61].

Although personnel training is crucial to ensuring an adequate response during a mass casualty event, having adequate resources and the knowledge to properly utilize them to treat disaster patients is of equal importance. Therefore, the ability to test both a hospital's personnel and resource response is critical. For example, an exercise simulating mass respiratory casualties will potentially expose weaknesses in resource availability and allocation since one cannot intubate more children than there are capabilities to mechanically ventilate them. Similarly, other equipment such as cervical collars, orthopedic splints, and chest tubes that are commonly used during trauma resuscitations come in child-specific sizes that should be stocked in anticipation of a mass casualty event.

During a disaster response, supplies for pediatric critical care become scarce as maximal surge capacities are reached. The immediate and large-scale burden on a hospital's supply can quickly overwhelm even a prepared facility. Additionally, depending on the disaster and damage done to infrastructure, transport of materials from one hospital to another for resource sharing may be hindered. Disaster planners and strategists recommend that hospitals maintain triple the usual pediatric intensive care unit capacity for a sustained period of at least 10 days [62]. Specific recommendations for size-specific pediatric mass critical care equipment are presented in the Bohn publication. Importantly, hospital supply chain rental practices from remote or regional locations may not be dependable in the early phases of a response to a mass casualty surge and damage to civil infrastructure. Therefore, children and adults may draw from the same critical inventory and planners must account for sufficient resources to address casualty needs of the entire population. Second, items must be listed in excess of one per bed space due to expectations that more than one patient will use the bed space during a 10-day period, or patients may require replacements of the item. Finally, planning for pediatric equipment needs is complex due to the range in sizes of age- and weight-specific equipment as previously discussed. The task force recommends at minimum to plan for a surge of critically ill pediatric patients to reflect ordinary pediatric intensive care activity [62].

The role of the pediatric surgeon

The pediatric surgeon is aptly trained in the care of children, trauma, and critical care; therefore, he or she should be intimately involved in the planning for disaster events. The pediatric surgeon is intimately familiar with pediatric surgical physiology, age-specific developmental and physiologic complexities, and finally, complex traumatic injury. However, in preparation for disasters, it is important to delineate roles as per the incident command system. Therefore, many surgeons still need training in disaster preparedness and incident command practices. Chokshi et al. conducted a survey among members of the American Pediatric Surgical Association and found that most pediatric surgeons felt responsible for assisting in a disaster, but few felt prepared to respond [37]. Furthermore, among children's hospitals surveyed by the Disaster Response Task Force in October 2011, there was little standardization among the respondents in their approach to disaster preparation [63]. Although the respondents reported that 70% had a structure in place to plan for a disaster, many felt they were better prepared for small-scale local events rather than large-scale regional or national events. Nevertheless, pediatric surgeons must be at the table when examining advancements and making plans for catastrophic disasters in the United States and abroad.

Finally, pediatric surgeons should coordinate with subspecialists at the PTC and pediatricians in the community. The dialogue should include how community physicians can augment hospital-based responses and how pediatricians can assist patients with special needs when their tertiary care pediatric center is unavailable for services in the event of a catastrophic disaster event. Surgeons will be key in coordinating with pediatric intensivists, neurosurgeons, otolaryngologists, orthopedic surgeons, urologists, and emergency physicians similar to the collaboration that is expected during trauma activations. Advance coordination with the pediatricians, especially those in the community, is underutilized. These primary care practitioners have regular contact with children and their families and can educate and prepare families for disasters. They may be a trusted resource for health-related information such as counsel during a pandemic [6,64–66]. Furthermore, community physicians can evaluate and triage patients during a disaster, thus decreasing the burden on hospital emergency rooms. The establishment of outpatient disaster triage centers in satellite locations during a disaster through telephone or in-person triage or treatment will provide capacity. The offloading of minor casualties will enhance access at tertiary care centers. Outside offices may also facilitate the distribution of countermeasures and vaccines to children in local communities. Incorporation of community pediatricians in disaster planning and drills will alert their office personnel to maneuvers that will help during a surge event such as rescheduling well-child visits and adjusting other service capabilities.

Conclusions

Recent events and studies have exposed the lack of disaster preparedness among those caring for children. Children present a complex developmental and physiological challenge during traumas and mass casualty events, as they can pose many hurdles from an individual as well as a systems perspective. The pediatric surgeon should lead a team of pediatric generalists and subspecialists in preparing families; hospital staff; local, regional, and national governments; and other community resources in educating and practicing for mass casualty events. The aggressive incorporation of pediatric patients and scenarios, especially for those with chronic medical or developmental needs, is of paramount importance in disaster preparedness. In conclusion, we provide recommendations compiled from peer-reviewed publications referenced in this chapter.

Recommendations

Hospital/system preparation	
Leadership	• Leadership with knowledge and expertise • Public health/government at centralized/regional emergency management coordinating centers • Expectations for clinician response delineated in contract
Identification of resources	• Regional centers - Network for referrals and transfers - Identification of local hospitals to assist with surge capacity - Integration of telemedicine • Intensive care unit (ICU) involvement in disaster preparedness and response • Identification of subspecialist experts in the type of disaster and consultation for medical guidance and to inform decision-making for mass critical care delivery • Identification of local hospitals that can assist with surge capacity or for transfer of noncritical patients from a trauma center
Communication	• Integrated communication systems and robust infrastructure of electronic medical records • The use of virtual ICUs, point-of-care (POC) testing, portable monitoring systems, and telemedicine to facilitate transfer and sharing of information
Practitioner preparation	
Training	• ICU and surgical clinician participation in disaster response training and education • Maintenance of pediatric care levels with additional training for disaster response • Frequent simulation involving all care teams, integrating pediatric-specific scenarios
Family preparation	
Communication	• Communication plan with family members in event of a disaster • Evacuation plans for foreseeable events such as hurricanes
Supplies	• Surplus materials, especially for families of children with special needs
Information	• Up-to-date medical needs of the child • Identification of the child and the child's specific health needs

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4

Organizing the hospital for pediatric trauma care

RICHARD A. FALCONE and LYNN HAAS

History of pediatric trauma centers

The year 2016 will mark the 40th anniversary of the *ACS Optimal Hospital Resources for Care of the Seriously Injured Patient* document. Pediatric trauma care was developed within the framework of the adult trauma system but now has emerged as an entity all its own.

Pediatric-specific trauma centers were first established in the early 1970s with published articles documenting the increasing effort to organize and improve overall care of injured children [1–5]. In 1982, an article was published in the *Journal of Trauma* that outlined standards of care for critically injured children [6]. This information led to the development of Appendix J, which was added to the hospital resource document in 1987 [7]. This document, Planning Pediatric Trauma Care, was endorsed by the American Pediatric Surgical Association (APSA) and the American College of Surgeons Committee on Trauma (ACS COT).

In 1987, the American College of Surgeons Verification Review Committee (ACS VRC) was established for the purpose of verifying compliance with trauma center standards. A chapter dedicated to resources required for development of a pediatric trauma center was included in the 1987 ACS resource document [7]. In October 1989, the first Level I pediatric consultation took place, with the first free-standing Level I pediatric trauma center verified by the ACS in September 1991.

During this same time period, other critical components supporting pediatric trauma center development continued to emerge. In 1983, a pediatric chapter was added to the Advanced Trauma Life Support (ATLS) course. In 1984, the U.S. Congress enacted legislation, authorizing the use of federal funds for the development of Emergency Medical Services for Children (EMSC). This national initiative under the direction of the Health Resources and Service Administration's Maternal and Child Health Bureau (MCHB) provided grant money to help improve emergency medical services for critically ill and injured children in order to reduce death and disability. This initiative did not promote a separate EMS system, but instead advocated for enhanced pediatric capability within the existing system. Overall, this program raised awareness that children respond differently than adults—physically, emotionally, and psychologically.

The National Pediatric Trauma Registry (NPTR) was developed in 1985 with the assistance of a grant from the U.S. Department of Education [8]. It was originally designed to explore the relationship between rehabilitation outcomes and acute care of injured children. However, it later assisted in defining pediatric trauma as a unique entity and continued to enhance pediatric trauma as its own specialty. The NPTR collected data until 2001 and was a major influence on the National Trauma Data Bank (NTDB) adding a pediatric component to the dataset. The first pediatric trauma report by the NTDB was published in 2007.

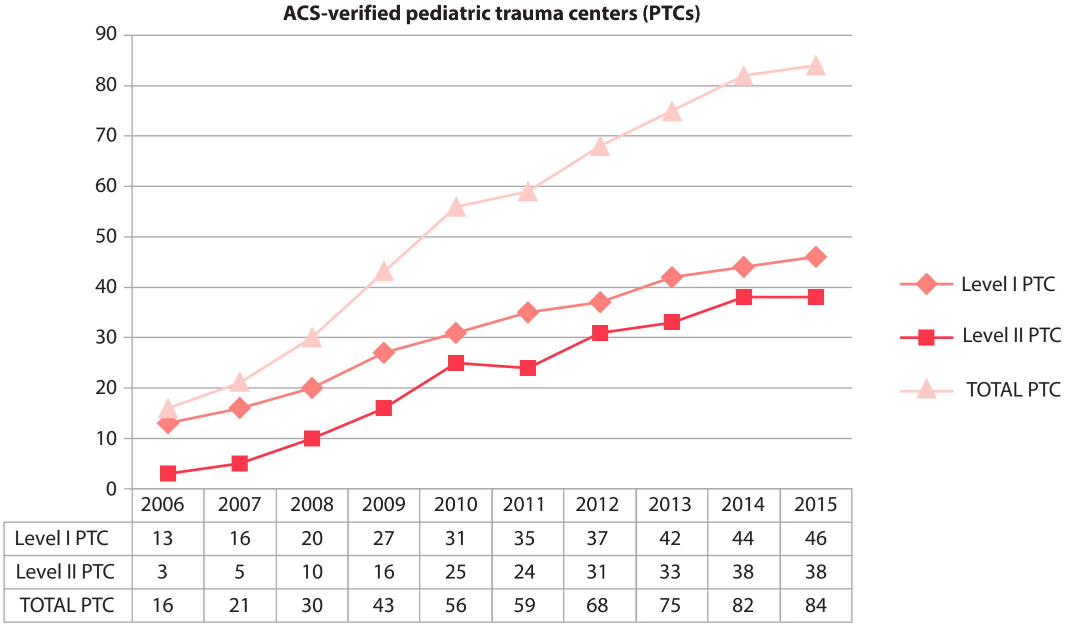
As pediatric trauma centers began to formally emerge, it became evident that there was a limited number and distribution of pediatric trauma centers across the United States. In 1993, the Institute of Medicine (IOM) released *Emergency Medical Services for Children*, a comprehensive report that revealed multiple deficiencies in pediatric care across the United States [9]. In an attempt to increase availability, trauma center with pediatric commitment was added as an option for adult trauma centers and published in the *Resource for Optimal Care of the Injured Patient: 1993* document [10]. The option of trauma center with pediatric commitment was removed from the 2006 resource document [11]. It was recommended that when an adult trauma center provided care for greater than 100 children less than 15 years of age, the hospital should undertake parallel trauma center verification—both adult and pediatric. However, all adult trauma centers must have the ability to stabilize and provide timely transfer of injured children when a pediatric patient arrives at their institution. Despite significant advances and expansion of the number of pediatric trauma centers, the majority of injured children continued to be cared for at either adult trauma centers or non-trauma centers. Over 17 million children still do not have access to a pediatric trauma center within 60 min of where they live [12].

Verification by the ACS as a trauma center is the most common form of trauma center verification. The most recent edition of *Resources for Optimal Care of the Injured Patient* (2014) advocates that pediatric trauma centers assume a leadership role in the care of injured children in local, regional, and state systems [13]. Pediatric trauma centers must meet the same resource requirements as adult trauma centers, in addition to pediatric resource requirements. As of 2016, the ACS divides pediatric trauma centers into Level I and Level II centers. Pediatric trauma centers, verified by the ACS, have multiplied fivefold over the last 10 years and do not include those centers in states with their own systems of verification (Figure 4.1). A trauma center can be designated by a state or regional authority and verified by the ACS COT.

Last but not least for the injured child is the importance of injury prevention, which gained momentum in the mid-1970s. In 1996, one research team described the changes in injury mortality from 1978 to 1991 and determined the number of preventable deaths with the current available intervention strategies [14]. They concluded that reduction in pediatric mortality was attributed not only to improved medical care, but also to increased use of seat belts and child safety seats, reduction in drunk driving, and overall better safety awareness [14]. Published in 1999, *Reducing the Burden of Injury* focused on prevention and treatment of injuries in children [15]. With the reduction of injury and increased awareness, injury prevention programs are now considered an integral component of pediatric trauma centers.

Planning for a pediatric trauma center

The decision to develop a pediatric trauma center must be embraced by the entire institution, since trauma, by its nature, has an impact on and requires the input of all areas of a hospital. In addition, the hospital interested in developing a pediatric trauma center should carefully consider the needs of its community and region for such a center. This analysis should provide insight into market share and predict whether trauma center development makes financial sense. This analysis also reviews geographic presence, evaluates current referral patterns, determines the actual



	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Level I PTC	13	16	20	27	31	35	37	42	44	46
Level II PTC	3	5	10	16	25	24	31	33	38	38
TOTAL PTC	16	21	30	43	56	59	68	75	82	84

Figure 4.1 Number of ACS-verified pediatric trauma centers from 2006 to 2015.

and potential referral base, assesses implementation costs, and provides a roadmap for development. A general time frame for verification as a trauma center may be of benefit within the market analysis as this change generally takes a significant period of time.

Like the adult trauma center, fundamental components of a comprehensive trauma system include injury prevention, prehospital care, acute care facilities and treatment, and posthospital care either in the way of rehabilitation or posthospital follow-up. However, the many differences between adult and pediatric trauma patients, including anatomical, physiological, psychological, and social aspects, have significant impact on how to develop a comprehensive pediatric trauma center. Children require pediatric specialists who understand the differences in patterns of injury and physiological response. Additionally, in developing a pediatric trauma center it is critical to emphasize a family-centered approach that will provide support for both the child and the family. Understanding these differences and developing a systematic approach to incorporation of all of these factors are critical in the planning phase of pediatric trauma center development. In addition to available resources from the ACS, other organizations such as the Pediatric Trauma Society and the Trauma Center Association of America also have pediatric trauma–focused resources available. It may also be possible for some centers to collaborate with an established Level I pediatric trauma center to support their development and early improvement [16].

As standards for trauma center verification/designation vary between states, it is critical in the preplanning phase to investigate what is pertinent. For example, does the state/region have any specific criteria and/or standards that are equal to or above the ACS verification requirements? Is the trauma verification process through the state or by the ACS? Finally, is there a state designation process in addition to ACS verification requirements? All these aspects need to be understood and conveyed to the administration in the preplanning phase.

Facilities

The first-line requirements for a pediatric trauma center are the correct facilities and equipment to serve the injured child/adolescent. The basic concept of a trauma center is that services, whether initial management or an operative procedure, can be immediately provided 24 h/day, 365 days a year. As the definition of the pediatric age group varies and adolescents are frequently included within that group, pediatric injury can occur at all times of the day and night, just as in the adult population.

As a pediatric trauma center, ensuring all areas of the institution are pediatric prepared and also “pediatric friendly” is essential. This is frequently a difficult concept to describe, but nonetheless is an essential component. Family-centered care needs to be incorporated, so that family is integrally involved in clinical rounds and the decision-making process. Physical areas will need adaptations for children that consider the age span from an infant to adolescent. In addition, accommodations need to be made for parents/guardians. Even adolescents, who have the physical size of an adult, need the emotional support of family. The hospital is a stressful place for the child and family, so anything in the environment that can lessen this stress and bring comfort and distraction is of special value that enhances recovery.

Emergency department

The emergency department is the primary entry point into the hospital for the injured child and family. Since pediatric spans the ages from neonates to adolescents, equipment must be readily available and appropriate for all sizes. Published data have suggested that many emergency departments in the United States lack basic equipment and supplies needed to care for children of all ages [17]. In 2009, a nationwide assessment of all emergency departments began, based on the published *2009 Guidelines for the Treatment of Children in the emergency department* [18]. Starting in 2012, the EMSC Program implemented the *National Pediatric Readiness Project*. This comprehensive project used a variety of communication strategies, including direct mailings, coupled with a state-level management strategy, a web media presence, and a comprehensive public relations campaign. The overall purpose of this national quality improvement project is to ensure that all emergency departments are ready to care for children. The first documented review of the project demonstrated increased pediatric readiness compared to previous reports [19]. A careful review of the pediatric readiness toolkit should be performed to ensure appropriate resources are available. Information is available on the website http://www.pediatricreadiness.org/readiness-toolkit.

Variable sizes of monitoring, vascular access, and airway equipment are essential. Blood pressure cuffs should be available for neonatal, infant, child, adult-arm, and thigh in size. Electrocardiography monitors/defibrillators should have both pediatric and adult capabilities including pediatric-sized pads/paddles. The pulse oximeter should have pediatric-sized probes. In addition, venous access equipment should be available in a variety of pediatric-specific sizes including peripheral intravenous (IV), intraosseous needles, and central venous catheters.

Given the unique challenges of the pediatric airway, an organized, readily accessible pediatric-specific airway cart is crucial. This cart should include a variety of endotracheal tube types and sizes, laryngoscope blades, stylets, and suction catheters, along with various bag-valve-mask devices for infants and children.

Children can rapidly become hypothermic during a trauma evaluation and resuscitation so equipment for active warming is essential. Younger children have a larger surface area-to-weight ratio than adults, making them prone to heat loss. Various warming techniques need to be readily available in the resuscitation area including the ability to rapidly warm the trauma resuscitation room and to provide warm resuscitation fluids and blood.

Given the larger variety of equipment required for care of the injured child compared with an adult, careful organization of the trauma resuscitation area is paramount. Equipment should be easily accessible, clearly labeled, and safely and logically organized. One method of organizing the resuscitation area for pediatrics is the Broselow system. This system supplies the practitioner with information and equipment in an age-specific manner, all contained in a color-coded cart [20]. In addition, the Broselow tape is a rapid method of determining the child's weight based on height. A standard method for estimating weight in kilograms should be used (e.g., length-based system) for children who require resuscitation or emergency stabilization. Early calculation of a child's weight allows appropriate calculation of emergency medications, IV fluid boluses, and blood products. Pre-calculated dosing guidelines for children of all ages should be developed and easily accessible during a pediatric resuscitation. Sedation and analgesia for specific procedures need to be incorporated into pediatric preparedness. Staff should be continually educated and knowledgeable about what is in the Broselow cart or where all pediatric equipment is located. Inability to locate age/size-appropriate equipment at the time of pediatric trauma resuscitation can have a significant negative impact on outcome.

All centers do not need to use the Broselow system, but alternative methods should still meet the requirements of being easily accessible, clearly labeled, and safely and logically organized. Equipment packaged together within surgical trays for procedures such as chest tubes, central lines, and so on, must also be revised to accommodate all ages. A recently published checklist, based on the 2009 joint policy statement *2009 Guidelines for the Treatment of Children in the Emergency Department* [18] can be found online at http://aappolicy.aappublications.org/cgi/reprint/pediatrics;124/4/1233.pdf. This useful checklist provides overall assistance in preparing emergency departments to care for children.

Radiology

As with adults, plain radiographs and CT scanning are the major diagnostic modalities for injured children. Immediate access during the initial management phase is a high priority. Children are at an increased risk of cancer from CT scans because they are still growing and their cells are dividing rapidly. In addition, children have longer time to live, thereby increasing their life-long risk [21–23]. Even with this knowledge, the CT scan is a powerful adjunct to the practice of pediatric trauma and continues to be the standard of diagnostic assessment. Imaging protocols need to be designed specifically for children. These protocols should focus on the principles of ALARA—"as low as reasonably achievable" [24–26]— as well as limiting scanning to only regions of need. Two clinical decision rules, the Canadian C-spine rule [27] and the National Emergency X-Radiography Utilization Study (NEXUS) [28], are available to assess the need for imaging in patients with cervical spine injury following blunt injury. These rules aim to reduce unnecessary imaging by identifying patients with a higher likelihood of cervical spine injury. Other studies and guidelines are currently being developed for pediatric abdominal and head injury screening. These guidelines, which aim to inform providers of the most current indications for advanced imaging and when it can be avoided, should be adopted by all pediatric trauma centers. In addition to the specific imaging protocols, it is important that the pediatric trauma center preparation include the ability to safely sedate children for longer studies and for access to pediatric-specific interventional radiology equipment.

Pediatric intensive care

Intensive care must be readily available for the injured child. This care is preferably provided in a specific pediatric intensive care unit (PICU) with appropriately trained pediatric nurses and pediatric intensivists. If a PICU is not available, an intensive care unit with pediatric nurses involved in the care of injured children may be an alternative. A collaborative approach to the care of the child in the intensive care unit must exist between the surgeon and the pediatric intensivist and nurses as well as pediatric-focused pharmacists, nutritionists, and social workers.

Operating room

An operating room (OR) must be readily accessible in the trauma center. In addition to the physical space that must be easily accessible from the emergency room, anesthesia and perioperative nursing staff comfortable in caring for injured children must be immediately available. As a pediatric trauma center, the OR must have appropriate equipment for the management of critically injured children including monitors, vascular access and airway equipment, and surgical instruments. The benefits to the institution of an available OR extend beyond the trauma service. An OR is a costly resource that must be carefully planned and optimally utilized.

Pediatric floor/area

Care should be provided to the pediatric patients in dedicated areas of the hospital staffed by nurses with pediatric expertise. In addition, children should have an area in the hospital that is dedicated to their specific needs and interests. Within the child's room, there should be an area for parents to stay for the duration of the child's hospitalization. The area should be pediatric friendly, with areas safe for children to visit and where medical procedures do not occur. Special attention should also be given to adolescents who need a balance between independence and support during their care. Child life specialists are additional integral members of the care team for children. These specialists can help distract children during stressful times and procedures, engage them in activities pertinent to their developmental age, and help keep their lives as normal as possible while in the hospital. Return to a school schedule of learning can be very important for children spending extended periods in the hospital and should be incorporated into the trauma system development process.

Disaster preparedness

An essential role of a trauma center is to be prepared to help manage pediatric patients in disasters. This preparation must include a plan for managing children through the continuum of care and a plan to reunite children and parents. In addition, an area designed for rapid and safe decontamination of children is necessary. As a trauma center, the system will need to be prepared to manage both injured and noninjured children. Unfortunately, most hospitals are frequently unprepared to provide care for children during a disaster [29]. Data suggest that more than one-third of victims of disaster or multicasualty events are children, yet system planning does not include pediatric issues [29]. Efforts to improve planning for children who are involved in disasters are occurring at the local, state, and federal level. When planning the development of the pediatric trauma center, all aspects of disaster preparedness need to be incorporated into the process [30,31].

Rehabilitation

The fact that children are young and most are healthy does not mean they necessarily recover well from injury. In order to maximize outcomes for injured children, the pediatric trauma center should be closely integrated with rehabilitation services focused on pediatric patients. These services are crucial in ensuring that early attention is given to a coordinated plan for necessary therapy to maximize recovery and return to maximal functional capacity. Residual functional impairments that are commonly documented include physical, cognitive, educational, behavior, and social domains. All of these aspects can result in a significant social, emotional, and economic burden for the child's family and community. Early intervention and consultation are imperative as soon as it is noted that the child will probably survive.

Rehabilitation experts also play an important role in helping children and families transition back home, to school and, when needed, to long-term pediatric rehabilitation facilities. Over the past years, increased attention has been directed to cognitive and neuropsychology recovery for children. Outcome research has demonstrated that social and behavior disorders, frequently associated with childhood traumatic brain injury (TBI), are extremely troubling to parents, teachers, peers, and others [32]. A comprehensive evaluation on the wide spectrum of rehabilitation needs must be addressed when developing the trauma center concept.

Services/personnel

In order to function as a pediatric trauma center, a variety of physician specialists, pediatric-trained nurses, child life specialists, and social workers, as well as laboratory technicians and radiology technicians, are among the key personnel necessary to provide optimal care for injured children. Individuals essential to maintaining a trauma program include the trauma medical director, pediatric trauma program manager, and trauma registrar. Additional important members of a comprehensive program may include injury prevention coordinators, trauma nurse educators, research staff, and trauma-focused pediatric nurse practitioners. The number of individuals needed to support the trauma service varies in direct proportion to the number of injured children being treated on the trauma service, but the core team of a trauma medical director, pediatric trauma manager, and trauma registry is considered essential.

Trauma resuscitation team

The group of physicians immediately responsible for the care of the injured child includes surgeons, emergency medicine physicians, intensivists, and anesthesiologists. In addition to the physicians, nurses, respiratory therapists, paramedics, pharmacists, child life specialists, social workers, and in some institutions, pastoral services are all part of the trauma resuscitation team. This multidisciplinary group of providers must function together as a team. Each team needs a well-defined leader, clear roles for each member, and effective communication to ensure efficient and safe evaluation and care of trauma patients (Figure 4.2). Just like teams in other arenas, trauma teams not only need to practice the skills related to their individual roles but also must communicate effectively. Multidisciplinary trauma team training has been demonstrated to improve skills, enhance teamwork, identify latent safety threats, and enhance efficiency in identifying critical injuries [33–36].

In addition to the core responding group of providers, other key specialists who will be required to take care of injured children include orthopedic surgeons and neurosurgeons with experience in managing pediatric injuries. Team members from plastic surgery, otolaryngology, urology, and ophthalmology are also essential to the trauma team. Other medical specialists are also important in supporting the care of injured children. Radiologists with expertise in understanding the unique variations of findings seen during normal development as well as following injuries in children are also required.

Family presence

In addition to the family-centered care discussed earlier, family presence during the trauma resuscitation is an important part of comprehensive pediatric trauma care.

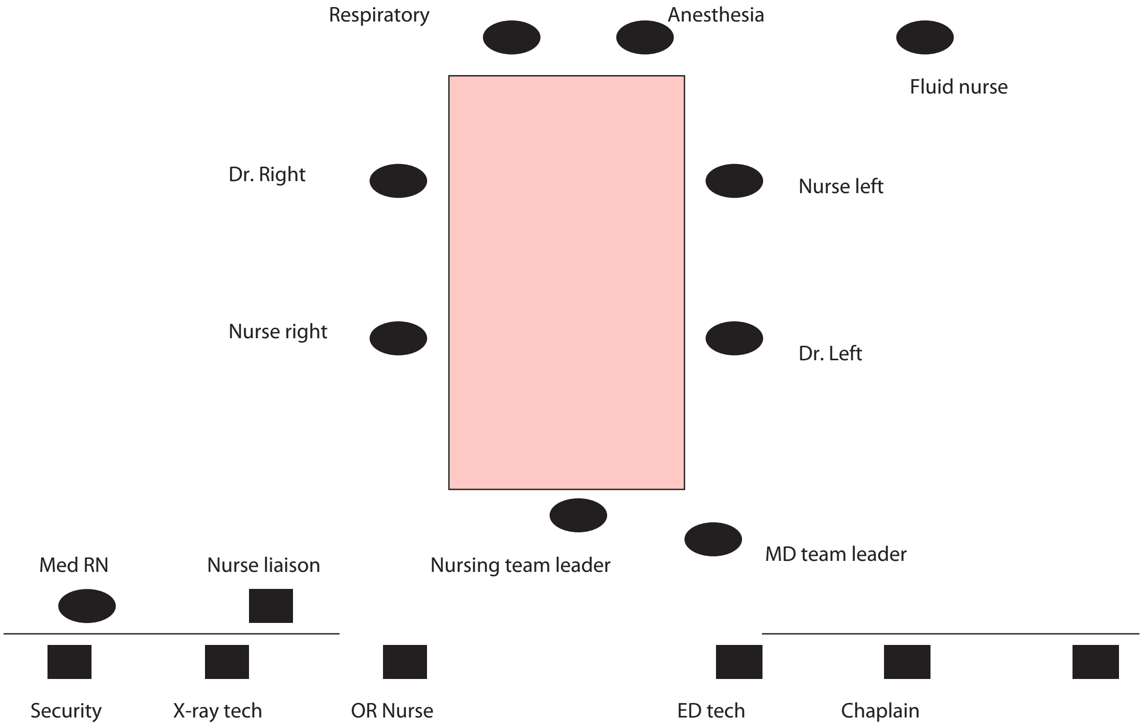


Figure 4.2 Example of multidisciplinary team member position setup around a trauma patient. Each provider identified should have a defined role during the resuscitation.

Family presence is defined in the medical literature as the "attendance of family members in a location that affords visual or physical contact with the patient during invasive procedures or resuscitation" [37]. Family presence merits considerable attention because it speaks to the heart of pediatric family-centered care. Support for family presence is not universal or a given because the environment during the resuscitation is often unpredictable. However, professional organizations such as the Emergency Nurses Association, the American Association of Critical Care Nurses, the American College of Critical Care Medicine, and the Canadian Association of Critical Care Nurses all support family presence and have practice guidelines that endorse this concept.

When family presence is allowed during trauma resuscitation, policies and procedures should be adopted to guide the practice [38]. The absence of a policy can lead to misunderstandings and variations in practice. Frequently, a chaplain or a social worker is the person of choice; but in reality, this can be anyone that has the psychosocial and emotional skills to support the family. Although family presence can be unsettling to some providers, the evidence supports a positive impact of family presence for both the child and the parents, even when there are undesirable outcomes [39]. It does not negatively affect the efficiency of the trauma resuscitation [40]. Family presence and engagement throughout the hospital stay and recovery should remain a focus of the pediatric trauma center.

Support services

Support services, such as social services, child life, psychology, and the presence of a child abuse team, are often underappreciated aspects of a pediatric trauma center. The family is a major component of the child's life; therefore, if the child is injured, the family experiences major consequences. Social services have the unique ability to investigate the intricacies of the family system as well as to identify secondary adversities and develop interventions to address these issues. A child life specialist is available in most children's hospitals to help the child deal with being in a hospital. This person is of great support to the family and siblings in fatal cases. The role of a child life specialist should be managed by someone else in your trauma system if you do not have this specific type of individual.

Research has shown that about one in six children and their parents develop persistent posttraumatic stress symptoms which are linked to poorer physical and functional recovery [41]. Posttraumatic stress disorder (PTSD) when not appropriately diagnosed can place a burden on family and lead to long-lasting psychological implications for the child [42]. New screening tools are now being used to diagnose these issues early in the course of recovery and should be implemented into the trauma center procedures.

A variety of terms can be associated with child abuse, including nonaccidental trauma, child maltreatment, child neglect, shaken baby syndrome, and so on. Whatever the terminology used, a system must be instituted in a pediatric trauma center to aggressively screen for potential child abuse. The trauma service should be an active advocate for the child and work within the hospital system to see that the child is returned to a safe environment.

Integration into the regional system

Pediatric trauma centers should be incorporated into a regional trauma system committed to providing optimal care for all injured individuals. The pediatric trauma personnel should participate at both the regional and state level as members of appropriate trauma committees, representing the pediatric population. Follow-up with referring hospitals is essential to provide feedback on pertinent trauma care issues. The administration of a hospital needs to understand that the pediatric trauma center must extend beyond the walls of the institution for the benefit of the patient and family.

The pediatric trauma center should work within the regional system to monitor and improve the triage of pediatric trauma patients to appropriate centers. Although the Centers for Disease Control and Prevention (CDC) triage guidelines exist, the pediatric trauma center leadership should collaborate with prehospital providers to ensure adequate compliance with guidelines. It has been demonstrated that children taken first to a nontrauma center have excess imaging and prolonged transfer times to definitive care [43]. Children arriving at the pediatric trauma center also require triage to ensure that the appropriate level of trauma team resources is mobilized. Developing a tiered trauma response system is essential with the goal of having the right resources available for the right patient at the right time. Tiered activation criteria are available from the ACS as well as from existing resources in the literature. An example of tiered activation criteria is shown in Table 4.1. Centers should carefully evaluate their over- and undertriage rates using the Cribari method or a resource utilization method [44,45].

Table 4.1 Sample tiered activation criteria from a Level I pediatric trauma center

Activation criteria
Highest level
1. Any penetrating wound of the head, neck, or trunk to include gunshot wound to the head, neck, or trunk or extremities proximal to the elbow/knee
2. Tachycardia and/or poor perfusion or unexplained tachycardia
3. Blood given prior to the patient's arrival
4. Hypotension
5. 40 mL/kg bolus prior to arrival
6. Respiratory difficulty as evidenced by the following:
a. Significant increase or decrease in respiratory rate
b. Significant retractions or grunting
c. Patient intubated prior to arrival
7. Unable to maintain or difficult airway
8. Glasgow Coma Score (GCS) ≤ 8
9. GCS deterioration by 2
Mid-level
1. Evidence of abdominal injury
a. Without hemodynamic compromise
b. Distended and/or tender abdomen
c. Abdominal bruising or seat belt mark
2. GCS 9–13
3. Spinal cord injury with neurologic deficit
4. Two or more proximal long bone fractures
5. Burns > 15% total body surface area (TBSA)
6. Ejection from vehicle
7. Significant vascular injury including amputation of limb proximal to wrist or ankle
8. Emergency department discretion
Lowest level
1. Motor vehicle collision
2. Struck or run over by motor vehicle (pedestrian or bike)
3. Fall greater than 10 feet
4. Any mechanism deemed to place the patient at risk for multisystem injury
5. Any patient immobilized with a backboard and/or cervical collar
6. Partial or full thickness burns between 5% and 14% TBSA
7. Any burn if less than 5% TBSA requiring immediate pain management

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PART II

General principles of resuscitation and supportive care

5

The ABCs of pediatric trauma

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Introduction

Pediatric trauma victims present a challenging set of problems to the emergency physician, pediatrician, and surgeon. Children rarely sustain lethal injury; however, delayed recognition and inappropriate management of the common problems encountered in the pediatric trauma patient can lead to a poor outcome. The ultimate common pathway leading to death in the injured child is profound shock: the inadequate delivery of oxygen to tissues. It is therefore the goal of the initial phase of resuscitation to rapidly evaluate and treat any immediate life-threatening injuries that compromise tissue oxygenation. This is known in Advanced Trauma Life Support (ATLS) courses as the primary survey, or the ABCs of trauma: airway, breathing, and circulation [1]. Appropriate management of the ABCs is necessary for optimal outcomes in pediatric trauma, regardless of whether it is managed in an adult or pediatric trauma center [2]. In fact, with a relatively limited number of pediatric trauma centers, most improvements in pediatric trauma care are likely to come from improvements at combined trauma centers [3].

When performing the primary survey of an injured child, one must keep in mind that frequent reassessment is mandatory. Children have tremendous physiologic reserve and may rapidly decompensate when their threshold level is crossed. Only by frequent evaluation and assessment can the physician detect and treat the child appropriately prior to decompensation. Before a child leaves the trauma room for a diagnostic procedure, his or her ABCs must be assessed and stabilized. The computed tomography (CT) scanner is no place to lose an airway or require chest tube placement. As the trauma workup proceeds into the secondary survey, any deterioration in an otherwise stable trauma patient, whether adult or child, should prompt a reassessment of the ABCs.

Performance of the primary survey is divided into three separate stages of airway, breathing, and circulation only for discussion purposes. In practice, it is a dynamic process in which the clinician must be aware that all three steps occur concurrently. The proficient physician managing pediatric or adult trauma must be able to evaluate all three simultaneously, not in sequence, and recognize that problems with the airway influence breathing and circulation, and vice versa. It is the goal of this chapter to provide a framework upon which to base the initial management of the “Golden Hour” in pediatric trauma.

Anatomic and physiologic considerations

Children differ from adults in several specific areas relevant to trauma care. Infants and young children, in particular, have a relatively large body surface area to body cell mass ratio and are thus prone to developing hypothermia. This is particularly true when exposed for resuscitation or operation or when given large volumes of intravenous (IV) fluids or blood products. To prevent hypothermia, it is important to keep injured children covered as much as possible and to have available warm blankets, heat lamps, room temperature controls, and fluid warmers in resuscitation areas and operating rooms (ORs). The child's vital signs and circulating blood volume also vary with age, which obviously affects the recognition and treatment of physiologic derangement. Young children have relatively large heads and are more likely to suffer head injuries, especially with deceleration mechanisms such as falls and motor vehicle trauma. Their craniums are also thinner and their brains are less completely myelinated, both of which tend to increase the severity of injury. Infants with open cranial sutures, larger subarachnoid spaces and cisterns, and greater extracellular space in the brain may tolerate expanding intracranial hematomas and cerebral edema better.

The glottis lies in a more superior and anterior position relative to the pharynx, which makes orotracheal intubation much easier than nasotracheal intubation, especially in an emergency. In children up to about 8 years of age, the airway is narrowest at the level of the cricoid cartilage. Traditional teaching has been to use uncuffed endotracheal tubes (ETTs), as the risk of tracheal mucosal injury and resultant subglottic stenosis was reportedly much lower than with cuffed ETTs. Recent literature has challenged this teaching. With better technology, including the advent of high-volume, low-pressure cuffs, many investigators have found that using cuffed ETTs results in reduced rates of both air leaks and airway manipulation, without increased risk of tracheal injury [4–6]. For critically injured children likely to experience prolonged mechanical ventilation, cuffed ETTs are now preferred. In pediatric patients, the trachea is relatively short, which increases the risk of malposition of endotracheal tubes, most commonly in the right main bronchus. Tube position must be checked carefully at the time of intubation and monitored regularly thereafter, especially upon returning from patient transport.

In children, the thorax is much more compliant to external forces and the vital organs are closer to the surface, both of which tend to increase the risk of blunt injury to the tracheobronchial tree, the heart, and great vessels. The elasticity of pediatric arteries and the normal absence of atherosclerosis offset this risk. In children, the mediastinum is more mobile so that an increase in pressure from a pneumothorax or hemothorax on one side is more apt to compromise both lungs. In the abdomen, the more pliable ribs do not offer as much protection from blunt injury to the liver, spleen, and kidneys compared to adults.

Airway

The main reason for ensuring a stable airway is to provide effective oxygenation and ventilation while protecting the cervical spine and avoiding increases in intracranial pressure. Airway control is intimately related to cervical spine protection, but the scope of this chapter will be limited to managing the airway only. Any child involved in a significant trauma should be assumed to have a cervical spine injury until proven otherwise. Movement of the neck, as is commonly employed to provide an airway, can convert a bony or ligamentous injury into a permanent disability. C-spine protection should be initiated at the scene and maintained in the emergency department (ED). Any child who arrives without neck stabilization should be held with in-line traction or have an appropriate-sized rigid cervical collar applied while the airway is evaluated.

Anatomy and assessment

Several anatomic features predispose the child to potential airway obstruction. The child's head is relatively large and causes flexion of the neck in the supine position. The tongue is larger in proportion to the rest of the oral cavity and predisposes the child to more rapid upper airway obstruction with posterior displacement of the tongue. Even a minimal amount of pressure on the submental soft tissue during bag-valve-mask ventilation can displace the tongue posteriorly and occlude the airway. The larynx is higher in the neck (C3–C4) compared with that of the adult (C4–C5); this alters the preferred angle of insertion of the laryngoscope blade and makes the cords appear to be more anterior. "Cocking" the laryngoscope, as is commonly practiced in adult intubation, will only push the cords more anterior and make intubation difficult. The infant epiglottis is short and angled away from the long axis of the trachea, increasing the difficulty of its control with the laryngoscope blade. Infant vocal cords are more cartilaginous and easily injured when passing the endotracheal tube. The airways are much smaller and the supporting cartilage is less well developed, making the trachea more susceptible to obstruction from mucus, blood, or edema. In addition, the pediatric trachea is much shorter than the adult trachea, and advancing the tube too far into the right main stem bronchus is common.

It can be difficult to recognize early airway obstruction in the child. Certainly the infant who is screaming or crying loudly and the older child who can converse with you have airways that are not in immediate jeopardy. The child who arrives comatose (Glasgow Coma Scale score < 8) or with obvious laryngeal trauma has an airway that is in immediate danger. Often the child is obtunded. If spontaneous breathing is absent, the airway should be opened with a jaw thrust maneuver taking care to protect the C-spine. A finger sweep to rule out a foreign body should be performed. If no breathing effort is seen after this maneuver, hand ventilation with a mask should be initiated and preparation made to intubate the child. During assisted mask ventilation, the operator must take care not to place undue pressure on the base of the tongue, as this will occlude the airway. It is the pseudostable pediatric trauma patient who can present difficulties in determining whether an airway is adequate. The patient may appear only slightly agitated, with nasal flaring, stridor, and air hunger. The child with an innocent-appearing face and neck burn may have significant airway edema. When in doubt, the following maneuvers should be attempted to secure the airway.

Managing the airway

Studies investigating field intubation have demonstrated complication rates as high as 25% [7]. Appropriate mask ventilation can provide adequate gas exchange until one skilled in the task can intubate the child [8]. Newer airway techniques, including the pediatric King laryngeal tube (KLT) airway and the laryngeal mask airway (LMA), have been shown to be an effective temporary airway in children until secure endotracheal intubation can be performed in the ED [9,10]. The KLT is a fenestrated supraglottic airway that can be blindly inserted into the hypopharynx and provides ventilation. The LMA is placed in the posterior pharynx and advanced until it seals over the vocal cords and larynx. Excessive extension of the neck must be avoided in any airway technique. Oral and nasal airways do not protect the airway. In fact, their insertion can induce emesis. Nasal airways are too small to be effective in the child. An oral or nasal airway is, at best, a temporary technique to improve bag ventilation in preparation for endotracheal intubation.

Oral endotracheal intubation is the "gold standard" for airway control. It is critical to maintain neutral alignment of the cervical spine during all airway manipulation. Even though nasotracheal intubation in adults requires less spine manipulation, in children it is difficult and time-consuming, and therefore has little role in managing the acutely injured child. The size of the nares is often not large enough for an appropriate-sized tube. In addition, the path that the tube has to follow to the cords is at a very acute angle, requiring direct laryngoscopy and forceps to accomplish. Enlarged tonsils and adenoids can bleed if blindly injured with the endotracheal tube.

Children less than 6 years of age should receive an appropriately sized cuffed endotracheal tube to minimize trauma to the cords and subglottic edema. Formulas exist for calculating endotracheal tube size (Table 5.1), but a quick reference is the size of the middle phalanx of the fifth digit. The Broselow tape, which bases drug doses and weight on the child's length, also estimates endotracheal tube size [11].

Table 5.1 Endotracheal tube size in relation to age

Age	Internal diameter (mm)
Term infant	3.0
6 months	3.5
1 year	4.0
2 years	4.5
4 years	5.0
6 years	5.5
8 years	6.0
10 years	6.5
12 years	7.0
14 years	7.5
Adult	8.0

Note: May estimate tube internal diameter with formula: ID (mm) – Age/4 + 4.

Stylets are helpful for pediatric intubation to give the tube a gentle "J" curve. The tip of the stylet should never be extended beyond the end of the tube, and a thin coat of lubricating jelly can aid in removing the stylet without extubating the child.

Endotracheal intubation

The process of intubating a child can be harrowing for those not accustomed to it. Direct laryngoscopy is the preferred approach for the pediatric airway because anesthesiologists and emergency physicians are most familiar with it. However, video laryngoscopy (glidescope) is a relatively new technique to allow endotracheal intubation and may enable an improved view in patients with a difficult airway. Current ATLS recommendations call for a rapid sequence induction of sedation and paralysis, especially in those with closed head injury and possible elevated intracranial pressure [1]. Attempts to intubate a partially responsive, coughing, combative child will cause further elevation of the intracranial pressure. The use of drugs in rapid sequence induction must induce unconsciousness and paralysis, as well as blunt the intracranial pressure response [12]. Our current choice of drugs for rapid sequence induction is listed in Table 5.2. Care should be taken if the patient is in shock not to induce hypotension with too much sedative. Paralysis should not be induced in the spontaneously breathing patient until the physician is capable of visualizing the cords.

Gentle mask ventilation with cricoid pressure should be attempted to preoxygenate the child. In-line cervical immobilization with the collar opened anteriorly should provide adequate exposure. Rapid sequence induction is initiated after proper equipment is obtained and the child has been preoxygenated. This should include a bag and mask connected to high-flow oxygen, suction, a laryngoscope with functioning bulb, and an endotracheal tube with stylet of appropriate size as well as tubes that are a half size larger and smaller than the estimated correct size. A Miller

Table 5.2 Drugs and doses commonly used for rapid sequence induction

Drug class	Drug name	Dose (mg/kg)
Short-acting sedatives	Etomidate	0.2–0.4
	Pentothal	2–4
	Versed	0.01–0.02
Short-acting paralytics	Rocuronium	0.6–0.9
	Vecuronium	0.1–0.2
	Succinylcholine	1–2
Vagolytic (infants)	Atropine	0.01–0.02

Note: Avoid propofol and ketamine in children with elevated intracranial pressure. Sedatives and barbiturates can aggravate hypotension.

(straight) blade is most often easiest to use and should be gently inserted into the oropharynx and the tongue elevated anteriorly to visualize the cords. Avoid the temptation to "cock" the laryngoscope, as this will further displace the cords anteriorly and increase the likelihood of breaking or loosening an incisor. The tube should only be inserted a few centimeters past the vocal cords. The trachea is short and intubation of the right main stem bronchus can easily occur. The tube should be placed no deeper than three times the endotracheal tube size, in centimeters, from the lips. The Broselow tape will also specify a depth of insertion [11]. Endotracheal tube position should be confirmed with a disposable capnometer, as well as auscultation of both lung fields and listening over the epigastrium for esophageal intubation. Breath sounds transmit easily in young children and listening in both axillae will give the best point of auscultation to determine if the breath sounds are equal. Symmetry of chest wall excursion with ventilation should be noted; diminished sounds and movement of the left side should be treated by withdrawing the tube 0.5–1 cm. If diminished sounds persist, a left-sided pneumothorax should be considered. Since the trachea is so short, movement of 1 cm in either direction can often displace the tube into an inappropriate position. Vigilance in securing the tube and constant checking of its position is mandatory. Current ATLS recommendations call for obtaining a chest x-ray, as well as lateral C-spine and pelvis films, at the end of the primary survey to confirm tube position as well as rule out injury [1].

Special airway situations

Any child with a severe burn to the face and neck should be assumed to have an airway in jeopardy. Heat injury to the upper airway results in edema of the pharynx, larynx, and tongue that can rapidly occlude the airway. As tissues become more distorted, intubation can become more difficult. Furthermore, children injured in a confined space can have a compromised airway, even without obvious face and neck burns. Inhaled toxic fumes and particles can irritate the airway and cause edema. Prophylactic intubation is appropriate whenever heat injury to the upper airway is suspected, or if transportation to another facility is expected. It is much easier to remove a tube that is not needed than to obtain an airway emergently in a swollen burn victim. In addition, carbon monoxide poisoning is difficult to detect, as the pulse oximeter will continue to read high saturation. Tracheal intubation ensures efficient delivery of oxygen under these circumstances.

In the child with severe face or neck trauma, alternative maneuvers to endotracheal intubation may be necessary to secure the airway. A child with severe facial trauma who is able to maintain an airway should have a quick primary survey and all immediate life-threatening injuries addressed. The child should then be transported to the OR where a formal tracheostomy can be performed. If the patient is unable to maintain an airway, a needle cricothyrotomy is preferred to a surgical cricothyrotomy, especially if the child is less than 10 years of age. Insertion of a 14-gauge needle or angiocath requires less skill and can provide a temporary airway until the child can have a formal tracheostomy in the OR. Needle cricothyrotomy provides good oxygenation, although normocarbia can be difficult to maintain and therefore it should be converted to a surgical airway as soon as possible. Other alternatives, including fiberoptic-assisted intubation and retrograde intubation or tracheostomies, are institution and operator dependent.

Laryngeal trauma is rare in children but may need to be addressed in the setting of penetrating trauma or when "clothesline" injuries are sustained on bicycles and all-terrain vehicles (ATVs). Endotracheal intubation can potentially worsen the injury by causing complete separation of the trachea from the larynx and total loss of the airway. Signs and symptoms of laryngeal fracture include stridor, subcutaneous emphysema of the neck, pneumothorax, and hoarseness. If the child is able to maintain an airway, oxygen should be provided until a surgical airway can be obtained in the OR. Cricotracheal separation is an airway emergency that often requires immediate tracheostomy in the ED.

Breathing

Once an airway is secure, attention must next be directed toward injuries that affect ventilation and oxygenation. Most of these injuries comprise the immediate life-threatening injuries of the chest. Although these will be discussed in detail elsewhere in this book, they must be mentioned now, as an adequate primary survey cannot be secured without including these injuries in the differential diagnosis. Ventilation and oxygenation must occur in an effective manner, and if they do not, correctable causes should immediately be sought. The intubated child with stable blood pressure and good saturation likely does not have an immediately life-threatening chest injury, but can still have a potentially life-threatening chest injury. The intubated child who decompensates after intubation most likely has a life-threatening chest injury and must be managed appropriately to preserve a good outcome. The major life-threatening thoracic injuries include tension pneumothorax, open pneumothorax, massive hemothorax, flail chest, and cardiac tamponade. Other potentially life-threatening injuries to consider are simple pneumothorax, hemothorax, pulmonary contusion, tracheobronchial tree injuries, blunt cardiac injury, traumatic aortic disruption, aerophagia, and traumatic diaphragmatic injury (Table 5.3).

Assessment and monitoring

Assessing adequacy of ventilation and oxygenation in a busy trauma bay can be problematic. The child's breathing should be observed, looking for symmetry of excursion or flail chest segments (rare in children). Auscultation can be difficult in a noisy ED, but the best point of auscultation to check for equality of breath sounds is in the axilla. Pneumothorax will initially result in loss of expiratory

Table 5.3 Potential life-threatening injuries addressed in primary survey

Immediate life-threatening injuries	Potential life-threatening injuries
Airway obstruction	Simple pneumothorax
Tension pneumothorax	Hemothorax
Open pneumothorax	Pulmonary contusion
Massive hemothorax	Tracheobronchial injury
Cardiac tamponade	Cardiac contusion
Aortic disruption	Flail chest
	Diaphragmatic rupture

breath sounds, followed by the loss of inspiratory breath sounds. To distinguish the loss of breath sounds associated with a hemothorax versus a pneumothorax, percussion can be attempted; however, dullness and resonance to percussion can be difficult to appreciate in a noisy ED. Fortunately, both are initially treated with placement of a chest tube and are easy to distinguish afterward. If the child is stable, a chest x-ray can be obtained prior to initiating therapy. A decompensating child with decreased breath sounds should not wait for an x-ray prior to decompression of the hemo/pneumothorax.

Any child who has been intubated will require mechanical ventilation. In infants less than 1 year of age, pressure regulated ventilation is our preferred mode of ventilation in order to minimize iatrogenic barotrauma. A peak pressure is chosen such that the resulting tidal volume is 6–8 cm^3/kg, and a rate of 20–40 is chosen and adjusted based on the pCO_2 on an arterial blood gas. If the child has a closed head injury, the pCO_2 should be maintained at approximately 35 mmHg; otherwise a pCO_2 of 40 mmHg is acceptable. In children over 1 year of age, volume control ventilation is our preferred method of ventilation. However, pulmonary compliance should be monitored closely, and if it acutely changes secondary to fluid resuscitation, pulmonary contusion, or other causes, pressure control ventilation must be considered to minimize barotrauma as much as possible. Initial settings in volume control are similar in that a tidal volume of 6–8 cm^3/kg is desired, but the older the child, the lower the rate necessary to maintain adequate ventilation.

Adequacy of prehospital ventilation can be monitored via continuous end-tidal CO_2 ($EtCO_2$) monitoring. Most prehospital protocols include rapid sequence intubation (RSI) for patients who are found to have a Glasgow Coma Scale ≤ 8. For adult patients, it has been documented that patients intubated in the field have worse outcomes than historical controls [13]. This may be explained by overaggressive hand-bagging causing hyperventilation, hypocapnia, and worsened cerebral ischemia. Further, in the prehospital setting, $EtCO_2$ may not correlate well with $PaCO_2$, given that many patients with severe head injury may have concomitant hemorrhage or severe chest injury [14]. In addition, the air leak associated with an ETT may contribute to an inaccurate $EtCO_2$. Despite this, $EtCO_2$ monitoring provides confirmation of ETT position and may help prevent hypercapnia from aggressive hand-bagging.

Most EDs are equipped with pulse oximeters and capnometers. Arterial blood gases are useful but can be difficult to obtain. If perfusion is adequate, arterial oxygen saturation can be monitored with pulse oximeters. The pulse oximeter is also useful for assessing poor circulation; if the extremities are cool and the pulse oximeters do not register, hypovolemic shock is undoubtedly present and must be addressed. If the child is intubated, an $EtCO_2$ monitor can be placed on the endotracheal tube. The absolute value on $EtCO_2$ should be correlated to the pCO_2 on blood gas initially, and changes in $EtCO_2$ then are monitored and useful in guiding changes in ventilation.

Tension pneumothorax

Trauma to the rib cage may result in rib fractures and parenchymal injury. A small parenchymal injury with air leak or a major tracheobronchial tear may result in pneumothorax. The child with a pneumothorax may have an asymptomatic simple pneumothorax or have severe respiratory distress from an open or tension pneumothorax. Physical findings of pneumothorax include absence of breath sounds on one side of the chest, hyperresonance to percussion, subcutaneous emphysema, and tracheal deviation away from the affected side. Physical findings may be very subtle.

A tension pneumothorax occurs with progressive entry of air that is unable to escape from the pleural space. This compresses the ipsilateral lung and results in a shift of the mediastinum to the contralateral side. Since the mediastinum is so compliant, it shifts earlier in the course, resulting in decreased venous return and more rapid cardiovascular collapse in the child. An open pneumothorax allows communication between the environment and pleural space. Equilibration of atmospheric and pleural pressure occurs with collapse of the lung and less shift of the mediastinum. Because of the loss of negative inspiratory pressure, respiratory distress can occur due to decreased ventilation on the ipsilateral side. Massive hemothorax occurs secondary to parenchymal injury, severe vascular injury, or intercostal bleeding from rib fractures. This condition is more common with penetrating chest trauma than blunt chest trauma.

Treatment of a tension pneumothorax is accomplished by insertion of a chest tube. Temporary relief can often be obtained with needle decompression, which should be performed in the second intercostal space, in the midclavicular line. Any child who has had needle decompression of the chest needs an appropriate-sized chest tube placed as soon as possible. Children are more susceptible to the associated mediastinal shift than adults. Therefore, any child with acute cardiovascular collapse, especially if it occurs shortly after the initiation of positive pressure ventilation, should have needle decompression or tube thoracostomy performed bilaterally if it is unclear which side is the symptomatic side. If acute cardiovascular collapse occurs, this decompression should be performed prior to obtaining a confirmatory chest radiograph. Needle decompression of the second intercostal space anteriorly may alleviate the condition long enough to allow for completion of the primary survey prior to placing a chest tube. However, if needle decompression fails to reverse the collapse, a chest tube should immediately be placed. Clinically, a hemothorax may be difficult to distinguish from a tension pneumothorax; however, treatment is the same for both conditions and an x-ray is not necessary prior to treatment. Massive hemothorax will not usually respond to needle decompression unless there is an associated tension pneumothorax component. A three-sided occlusive dressing that allows air to exit the pleural space on expiration and prevents its return on inspiration can stabilize a patient with an open pneumothorax. With massive open pneumothorax, intubation and positive pressure ventilation may be necessary to overcome the defect.

Tube thoracostomy

Even in emergency situations, chest tube placement should be performed aseptically. The skin should be prepared with an antiseptic and sterile towels draped to expose the appropriate chest. The most important landmark is the nipple, which should be visible after draping. Usually the fifth or sixth interspace is located at the level of the nipple, and a skin incision is made one or two fingerbreadths below the nipple in the anterior axillary line after anesthetizing with 1% lidocaine. A hemostat is then used to tunnel the chest tube for 1–2 cm in the subcutaneous space. The hemostat is then inserted on top of the rib and pushed firmly until the pleural space is entered. If tension is present, this maneuver alone will alleviate the tension and restore hemodynamic stability. An appropriate-sized chest tube is then inserted into the pleural space (Table 5.4). Many pediatric chest tubes come with a sharp trocar, which should never be used to blindly place the chest tube. The trocar can be safely used as a stylet to help guide the tube into the previous dissected tunnel and entrance into the pleural space. It should always be pulled back 1–2 cm from the end of the chest tube, but can then help stiffen the tube for easier placement. The other method of inserting the tube would be to remove the trocar completely, grasp the tube in the end of a hemostat, and direct it through the tract and into the pleural space. The tube should be gently inserted until it is felt contacting the apex, then withdrawn 2 cm and secured with a suture. Fogging of the tube should be noted on insertion, and tidal movement of the water seal chamber should be noted with ventilation. A chest x-ray is always obtained to check tube position.

Table 5.4 Chest tube size (French)

Size of patient (kg)	Pneumothorax	Hemothorax
<3	8–10	10–12
3–8	10–12	12–16
8–15	12–16	16–20
16–40	16–20	20–28
>40	20–24	28–36

Other chest injuries

One must keep in mind that pneumothorax may be associated with more severe injuries of the tracheobronchial tree. A large continuous air leak after chest tube placement or continued respiratory distress may signal a larger tracheobronchial injury. Bronchoscopy in the OR should be performed soon after the primary survey to diagnose the injury in those who fail to resolve their air leak, or who remain difficult to ventilate and oxygenate. If the air leak is on the left side, passing the endotracheal tube into the right main stem bronchus may temporarily allow adequate ventilation and oxygenation until it can be addressed operatively. Tidal volumes must be decreased and rate increased to avoid a pneumothorax on the right side as well. Blood loss from a massive hemothorax should continuously be monitored to avoid hypotension and determine the need for thoracotomy. In general, loss of more than 20 mL/kg of blood from the chest with continued bleeding should be addressed surgically.

Although a true flail chest is rare in children, the compliance of the chest wall frequently allows impact to cause an occult pulmonary contusion without obvious rib fracture. This underlying pulmonary contusion and/or laceration of the lung parenchyma can result in respiratory distress. A large pulmonary contusion can result in hypoxia from severe ventilation–perfusion mismatch. Management of severe pulmonary contusion should aim to maintain the child in a state of euvolemia [15]. Attempts to avoid pulmonary edema by keeping the child hypovolemic are likely to result in hemodynamic instability and worsen the ventilation–perfusion mismatch. If the child is able to maintain saturation with spontaneous ventilation and supplemental oxygen, the contusion is best treated with aggressive pain management, including epidural catheter or rib blocks to provide adequate pain control for aggressive chest physiotherapy. A pulmonary contusion or flail segment causing severe paradoxical motion and hypoxia or hypercarbia is best managed with intubation and positive pressure ventilation. Keys to management include employing an aggressive pulmonary toilet, providing sufficient tidal volume to prevent atelectasis, and maintaining a normovolemic state. Positive end expiratory pressure is beneficial, and positive pressure ventilation is often needed for 2–3 days before the patient's chest wall is stable enough to allow for spontaneous ventilation.

Potentially life-threatening injuries, which usually do not manifest symptoms early in evaluation, include traumatic aortic rupture and diaphragmatic rupture. The mobile mediastinum that makes the child more susceptible to tracheobronchial injuries makes the child less likely than the adult to sustain a torn aorta [16]. Although rare, an aortic injury should be suspected, especially in adolescents with chest trauma secondary to a significant deceleration mechanism. Signs suggesting a torn aorta include the chest x-ray findings of a widened mediastinum, apical cap, left hemothorax, deviated left main stem bronchus, deviated nasogastric (NG) tube, or first and second rib fractures. In a severely injured patient with multiple potential sources of hypotension, the presence of a widened mediastinum should not interfere with completion of the primary survey. There is the temptation to rush in to repair of the aorta due to its devastating consequences should it rupture. However, the unstable pelvis, bleeding liver and spleen, or open femur fracture must be addressed prior to placing the patient in a thoracotomy position for repair of the torn aorta [17]. Hypotension induced by a torn aorta is acute in onset, extremely short in duration, and the patient expires rapidly.

Diaphragmatic rupture can result from a fall from excessive height or crush injury to the chest and abdomen. Loss of diaphragmatic function as well as herniation of abdominal contents into the thorax can result in respiratory distress. It can present subtly on chest x-ray with loss of left diaphragm border, or obvious loops of bowel can be seen in the chest. Axial cuts on CT scan can miss a small defect as well. A plain film with NG tube in stomach noted above the diaphragm and/or upper gastrointestinal (UGI) with bowel in the chest is diagnostic. Initial treatment in the primary survey should be placement of an NG tube to decompress the abdominal contents in the chest. The diaphragmatic defect is most often repaired from an abdominal approach.

A nonlife-threatening condition common in pediatric trauma victims that can cause significant respiratory distress is massive aerophagia. Small children who present to the ED crying and screaming can swallow a significant quantity of air and induce massive gastric distension. This aerophagia can result in increased abdominal girth, respiratory compromise, and emesis with potential for aspiration. This can be rapidly cured by early insertion of an NG tube.

Cardiac injury/ER thoracotomy

Blunt injury to the heart is rare in the child; however, it must be assumed with any penetrating trauma to the chest, especially if the wound is potentially transmediastinal. If a child's cardiopulmonary status acutely deteriorates, bilateral chest tubes should be placed for the likely tension pneumothorax; if these fail to alleviate the condition, a pericardiocentesis can be performed. Clinicians facile with focused assessment with sonography for trauma (FAST) may also check the epigastric window for evidence of pericardial fluid. A positive pericardiocentesis for blood or positive FAST for pericardial fluid is an indication for urgent thoracotomy or sternotomy to identify and repair a cardiac injury. Myocardial contusion is rare in children, but can occur in adolescent drivers who may sustain a significant chest impact from the steering wheel. Rarely is a cardiac contusion severe enough to cause heart failure.

ER thoracotomy is a topic of debate in the literature and in many trauma centers. Even though children have much greater physiologic reserve than adults, loss of vital signs that do not return with adequate cardiopulmonary resuscitation (CPR) prior to arrival in the ED is almost universally fatal. This is especially true when the injury is secondary to blunt trauma and does not warrant an ER thoracotomy. Over the years, a number of institutions have reviewed their success rate with ER thoracotomy in blunt trauma, and few if any survivors have been noted [18,19]. Even those children whose vital signs return with CPR prior to arrival in the ED have a 25% survival rate, at best, and two-thirds of those who do survive have significant impairment in one or more activities of daily living [20]. In contrast, an ER thoracotomy can be lifesaving with penetrating chest trauma when vital signs are not lost until the child arrives in the ED.

Circulation

After a patent airway is established and adequate ventilation has been assured, the diagnosis and management of shock takes precedence. Evaluation of the circulation is a process that must be performed simultaneously with the assessment of the airway and breathing. Successful treatment of shock requires rapid recognition that the child is in shock and initiation of simultaneous treatment maneuvers. Direct pressure may be required to control external bleeding, especially from scalp, neck, and groin wounds. Long bone and pelvic fractures should be stabilized with traction and splinting.

Pediatric physiology

In general, the physiologic concepts of hemorrhagic shock apply to both children and adults. However, children are unique in several aspects of anatomy and physiology that make recognition of shock more difficult, but at the same time provide them tremendous reserve to survive many injuries compared to adults. Most notably, the variability in size and weight that one encounters in dealing with pediatric trauma poses a problem in ensuring that appropriate equipment and medications will be available for the resuscitation of the child.

Normal circulating blood volume in a child is 7%–8% of total body weight, 70–80 mL/kg. Although in relative terms the circulating volume is 20% greater than in adults, what may appear to be a small amount of blood loss can be very significant in a young child. A 200-mL estimated blood loss in a 10-kg child is equal to 25% of the child's blood volume. Children also have a higher body-surface-area-to-mass ratio. This leads to an increase in insensible water loss that makes them susceptible to hypovolemia and increased heat loss, which can lead to hypothermia. In extremely young children, hypothermia is a major problem associated with trauma resuscitation. Hypothermia aggravates pulmonary hypertension, hypoxia, and acidosis and results in a significant increase in oxygen consumption. The extremely compliant mediastinum makes infants and children more susceptible to wide swings induced by tension pneumothorax or hemothorax. Shifting of the mediastinum not only decreases venous return and cardiac output, but can also interfere with ventilation of the contralateral lung.

The clinician evaluating pediatric trauma must be familiar with the wide variability in normal vital signs based on age. A pulse rate and blood pressure that are acceptable in an infant may indicate significant hypovolemia in an adolescent (Table 5.5). The goal of management is to recognize that shock exists before the vital signs change. The signs of late hypovolemic shock are easy to recognize, but the clinical presentation of early shock requires a high index of suspicion. The clinician must rely on subtle findings during the physical examination as well as the vital signs (Table 5.6).

Assessment

Shock is a state in which there is inadequate delivery of oxygen to meet the demands of the child. Absolute values of blood pressure have little to do with defining the shock state. A child with a normal blood pressure can be in shock, just as a child with low blood pressure can be well perfused and not in shock. The earliest warning signs that a child is in shock include signs of decreased skin perfusion (capillary refill, temperature, and color), central nervous system perfusion (lethargy, inappropriate response to painful procedures, and lack of recognition of parents), pulses (tachycardia and presence or absence of pulses), and falling blood pressure. With a quick physical exam, the physician should be able to readily estimate the degree of shock and estimate blood loss (Table 5.6). After the airway and breathing are secured, most astute trauma physicians palpate the child's feet or hands. A child who has warm feet with bounding pedal pulses is not in hypovolemic shock. A child with cool feet, weak and thready pedal pulses, depressed capillary refill, and mottled cool extremities is already in significant shock. The child with hypotension and a markedly depressed mental status is in late shock with blood loss up to 40% of blood volume. Waiting until hypotension is present to begin treating shock is waiting too late.

There are no laboratory tests or x-rays that can rapidly estimate the degree of blood loss and shock. In acute hemorrhage, the hemoglobin level does not change immediately; it will fall only after compensatory fluid shifts have occurred and resuscitation has begun. The best laboratory predictor of shock and volume loss is the arterial base deficit. Adult trauma surgeons have identified base deficit as a predictor of survival, and recently this test has been demonstrated to be predictive of morbidity and mortality in pediatric trauma victims [21–23]. As anaerobic metabolism is increased in response to inadequate tissue perfusion, lactic acid is produced. Most anxious children hyperventilate, which helps compensate for the developing metabolic acidosis. If shock persists, the metabolic acidosis worsens. Sodium bicarbonate can improve the laboratory values obtained, but until the cause of shock is addressed and resuscitation is initiated, the overall clinical picture will not improve. Sodium bicarbonate

Table 5.5 Normal vital signs by age

Age	Weight (kg)	Heart rate (beats/min)	Pressure[a] (mmHg)	Respirations (breaths/min)	Urine output (mL/kg/h)
0–6 Months	3–6	160–180	60–80	60	2
Infant	12	160	80	40	1.5
Preschool	16	120	90	30	1
Adolescent	35	100	100	20	0.5
Total	**998**			**908**	**90**

Source: From American College of Surgeons, *Advanced Trauma Life Support for Doctors Instructor Manual*, Chicago, 2013.

[a] Systolic blood pressure should be 80 + 2 age (years).

Table 5.6 Systemic response to blood loss in pediatric trauma patients

System	<25% blood loss	25%–45% blood loss	>45% blood loss
Cardiac	Tachycardia	Weak, thready pulse, and tachycardia	Hypotension, tachycardia to bradycardia
CNS	Lethargic, irritable, and confused	Changing level of consciousness and dulled response to pain	Comatose
Skin	Cool and clammy	Cyanotic, decreased capillary refill, and cold extremities	Pale and cold
Renal	Normal urine output, increased specific gravity	Decreased urine output	No urine output

Source: From American College of Surgeons Committee on Trauma. *Pediatric Trauma in Advanced Trauma Life Support for Doctors, Instructor Course Manual*, Chicago, 1997.

has not been shown to improve survival and may aggravate any existing respiratory acidosis with increased CO_2 production [24,25].

IV access

In order to resuscitate the child from shock, IV access is a must. In the very young, this can pose more of a problem than securing the airway. At the same time that access is being established, blood should be drawn for a standard trauma laboratory panel. A specimen for typed and crossed blood must be sent early in the resuscitation. Establishing two large-bore peripheral intravenous (PIV) catheters is clearly the first choice for resuscitation [1]. A short catheter should be chosen to minimize resistance to flow. This can be a daunting task in a small, hypovolemic child. Preferably, lines should be placed above and below the diaphragm. The most desirable sites for PIV access include percutaneous IVs in the antecubital fossa, distal saphenous vein, or other peripheral vein. The veins are usually more superficial than initially anticipated. Another tip is to rotate the needle and angiocath 180° so that the bevel hooks under the venotomy and ensures that the angiocath will thread into the vein.

Previous texts have recommended a distal saphenous vein cutdown in the event that peripheral lines cannot be obtained. However, this can be tedious and extraordinarily difficult even for seasoned pediatric surgeons. After 2–3 attempts at a PIV, the patient should have an intraosseous catheter placed, especially if the patient is not at a pediatric trauma center.

Other options include a percutaneously placed central venous catheter. In elective circumstances, the jugular or subclavian approach would be preferred. However, in the ED environment, and with the possibility of cervical spine trauma, the risk of pneumothorax or spine injury may be prohibitory. Temporary cannulation of the femoral vein with a large-bore IV catheter or venous introducer provides central venous access in a timely fashion. Femoral catheters should be removed as soon as possible as long-term use may increase the risk of venous thrombosis [26]. The line must be placed as aseptically as possible, and many trauma surgeons demand that all lines placed in the field or ED be removed once the patient is stable in the hospital. The groin is sterilely prepped and draped and the femoral pulse is palpated. With a finger over the palpable arterial pulse, the femoral vein is aspirated with a needle and syringe just medial to the palpable pulse. A wire is threaded by Seldinger technique, and the line placed over the wire. Long multiple lumen catheters should be avoided due to the resistance to flow. A single lumen six French catheter introducer, if available, or even a large-bore angiocath should be sufficient for large volume resuscitation.

In children less than 6 years old, intraosseous (IO) infusion provides a rapid and safe route of success. Blood products, fluids, and medications can be given through this type of catheter [27,28]. Although not a good long-term route of IV access, it allows the initiation of fluid resuscitation, and with improved circulatory status, a peripheral route of venous access may become feasible. Complications with IO needles are rare if placed appropriately. A 16- or 18-gauge bone marrow aspiration needle is placed in the tibia, 2–3 cm below the tibial tuberosity, angled slightly away from the growth plate. If the tibia is fractured, it can be placed in the femur 3 cm above the femoral condyle. The humeral head is an alternative site for IO access that has become more popular in recent years.

In all pediatric trauma victims, percutaneous PIV access should be attempted first. If this fails in a child less than one, and a pediatric surgeon or intensivist is not available, an IO line should be obtained and the child transferred as soon as possible. In the child 1–6 years of age, a percutaneous femoral line may be feasible prior to resorting to an IO line. Most children over 6 years of age have veins of sufficient size for percutaneous peripheral placement. If in extremis and access is difficult, a femoral central line or IO line would be the best choices for access.

Resuscitation

Once shock has been identified and IV access has been obtained, resuscitation should be initiated. Many algorithms for resuscitation exist, and most are based on ATLS recommendations (Figure 5.1). The most recent ATLS guidelines for adult trauma patients recommend less fluid resuscitation with crystalloid and earlier transfusion of blood and blood products [29]. In the prehospital setting, management of hemorrhage and shock includes early rapid crystalloid replacement. However, whether the use of aggressive prehospital fluid resuscitation improves mortality is a matter of debate. IV fluid resuscitation should not be reason to delay patient transport to a definitive care facility [30]. Upon arrival to the trauma bay, any injured child who shows clinical signs of hypovolemic shock should have prompt surgical consultation. A 20-mL/kg bolus of lactated ringers or normal saline is given as soon as shock is suspected. Response to this bolus is monitored. It may be repeated once or twice if perfusion is not improved. If after a second bolus of crystalloid the child is still clinically in shock, a 10-cm^3 kg bolus of cross-matched packed red blood cells (or type-specific or O-negative cells) should be given, in addition to the equivalent amount of fresh frozen plasma. Although not studied as extensively in the pediatric population, the adult trauma literature suggests resuscitation should be continued so that the patient receives packed red blood cells, fresh frozen plasma, and platelets in a 1:1:1 ratio. At this point in the resuscitation, if the child is not in an institution capable of handling a hemodynamically unstable child, preparation for transfer should be initiated. Furthermore, surgical consultation is needed immediately. Children with stable spleen and liver lacerations, as well as stable fractures, will usually stabilize after a 10-cm^3/kg bolus of packed cells. Those who do not and continue to exhibit signs of hypovolemic shock are likely to need their primary survey completed in the OR. The primary survey is not complete until the child is

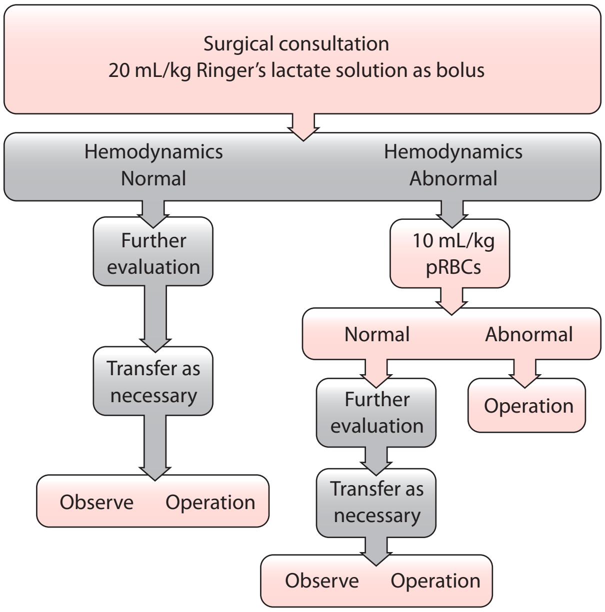

Figure 5.1 Resuscitation flow diagram for the pediatric trauma patient [31]. (From American College of Surgeons, *Advanced Trauma Life Support® for Doctors Instructor Manual*, Chicago, IL, 2013; American College of Surgeons Committee on Trauma. *Pediatric Trauma in Advanced Trauma Life Support for Doctors, Instructor Course Manual*, Chicago, IL, 1997.)

hemodynamically stable and does not have an ongoing fluid requirement. Until that time, if an adequate airway and ventilation are confirmed, hypovolemic shock must be assumed and a source sought and treated.

Conclusion

Initial management of the pediatric trauma victim is similar to that of the adult trauma victim. However, it requires sufficient knowledge of the physiologic and anatomic differences between children and adults. Successful management requires adequate assessment and control of the airway, breathing, and circulation. Evaluation of the ABCs is a dynamic process that requires simultaneous assessment and resuscitation, as well as persistent reassessment until the child is well oxygenated and hemodynamically stable. Although class I and class II data are rare in the current literature, guidelines such as those developed through the ATLS program can be used to successfully manage most pediatric trauma victims.

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6

Clearance of the cervical spine in children

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Immobilization of the cervical spine at the scene of injury represents standard of care in prehospital management of pediatric trauma patients. Exclusion of injury after formal trauma evaluation and the decision to discontinue immobilization ("cervical spine clearance") can be straightforward in awake and asymptomatic patients but challenging in preverbal or very young children, patients with severe traumatic brain injury (TBI), intoxicated patients, or patients with otherwise impaired consciousness. These challenges are heightened by the unique anatomy and injury patterns of pediatric trauma patients, which make their evaluation different from that of most adult trauma patients. Expeditious clearance of the cervical spine is important to avoid the complications of spinal immobilization that include pain, decubiti, and aspiration. Debate exists around the use of various imaging modalities for cervical spine clearance in children and when they should be employed, especially considering the need to reduce radiation exposure in children due to the risk of future malignancy. This chapter will discuss the unique aspects of pediatric cervical spine anatomy, injury patterns, and evaluation. Current practice will be reviewed, as well as a summary derived from published protocols providing guidance for cervical spine clearance in children.

Epidemiology

There are approximately 1300 new cases of cervical spine injury in children per year in the United States, for an incidence of 18.1 injuries per million children per year [1]. Cervical spine injury in children accounts for 1%–1.5% of pediatric trauma admissions [2,3]. About 60%–80% of spinal injuries in children are in the cervical spine. Victims tend to be male, with a 1.5:1–2:1 male–female ratio [2]. Injuries are most commonly seen in the adolescent age group, followed by school-age children, and mechanisms include motor vehicle collisions (MVC), falls, and sports-related injuries [4]. The distribution of injury type is different among different age groups in the pediatric population. Large series have shown that children less than 8 years old have a predisposition to occipitoatlantoaxial complex injuries as well as pure ligamentous injuries as opposed to fractures [2]. In these cases younger age and a high energy mechanism of injury are predisposing factors. A recent retrospective review from Johns Hopkins noted a 40%–60% rate of C4 or higher injuries in children less than 9 years old, while adolescents suffered high injuries in only 37% of cases [4]. In children 9–16 years of age, subaxial cervical spine injuries tend to occur between C5 and C7, consistent with the approximation of their cervical anatomy to that of adults [5]. Unfortunately, cervical spine injuries in patients younger than 8 years have a higher incidence of neurologic deficit (62% versus 47%) and higher mortality (15%–28% versus 11%) compared to older children and adults [6].

Infants represent a special subpopulation due to their inability to communicate, and most published series exclude infants less than 1 year of age from analysis, making extrapolation of existing data difficult. In a recent report of 905 infants less than 1 year of age sustaining low-impact head trauma, the incidence of spinal injury on imaging was 0.2% [7]. However, although rare, spinal injuries in this age group have been shown to be much more devastating. A report of 206 children less than 9 years of age presenting with spinal injury indicates a 25% in-hospital mortality for children less than 3 years of age and a 9% in-hospital mortality in the 3–9 years age group [8].

Unique pediatric cervical spine anatomy

The cervical spine in children displays unique biomechanics during injury. The fulcrum of motion is at the C2–C3 level, rather than the adult C5–C6, which predisposes children to high cervical spine injuries. In addition, the spinal column itself is more mobile due to ligamentous laxity, shallow facet joints, underdeveloped spinous processes, and physiologic anterior wedging. The large head and weak neck muscles common to younger children combine with the mobile spine to allow high shear and torque forces during injury. The unique anatomy of the cervical spine in children exists up to the age of 8–10 years, and by 10–12 years approaches adult proportions with similar clinical sequelae of injury [9].

The pediatric spine also has a number of normal variants not commonly encountered in adults which can confound the interpretation of imaging. These include pseudospread of the atlas on the axis (pseudo-Jeffersonian fracture) in children up to 7 years of age, physiologic pseudosubluxation of C2 on C3 in children less than 8 years of age, absence of lordosis, widening of prevertebral soft tissues, and the presence of ossification centers that can mimic fractures [9]. Pseudosubluxation of C2 on C3 is present in 19% of normal children less than 7 years old; less commonly it can be seen at C3–C4.

These anatomic and functional differences have implications for injury diagnosis. A report from Seattle described 37 children who were diagnosed by imaging with acute cervical spine injury. On blinded review by a senior radiologist, 19% of the cases were found to have been misdiagnosed based on initial emergency room imaging evaluation. When examined for the cause of misdiagnosis, five out of seven of the mistakes were related to misinterpretation of normal and developmental variants [10]. This effect was most prevalent in children less than 8 years old.

During immobilization in the field, the prominent occiput of younger children results in cervical flexion even when a hard collar is employed. Prehospital responders should be aware of this phenomenon and should use either an occipital recess or thoracic elevation in order to stabilize the cervical spine in line.

Common patterns of injury

The anatomic and functional differences of the pediatric spine result in unique patterns of injury, especially in children less than 8 years of age. These children tend to have higher percentages of high cervical spine injury (occiput through C2) compared to older children, in the range of 60%–70% of all cervical spine injuries in this age group. High C-spine injuries in children include occiput-C1 dislocations and distraction, atlas or Jefferson fractures (especially in adolescents), rotary subluxation of C1 on C2 in young children, and ligamentous disruption of the atlantoaxial joint, which can result in severe neurologic injury. C2 fractures, especially odontoid fractures, are the most common cervical fractures in children. Subaxial injuries are much less common in younger children and in pediatric patients tend to be associated with adolescents and with sports-related and motor vehicle accidents [6]. One particular lower cervical spine fracture seen more commonly in children is hyperextension teardrop fracturing of the anterior–inferior corner of the vertebral body. This is more commonly observed in children than in adults due to the more osteopenic bone of the immature spine [11].

Infants less than 1 year of age are at extremely low risk of cervical spine injury in the setting of a low energy mechanism (e.g., falls < 10 feet). However, victims of nonaccidental trauma or infants suffering high-energy mechanisms such as MVCs are at higher risk of cervical spine injury due to the extreme laxity of their ligaments, weak musculature, and large heads with the ensuing potential for high shear and torque forces on the spinal cord.

Spinal cord injury without radiographic abnormality

Spinal cord injury without radiographic abnormality (SCIWORA) is a common phenomenon in children relative to adult trauma victims. Ninety percent of SCIWORA cases occur in the pediatric population [1]. This is defined as cervical spine injury, occasionally severe disruption, which is seen without evidence of bony abnormality on plain radiographs or computerized tomography (CT). Of note, this includes absence of abnormality on both static and dynamic (flexion/extension) films. The likely mechanisms include the relative inelasticity of the spinal cord relative to the highly mobile spine, ligamentous disruption, and possible ischemia from vessel injury or spinal hypoperfusion [9]. Extra-axial hemorrhage can also result in spinal cord injury in the absence of bony findings [11]. Neonates and infants suffering from nonaccidental trauma are particularly predisposed to this injury. In the largest reported series of pediatric cervical spine injury, in those patients with spinal cord injury, approximately half demonstrated no radiographic evidence of bony injury [12]. While this is a phenomenon of children, its occurrence is rare. A recent report from Ontario, Canada, demonstrated that out of 578 patients with vertebral trauma, the incidence of associated spinal cord myelopathy was 8%, and of those patients, only 3 had SCIWORA. Of these, the magnetic resonance imaging (MRI) findings included cord contusion in two and central disk herniation in one; for the cord contusion patients, the deficit was found to be permanent. Analysis of several single institution series for incidence of SCIWORA among patients with documented traumatic spinal cord injury reveals an incidence of 4%–28% and a mean incidence of 14% [13], meaning that in 86% of cases, injury will be observable on radiographic studies.

MRI is required in these cases to identify spinal cord or ligamentous injury. In the unconscious child, some experts advocate proceeding directly to MRI for cervical spine evaluation if the duration of impaired consciousness is expected to be prolonged past 72 hours [1]. Of note, controversy exists over whether cervical spine immobilization is required in cases of extraneural MRI findings (e.g., ligamentous injury) if dynamic films reveal stability of the cervical spine. Some centers now recommend abbreviated immobilization (2 weeks) when the patient is asymptomatic and has only extraneural MRI findings [2].

Initial stabilization and treatment recommendations

Protection of the cervical spine should be part of the initial response to evaluation of children with significant trauma. Early cervical spine immobilization allows for attention to Advanced Trauma Life Support (ATLS)-guided resuscitation. Soft collars do not provide immobilization, and therefore hard collars should be used in this situation. A variety of such collars are in use, and those most commonly used are the Philadelphia and Miami Junior collars. There is no direct comparative study of the differences between these options.

A detailed physical examination is conducted during the secondary survey to evaluate for superficial injury over the spine, hematoma, misalignment, tenderness, and focal neurologic deficits. After stabilization and assessment, the physician must decide whether radiologic evaluation is indicated, and if so, which modality to employ.

Clinical examination

A significant body of evidence suggests that, in the absence of clinical or physical exam findings concerning for cervical spine injury, an underlying or missed injury is highly unlikely to be present. This observation has been published primarily in the last 10 years and involves several multi-institutional studies relying on prospectively collected data.

In a subgroup analysis of the NEXUS study, which sought to identify a risk stratification system for blunt trauma victims with potential cervical spine injury, no pediatric patients who met low-risk NEXUS criteria were found to have a cervical spine injury. Clinical criteria of the NEXUS instrument include presence of a focal neurologic deficit, midline spinal tenderness, altered level of consciousness, presence of intoxication, and presence of a distracting injury. Patients with absence of all of these findings were categorized as low risk. The authors note that in the medical literature as a whole, there are no cases of a child with an occult cervical spine injury that would have met NEXUS low-risk criteria. While the study was underpowered to safely recommend global application of these criteria in pediatric trauma patients, these results certainly support the correlation of a negative clinical examination with a very low likelihood of occult cervical spine injury [3].

A large multi-institutional study through the American Association for the Surgery of Trauma was reported in 2009, in which over 12,000 trauma patients less than 3 years of age were examined for cervical spine injuries. An incidence of cervical spine injury of 0.66% was identified in this age group, and of those patients, only eight of the injuries were associated with injury to the spinal cord itself. Four independent predictors of cervical spine injury (Glasgow Coma Scale [GCS] ≥ 14, $GCS_{eye} = 1$, MVC mechanism, and age ≥ 2 years) were identified by multivariate analysis and assimilated into a scoring system. A score of < 2 was considered low risk. In the pediatric trauma cohort, >70% met low-risk criteria. A score of < 2 had a negative predictive value of 99.9% for the presence of cervical spine injury [14]. Using this algorithm, there were no missed cervical spine injuries.

Most recently, the PECARN network conducted a 17-center case-control study in which pediatric blunt trauma victims sustaining cervical spine injury were compared to three separate sets of case-matched controls. Five hundred and forty cases of cervical spine injury were identified. After analysis, eight factors were identified which were associated with cervical spine injury: altered mental status, focal neurologic findings, neck pain, torticollis, substantial torso injury, conditions predisposing to cervical spine injury (e.g., various connective tissue disorders, previous cervical spine surgery, etc.), diving, and MVC. The presence of one of these eight risk factors was 98% sensitive for detection of cervical spine injury in this patient population, and in the patients with cervical spine injury who did not have any of the eight risk factors, normal neurologic outcomes were reported [15].

Taking these findings together, six variables are common to multiple models of cervical spine injury risk: altered mental status, focal neurologic deficit, complaint of neck pain and tenderness, substantial injury to the torso, high-risk motor vehicle crash, and diving. The sensitivity of these six variables for detecting cervical spine injury is estimated at 97% [15].

Diagnostic modalities

In those patients who do display clinical findings concerning for cervical spine injury, a variety of diagnostic modalities are available including plain radiography, CT, and MRI. In the pediatric population the use of CT is controversial. CT of the cervical spine is becoming much more common, with a sixfold increase in the last 20 years. Much of that increase has been cervical spine and chest imaging in blunt trauma patients. A perceived advantage of CT over plain film radiography, supported by the adult literature, is weighed against the known risk of future malignancy related to radiation exposure in children, specifically to the thyroid, which is within the radiation field and is intrinsically radiosensitive. Additionally, the relative rarity of cervical spine injuries in children as opposed to adults suggests that the same imaging paradigms cannot be applied equally in the two populations. Recent efforts have focused on delineation of the relative sensitivity of the various imaging modalities in children and on the definition of criteria for which imaging should be escalated to cross-sectional modalities.

Plain radiography

Plain radiography can range from a single lateral cervical spine film as a screening tool to a series of three to five views of the cervical spine. The common views include lateral, anterior/posterior, odontoid (open mouth), swimmer's view, and bilateral oblique views of the neck. In all cases, the technical adequacy of the study is of great importance. Inadequate imaging, especially of the craniocervical junction and the cervicothoracic junction, is frequently cited as a criticism of the use of plain radiography.

The PECARN network evaluated the sensitivity of plain radiograph in cervical spine injury detection in a report by Nigrovic et al. All patients less than 16 years old sustaining blunt trauma-related cervical spine injury were evaluated, and patients with at least two views of the cervical spine were included. The estimated sensitivity was 90% in all patients, and was better for older children (93%) than for children less than eight (83%). The estimated sensitivity for ligamentous versus fracture injury was similar at 88% and 91%, respectively. Only 10% were found to be inadequate studies [16].

Further studies have evaluated the utility of adding views to the traditional lateral cervical spine radiograph. Silva et al. described a retrospective single institution series of 234 patients undergoing cervical spine radiographs and cervical spine CT, which was used as the reference standard. The sensitivity of lateral radiograph alone was 73% with specificity of 92%. The addition of further views (A/P, odontoid, swimmer's, flexion/extension, or oblique) did not change either the sensitivity or the specificity of the study [17]. Oblique imaging in conjunction with three-view radiography has been thought to improve imaging of the posterior elements of the spine, subluxations, and neural foramina impingement. In a report from Boston, 109 children with both standard three-view imaging (A/P, lateral, and odontoid) and oblique imaging were analyzed for utility of the oblique view in aiding diagnosis. The oblique view failed to improve detection of cervical spine injury in all imaged patients and in 96% of imaged patients for whom standard three-view imaging had revealed an acute abnormality. This calls into question the utility of the oblique view in children [18].

The cervicothoracic junction is a common site of inadequate imaging in lateral radiography. In an effort to improve the quality of the lateral cervical spine radiograph in children, Kulaylat et al. performed a retrospective study of patients who had traditional downward inline traction applied to the arms and standard cervical spine stabilization compared to cephalic stabilization, which added gentle upward inline traction. Adequacy of cervicothoracic junction visualization was assessed by a case-controlled retrospective review. Cephalic stabilization resulted in improved cervicothoracic junction visualization, with an odds ratio of 3.8. When stratified by age, those patients less than 12 years old were significantly more likely to have adequate visualization, with odds ratios of 6.5 for patients less than 4 and 7.1 for patients 5–12 years old [19].

Flexion/extension (dynamic) radiographs

Patients with symptoms of pain or tenderness whose initial screening radiographs are normal often undergo flexion and extension films in the erect position to evaluate for ligamentous injuries which result in instability (Figure 6.1). The value of these additional films has been questioned in children [20]. A retrospective comparison of static cervical films followed by flexion/extension films concluded that the additional films were not helpful when plain films were normal (no acute abnormality or loss of normal lordosis) [21]. A report of 247 children by Dwek and Chung as well noted that in children with normal static cervical radiographs, no additional information or abnormality was noted with flexion/extension films. Additionally, in cases where the child is unable to follow instructions or participate fully in the dynamic component of the exam, these films are by definition limited.

Cervical spine CT

Axial CT scans with sagittal reconstruction can help evaluate the extremes of the upper or lower cervical spine when they are difficult to see on plain films or to elucidate

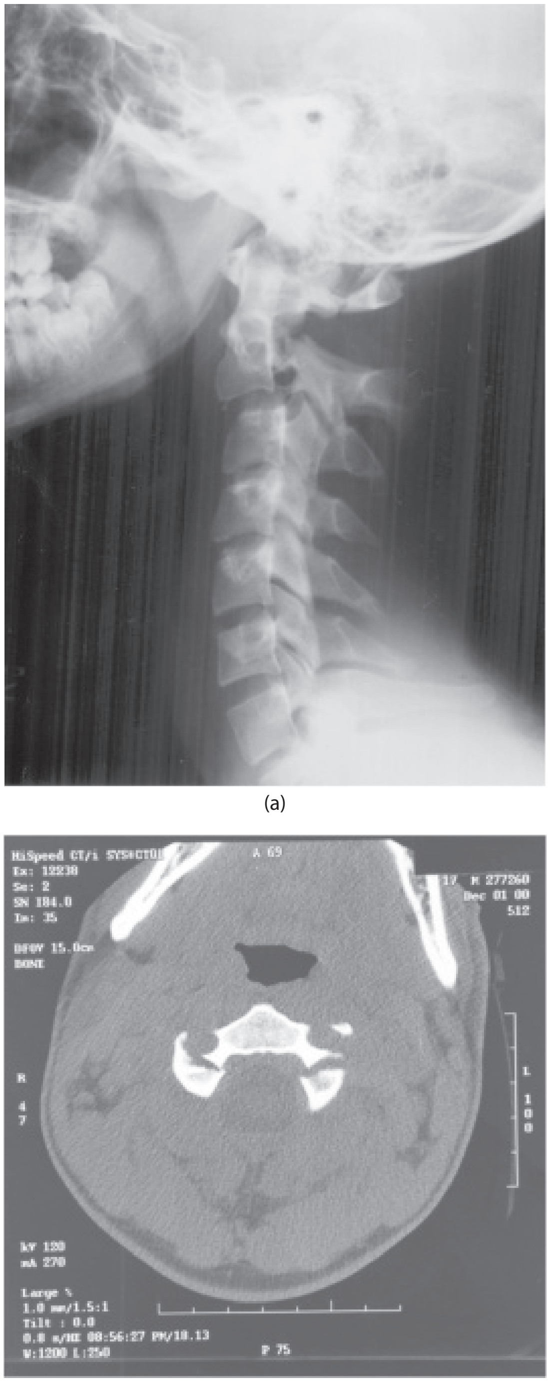
Figure 6.1 C7 compression fracture sustained by a 15-year-old who fell 8 feet from a swing.

abnormalities seen on plain radiography (Figures 6.2 through 6.4). CT can also assist to differentiate between the normal variants of pediatric anatomy described in the section Unique pediatric cervical spine anatomy and actual traumatic injury.

The additional radiation exposure incurred by CT scanning is of particular concern in the pediatric population, in whom cell turnover is high, development is incomplete, and the length of time available for mutation accumulation is longer than in adult patients. Based on data from atomic bomb survivors, Dr. David Brenner estimates the risk of a child developing a fatal cancer from the radiation exposure of a single CT scan is 1:1000 [22].

Several groups have estimated the risk of cancer from radiation exposure incurred during cervical spine CT. Out of every 100,000 patients undergoing cervical spine CT, the risk of all cancers ranges from 100 in males to 700 in females (0.1%–0.7%). Specific to thyroid cancer, for every 100,000 patients undergoing cervical spine CT, reference ranges are from 1.9 to 60 cases in males, and 5.3 to 330 cases in females [23]. In a theoretical study of thyroid radiation exposure, Muchow et al. compared the radiation dose from plain cervical radiography to that incurred after cervical CT in 617 patients less than 18 years of age. Absorbed thyroid radiation was calculated at 0.9 mGy for males and 0.96

Figure 6.2 A 4-year-old who struck a table after jumping from a chair. The minimal anterior tilt of the odontoid process relative to the vertebral body of C2 was difficult to interpret because of the synchondrosis. The fracture was confirmed by the finding of abnormal irregular lucency along the base of the odontoid on a 3D reconstruction of thin-cut computed tomography.



(a)

(b)

Figure 6.3 **(a)** Motor vehicle injury in a 17-year-old patient resulting in fractures through the posterior neural arch of C1 and pedicles of C2 with anterior displacement. **(b)** Further definition of fractures was aided by computed tomography.

Figure 6.4 Cervical spine film of a 10-year-old following a trampoline injury raised concern about possible subluxation of C2 relative to C3. Computed tomography showed no evidence of fracture or soft-tissue swelling, which confirmed that the original findings represented pseudosubluxation.

mGy for females in plain radiography, whereas CT resulted in doses of 63.6 mGy in males and 64.2 mGy in females. This study calculated the mean excess relative risk of thyroid cancer induction from one cervical spine CT to be 13% in males and 25% in females, whereas the risk from plain radiography was 0.24% in males and 0.51% in females [24]. Finally, Jimenez et al. [25] described the radiation dose to the thyroid of 363 children undergoing head and cervical spine CT. Anthropomorphic dosimetry phantoms were employed to represent children aged 0–8 years. Radiation exposure from CT versus three separate options for plain radiograph sequences was calculated. This was calculated at 90–200 times higher radiation exposure from CT compared to plain radiographs, and the mean excess relative risk for thyroid cancer was calculated to be 2.0 for children 0–4 years old and 0.6 for children 5–8 years old [25].

While CT certainly results in higher radiation exposure to children, it may also provide more sensitive and rigorous imaging of the cervical spine than plain radiograph sequences. The reported sensitivity in high-risk adult patients has been reported to be 95% with specificity of 93% for detection of cervical spine injuries [26]. Rana et al. described 318 pediatric patients imaged for potential cervical spine injury. CT scan was found to be 100% sensitive, 97% specific, with a positive predictive value of 79% for cervical spine injury. No injuries were missed in the CT-imaged patients. Plain radiograph sequences resulted in five false negatives which were subsequently identified on CT scan, but these injuries were of questionable clinical significance, as they required no subsequent intervention. The sensitivity in this series of plain radiography was 62%, with a specificity of 1.6% and a positive predictive value of 62% [27].

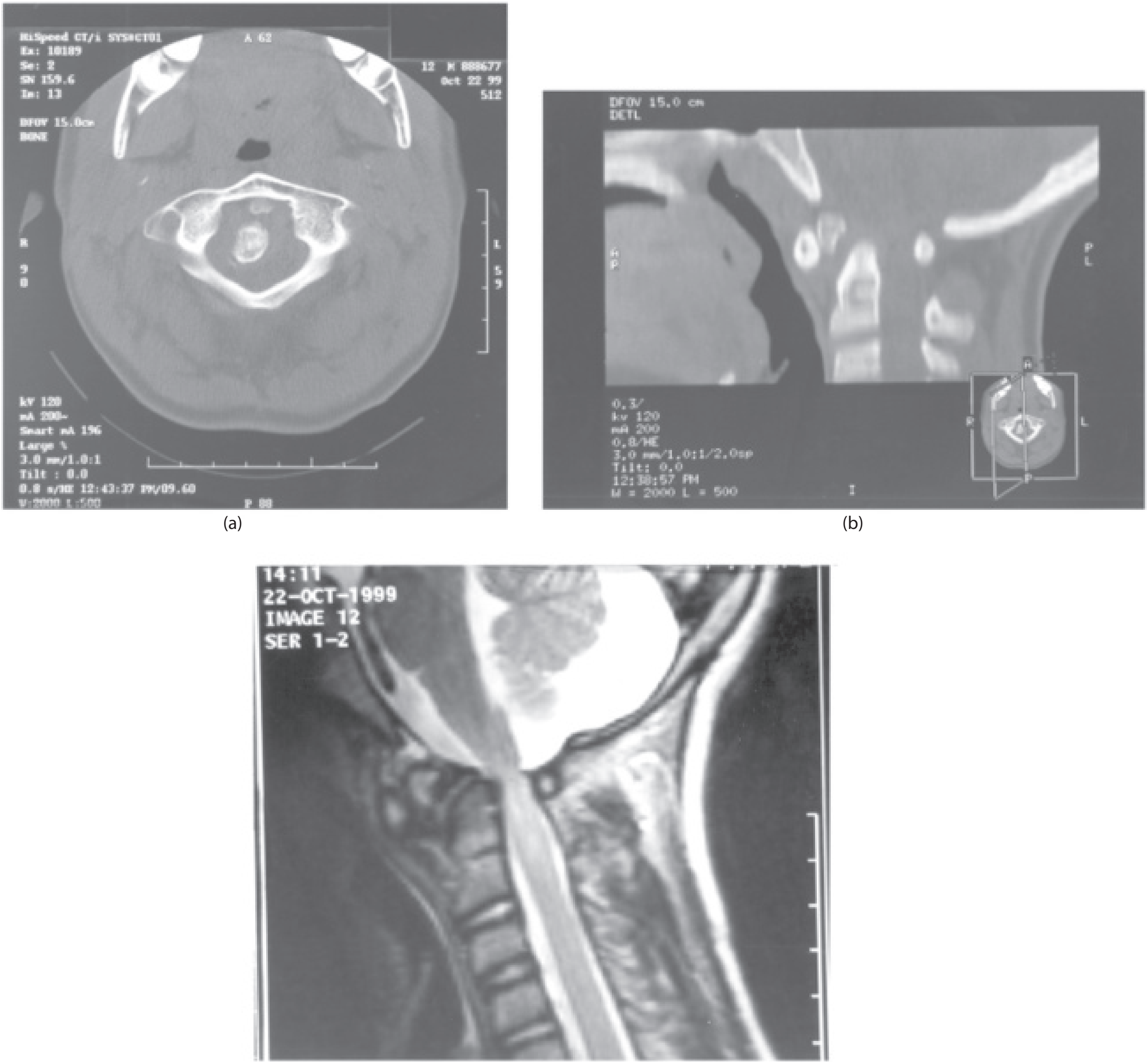
Current practice in the use of CT versus plain film radiography varies depending on setting and the training of the evaluating physician. A survey of emergency medicine physicians using a clinical vignette of possible cervical spine injury indicated that general emergency medicine physicians were four times more likely to order CT scans than pediatric-trained emergency medicine physicians [28]. In a retrospective statewide review in Massachusetts, patients presenting to a community hospital instead of to a level 1 trauma center were more likely to undergo CT scan with an odds ratio of 2.2. There was a trend toward increased use of CT scanning in adult versus pediatric trauma centers with an odds ratio of 2.1 [29]. Adelgais et al. recently reported that, despite a stable rate of cervical spine injury between patients presenting to pediatric trauma centers and general emergency departments over the last decade, the prevalence of cervical spine CT scan increased by 9.6% in pediatric centers and by a much higher 27% in general emergency rooms [30]. An analysis of the Pediatric Health Information System database indicated that over the last decade the use of plain film radiography for cervical spine injury diagnosis has decreased by 24% and that of CT has increased by 11%. Of those children who received cervical spine CT, many were either discharged within 72 hours or had low-risk mechanisms of injuries. While an administrative database does not include information about symptoms or other risk criteria, the study does suggest that overall use of CT is increasing while plain film use is decreasing in pediatric patients despite concern about radiation exposure [31].

Cervical spine MRI

MRI provides excellent detail of soft tissue injuries, including vessel injuries, ligamentous disruption, disc herniation, and spinal cord injury or hematoma (Figure 6.5). Fractures are not always seen on MRI; therefore, plain radiographs should precede MRI studies.

In a study by Junewick et al. [32], children who underwent cervical C-spine CT and then had a subsequent MRI performed during the same presentation were examined for the incidence of occult craniocervical junction injuries. Of 45 patients meeting inclusion criteria, 30 (67%) had a positive MRI finding in the setting of a negative cervical spine CT, and 17 (38%) had findings that met criteria for a significant craniocervical junction injury [32]. Most of these patients were less than 8 years of age, and the most common mechanism of injury was motor vehicle accidents.

There is considerable interest in whether MRI provides an advantage in cervical spine evaluation for obtunded patients or those with severe traumatic brain injury. These patients are unable to participate in a clinical exam, and therefore concern exists that even with a negative cervical spine CT, a potentially unstable ligamentous injury could be missed. The data are limited on this subject. Flynn et al. [33] reported their experience with an institutional protocol incorporating cervical MRI in patients with high risk for cervical spine injury who met the following criteria: (1) obtundation or nonverbal child with suspicious mechanism, (2) neurologic symptoms without



(a)

(b)

(c)

Figure 6.5 A 12-year-old with a trampoline injury and neck pain. **(a)** Computed tomography showed fracture of superior aspect of odontoid. **(b)** The 1-cm fragment was displaced anterior and inferior. **(c)** Magnetic resonance imaging revealed severe central canal stenosis at the cervical-medullary junction and edema within the cervical cord at the C2 and C3 levels. In addition, distension of the cerebrospinal fluid spaces within the posterior fossa was evident, likely due to the degree of stenosis.

radiographic findings, (3) equivocal plain films, and (4) inability to clear the spine clinically after 72 hours. They found that MRI identified injuries not seen on radiography in 23% of imaged patients, and that in 34% of these patients, management was altered by the MRI findings [33]. A review from Washington University described 63 pediatric TBI patients with GCS < 8 who received both CT and MRI of the cervical spine. Of these patients, five had unstable cervical spine injuries, all of which were detected by CT, and of note, one of these injuries was missed on MRI because it was primarily a bony injury. There were seven injuries detected on MRI that were missed on CT, all of which were determined to be stable. CT was 100% sensitive and 85% specific for unstable injury, whereas MRI was 80% sensitive and 81% specific. For overall injury, CT was 63% sensitive with a negative predictive value of 86%. MRI was 68% sensitive and had a negative predictive value of 88%. The findings in this study are limited by the small number of patients with cervical spine injuries [34]. Another report from Henry et al., similarly constructed, reported CT sensitivity for cervical spine injury to be 13% and specificity to be 99%, whereas for MRI sensitivity was

100% and specificity was 99%. The low sensitivity of CT was related to its inability to detect soft tissue injury in 10/12 patients in which such injury was seen on MRI. In contrast, MRI was able to detect all osseous injuries identified on CT [35]. Gargas et al. described 173 patients who, after presenting with blunt trauma, were immobilized and imaged by CT for cervical spine symptoms, obtundation, or uncooperativeness. In those patients, MRI identified 30 patients or 17% who had underlying spinal cord contusion or ligamentous injury. Of those, five or approximately 3% of the patients with normal CT findings were identified to have unstable ligamentous injuries which required surgical stabilization. The authors do not comment on the sensitivity of MRI for bony fractures in this study [36].

Taken together, these data indicate that MRI does provide increased detection of soft tissue and ligamentous injury, some of which are unstable, in patients with high risk for cervical spine injury. However, the incorporation of MRI into standard screening protocols would be controversial due to its high cost and sensitivity for injuries that ultimately do not require intervention.

Current practice and protocols

Prior to the last 10–15 years, clinical practice in clearance of the cervical spine in pediatric patients was guided by extrapolation from adult data and by consensus guidelines such as the Eastern Association for the Surgery of Trauma guidelines. However, as discussed above, data specific to pediatric patients have blossomed in the last decade so that it is now possible to develop protocols for cervical spine clearance in children based on level II and III clinical evidence. Several institutions have published protocols including pre- and post-protocol trends in radiation exposure and frequency of missed injury. Individual institutional experiences have shown that adherence to these protocols increases the number of children cleared clinically without radiography. In addition, the frequency of CT scanning is reduced by 22%–60%, offset in some cases by an increase in the number of cervical plain film series ordered. Importantly, following these protocols, no missed injuries have been reported [7,37–40]. This summary of current recommendations is based on the literature detailed above including the available published protocols in pediatric cervical spine clearance.

Imaging of the cervical spine is advised for children who have any one of the following seven clinical findings: (1) midline cervical tenderness or complaints of cervical pain or torticollis, (2) endotracheal intubation, (3) altered level of consciousness including due to intoxication or medication, (4) focal neurologic deficits, (5) distracting injury, and (6) presence of a high risk mechanism (e.g., nonaccidental trauma, high-speed motor vehicle accident, hanging injuries, and diving injuries), or (7) an inability to verbally communicate. If none of these risk factors is present, the patient is clinically cleared, no further imaging is required and cervical spine precautions may be discontinued.

In children who exhibit one or more of these criteria, imaging is recommended. The first step is screening by cervical radiography. While the addition of multiple views is debated, a lateral cervical spine film with good technique and visualization of the spine from the occiput to T1 is an absolute minimum, and most published protocols recommend at least a three-view cervical spine series encompassing anterior/posterior and odontoid views in addition to the lateral view. In patients who are already undergoing CT scan of the brain for trauma, it is acceptable to substitute an extended CT head that encompasses the C1 and C2 vertebrae for the additional views in the plain film series.

Any abnormality on plain film imaging or questionable films should prompt spine service consultation and CT of the cervical spine through T3. If the CT is normal, then repeat examination is performed. A normal examination results in cervical spine clearance without further investigation and discontinuation of cervical spine precautions (Figure 6.6).

Any persistent pain or neurologic deficit should prompt evaluation for SCIWORA. Most protocols recommend MRI of the cervical spine for this purpose rather than flexion-extension films. Cervical spine immobilization should be continued throughout this process until formal clearance of the cervical spine is obtained. If SCIWORA is documented, then cervical spine immobilization is continued until follow-up by a spine specialist.

Finally, any patient who presents unconscious, obtunded, or who requires intubation and medical sedation should be imaged with CT of the cervical spine. If the patient's impaired mental status continues past 72 hours, then MRI of the cervical spine should be obtained in an attempt to clear the neck of ligamentous injury so that spinal precautions can be discontinued. In patients for whom prolonged obtundation or intubation are expected, some centers recommend early MRI of the cervical spine instead of CT. This practice has not been investigated sufficiently to provide concrete recommendations.

Conclusions

Cervical spine injury is rare in pediatric blunt trauma patients. However, due to the potentially devastating nature of these injuries, as well as the unique anatomy of the pediatric spine, careful evaluation of the cervical spine including systematic cervical spine clearance is paramount. Pediatric trauma providers should be well educated in the unique anatomy and functional performance of the pediatric cervical spine and the implications of these characteristics for patterns of injury. They should also be familiar with risk factors for pediatric cervical spine injury and the use of various imaging modalities in its diagnosis. In the pediatric population, the decision to image the neck should take into account the potential risk posed by unnecessary irradiation. Unnecessary imaging can be avoided by recognizing that the clinical exam in children is exquisitely sensitive for cervical spine injury, and that a cohort of low-risk patients can be identified in whom clinical history and exam alone are sufficient for cervical spine clearance.

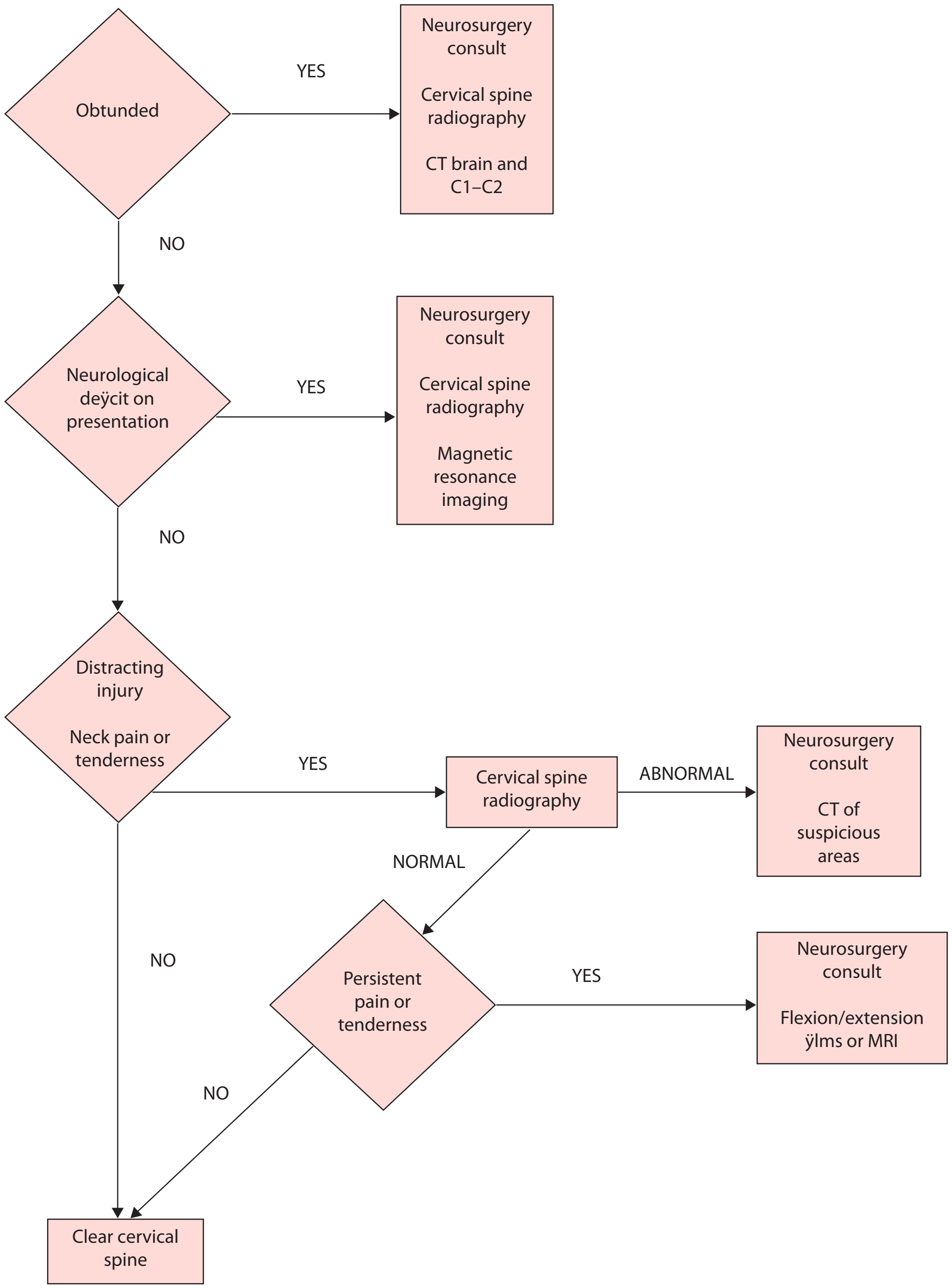


Figure 6.6 Algorithm for clearance of the cervical spine in children.

Imaging use should be directed by protocols which emphasize plain films before CT in order to reduce radiation exposure, and which involve early consultation with spine specialists for patients with suspected injury. In patients who cannot be cleared using these means or who have persistent symptoms after normal radiographs and CT, MRI is becoming an increasingly valuable way to evaluate for ligamentous and soft tissue injury in a timely fashion such that prolonged immobilization is avoided.

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7

General principles of resuscitation and supportive care: Burns

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Introduction

In the United States, burn-related injuries are common among children, with the incidence being higher in children than adults. Each day about 300 children are seen in emergency departments in the United States for burn injuries, and two of these children will die from their injuries [1]. Burn injuries are consistently among the top causes of injury-related death in children under 15 years old [2]. Burn injury is the fifth most common cause of nonfatal injury in children and the eleventh most common cause of death worldwide [3].

Children just gaining independent mobility are often curious, leading to spills and contact with unfamiliar hot objects. Because of these tendencies, infants and toddlers make up a disproportionate percentage of burn-injured children [4]. Scald burns, followed by contact burns, are the most common etiology of thermal injury among children [5]. Although burn injury incidence declines with age, flame burns become more common with increasing age [1,5]. Most accidental burns are preventable [4], and prevention strategies are considered to have led to a decline in the incidence of burn injuries in the United States [6].

Although burn injuries remain a significant health burden for children, burn care has improved, reducing overall mortality [7,8]. In 1949, the total body surface area (TBSA) of burn injury at which 50% of children died (LD_{50}) was 49% [9]. With improvements in the initial and definitive management of burn injuries in children, the LD_{50} for TBSA increased to over 90% in 1987 [10,11]. Improvements in pediatric burn mortality have shifted focus to a greater emphasis on aftercare, social reintegration, and the impact of burn injury on the quality of life.

Initial assessment

The assessment and treatment of burns among children and adults are similar. Several aspects, however, differ in children and should be highlighted. As with all injuries, the establishment of a stable airway and ensuring adequate ventilation and perfusion are initial priorities when treating children with burn injuries. After these goals are addressed, the burn wound should then be assessed for size and depth to determine definitive treatment in either the inpatient or outpatient setting.

Airway management

Airway compromise after pediatric burn injury may be minimal initially but it can progress rapidly. Signs suggestive of a potential airway or inhalational injury include burns to the face, singed nasal hairs, carbonaceous sputum, stridor, and labored breathing. The airway examination should include evaluation of the supraglottic and oropharyngeal regions for signs of injury such as direct burns or edema. Children sustaining severe full-thickness burns of the neck are at increased risk for airway compromise related to edema because of a relatively narrow airway and short neck [12]. Airway compromise may develop in children with neck burns up to 36 hours after injury when edema is greatest in the affected tissues.

During the primary survey of any child with burn injury, supplemental oxygen should be supplied by face mask and oxygen saturation assessed. Early intubation should be considered for children at high risk for airway compromise based on history and physical examination because a relatively small amount of airway narrowing can significantly and rapidly decrease the cross-sectional area of a small pediatric airway. Initial placement of the appropriate size cuffed tube is important because progressive airway compromise may make reintubation difficult or unsafe [13]. Care should be taken to secure the endotracheal tube once it is in a safe and functional position to prevent accidental extubation [14]. Strategies for maintaining airway fixation depend on the clinical scenario but may include the use of a nasotracheal route, direct fixation of the tube to the tissues of the nasal septum or maxillary incisors, and the use of external devices that do not rely on adhesive for fixation [15]. Tracheostomy is rarely performed in pediatric burn patients but may be indicated when it is difficult to otherwise establish a secure airway because of the extent of the burn injury, or in large burns, or in the presence of significant inhalation injury when prolonged intubation is anticipated [16].

Management of ventilation

Respiratory failure remains a significant cause of morbidity and mortality after the pediatric burn injury. The potential causes of respiratory failure in the acute setting are diverse and include decreased chest wall compliance from burn-related edema and thick eschar, chemical and thermal airway injury, and systemic inflammatory response syndrome in response to the burn injury. As many as 5% of scald injuries at pediatric burn centers are associated with the need for mechanical ventilation even in the absence of significant head and neck involvement [12]. Risk factors for respiratory failure among children with scald injuries include large burns, young age, and an injury related to child abuse. The association of scald injuries with respiratory failure mandates close monitoring of at-risk patients for up to 72 hours after injury [12,17]. Pneumonia is the most frequent major complication of burn injury. The incidence of pneumonia increases with the number of ventilator days [18].

Up to one-third of pediatric burn patients requiring hospitalization have an associated inhalation injury [19]. Inhalation injury significantly increases mortality [20] and contributes more significantly to mortality in children than in adults [21]. Burn-injured patients exposed to the products of combustion in an enclosed space are at risk for inhalation injury. Damage to the airways can result from direct thermal injury or injury caused by chemical irritants. Thermal injury most often occurs above the carina as heat is dissipated rapidly in the oropharynx. Direct thermal injury to the lower airway occurs in less than 5% of patients sustaining an inhalation injury and is more likely when steam exposure is part of the injury mechanism [17]. Chemical inhalation injury can affect the entire respiratory tract and occurs after inhalation of combustion by-products such as those from synthetic materials. Inhaled chemical toxins damage epithelial and endothelial cells of the respiratory tract and can lead to a devastating inflammatory response. The airway changes associated with chemical irritation include bronchoconstriction, increased vascular permeability, vasodilatation and ventilation disturbances [17]. Injury to the bronchial epithelium results in protein leakage and alveolar collapse. Airway injury can evolve over time, so that significant airway compromise may still occur up to 48 hours after injury [17].

Carbon monoxide (CO) and cyanide are agents known to be associated with increased morbidity and mortality after injuries sustained in enclosed spaces, such as house fires. CO has a 200-fold increased affinity for hemoglobin compared to oxygen, displacing oxygen and creating carboxyhemoglobin. The presence of carboxyhemoglobin decreases the oxygen-carrying capacity of blood and decreases oxygen delivery to tissues. Current treatment of CO toxicity is the administration of 100% oxygen that decreases the half-life of carboxyhemoglobin several fold compared to room air [22]. Hyperbaric oxygen also shortens the half-life of carboxyhemoglobin [22,23] and has been proposed as a potential treatment for severe CO poisoning. A recent systematic review, however, did not show a benefit of hyperbaric over standard treatment on neurological outcomes and its impact on mortality remains uncertain [22].

Cyanide acts by inhibiting the mitochondrial electron transport chain leading to inhibition of aerobic respiration. In suspected cyanide toxicity, hydroxocobalamin should be given immediately because of its treatment potential and relatively low incidence of side effects. Hydroxocobalamin binds cyanide enhancing renal excretion and improving survival among patients with otherwise fatal cyanide levels [24]. Cyanide and CO may have synergistic effects, with even low blood concentrations of these chemicals leading to tissue hypoxia [25]. Hydroxocobalamin is safe in cases of simultaneous CO exposure, and has a rapid onset of action [17,26]. Because cyanide and CO exposures often occur together in house fires, both toxicities should be treated when one is suspected [26].

Inhalation injury can be diagnosed and treated using bronchoscopy. Bronchoscopy allows for direct visualization, diagnosis, and assessment of severity of inhalation injury [27]. The severity of inhalation injury diagnosed with bronchoscopy correlates with survival [17,28,29]. Correlation of bronchoscopic findings with other clinical outcomes such as fluid requirements, ventilator days, acute respiratory distress syndrome, and acute renal failure has been variable [27,28,30]. Because bronchoscopy is associated with minimal morbidity and may provide useful clinical information, it should be used for diagnosis when available in the setting of inhalation injury [27,31]. Pneumonia is the most common complication after inhalation injury and is associated with increased mortality [29]. Bronchoscopy has been beneficial for managing inhalation injury patients with pneumonia. Routine bronchoscopy combined with lavage has been associated with a reduction in mortality [32]. The proposed mechanism of this treatment is the clearance of secretions to prevent atelectasis and attenuate inflammatory response [32].

Burn wound evaluation

Assessment of the size and depth of the burn injury is an essential step in the initial management of children with burn injuries. Burn size and depth help determine resuscitation strategies, the need for burn center referral, the need for monitoring, and the need for surgical treatment. Burns can be classified as superficial, partial thickness (superficial and deep), and full thickness based on the extent of epidermal, dermal, and hypodermal involvement (Figure 7.1). Thinner skin in infancy places younger children at risk for deeper burns [33]. Burn injury mechanisms such as scalds resulting from liquid spills often do not lead to uniform depth throughout the affected skin areas, with many injuries having areas of several depths.

Although clinical evaluation is an effective and cost-effective approach for wound assessment, estimations by experienced burn surgeons predict the likelihood and time required for healing only about 75% of the time [34]. Features that can be used to predict burn depth include the mechanism of injury, the wound appearance, and the amount of associated pain (Table 7.1). Differentiating partial and full-thickness burns can be difficult, requiring repeated evaluations over 72 hours after injury to obtain a more accurate assessment of wound depth. The inflammatory response to a burn injury continues to progress after injury. Full-thickness injuries sometimes have an appearance similar to partial-thickness injuries.

The use of laser Doppler imaging (LDI) to estimate burn depth has been integrated into the initial assessment of burn wounds at an increasing number of burn centers. The approach measures tissue perfusion by measuring frequency changes associated with blood cell movement through the dermal vasculature. The use of LDI in conjunction with clinical assessment has several benefits, including reduced morbidity and costs associated with decreased length of stay and avoidance of unnecessary surgery [35]. The approach is also useful for identifying deeper areas within a larger burned region that can be targeted for surgical excision, leaving surrounding areas to heal. The use of LDI in children was initially questioned because of the need for the patient to remain still during the scan. This technique, however, has been shown to be easy to use in children and to improve the accuracy of burn depth assessment [36,37].

Estimation of the extent of the burn injury is also a critical step in the initial management of pediatric burn injuries. Only partial- and full-thickness burns are included in estimates of TBSA. Several approaches can be used depending on the extent of the injury and available resources. The TBSA of small burns can quickly and easily be estimated using the palmar method. This approach is based on the finding that the surface of the patient's entire hand and fingers is about 1% of TBSA. Estimating the number of the patient's palm prints that would cover the affected area is an effective approach for obtaining an initial estimate in smaller burns. In a field setting or at the time of initial emergency department evaluation, the "rule of nines" is a practical approach for estimating the extent of a burn injury. This quick calculation is more accurate in adults than in children because of the larger proportion of body surface area of the head in children but is easy to learn and apply (Figure 7.2). When arriving at the site of definitive burn care, more accurate approaches for evaluating the extent of burn injury should be used. The Lund and Browder chart provides estimates of TBSA among different age groups and has been used for many years to evaluate burn injuries (Figure 7.3). The Lund and Browder charts, however, require manual mapping of the burn injury onto the diagram and a subjective estimate of the proportion of affected areas. These methods can sometimes lead to a significant overestimate of the affected TBSA [38–41]. Computer programs and mobile phone applications have been developed for calculating TBSA in children and adults. These methods have

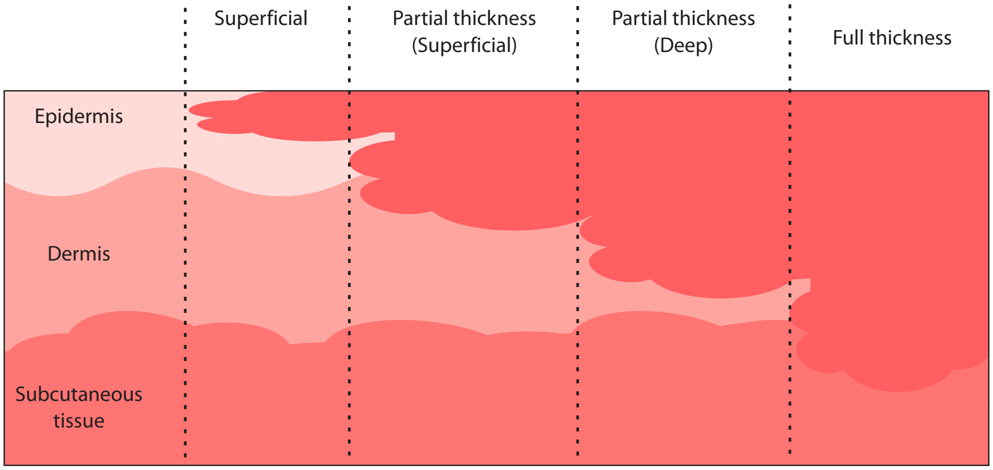


Figure 7.1 Burn classification by depth of burn injury.

Table 7.1 Burn classification

Burn depth	Color	Appearance	Pain	Typical healing
Superficial	Red	Blanching, dry, no blisters	Mild	3–6 days, nonscarring
Superficial partial thickness	Pink, red	Blanching, wet, blisters	Moderate to severe	7–20 days, usually nonscarring
Deep partial thickness	Red, white, yellow	Nonblanching, wet, +/− blisters	Mild to moderate	>21 days, may lead to scar and contracture
Full thickness	White, brown, black	Dry, nonblanching	Nonpainful	Prolonged healing with scar and contracture

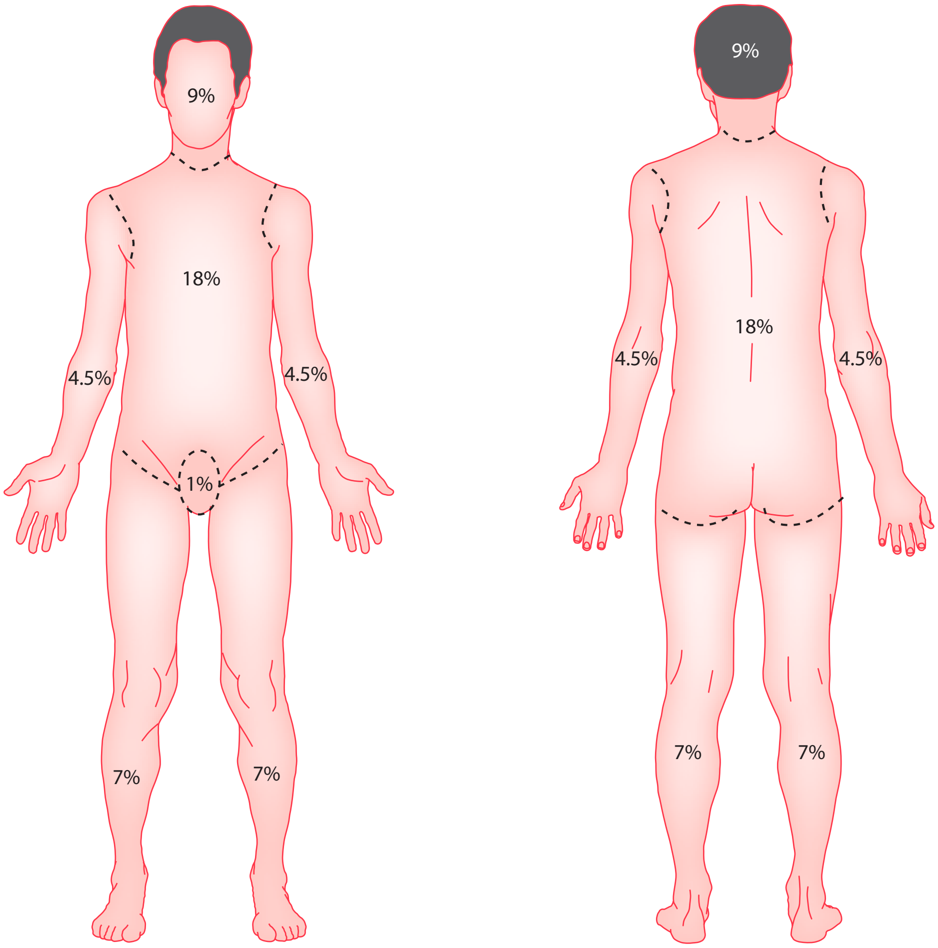


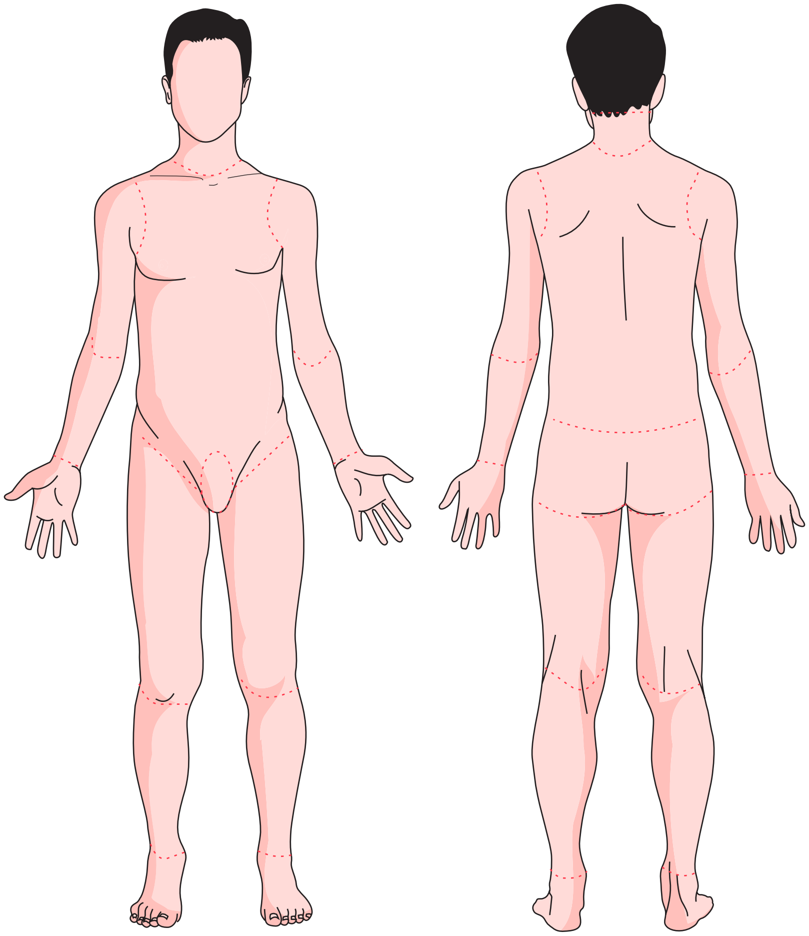
Figure 7.2 Rule of nines for estimating total body surface area of burn injuries.

a particular advantage for children because correction for the age-related distribution of surface area in different body regions is an incorporated function. The ease of use and the accuracy of these electronic tools favor their use when definitive care is being planned [40,42].

Once burn size and depth have been determined, triage and treatment decisions can be made. Children with burns requiring specialized care available at burn centers should be transferred after stabilization to received definitive care, including children with large burns (>10% TBSA), burns involving critical body regions, and observed or suspected concomitant injury (Table 7.2) [43,44].

Resuscitation

Thermal injury triggers release of inflammatory mediators by endothelial and nerve cells including complement proteins, kinins, histamine, serotonin, prostaglandins, neuropeptides, and oxygen free radicals [44]. These changes lead to increased capillary permeability and movement of fluid from the intravascular space into the interstitial space. Although



Location	Estimated total body surface area in location by age			
	0–1 years	1–4 years	5–9 years	10–15 years
Head	19	17	13	10
Neck	2	2	2	2
Anterior trunk	13	13	13	13
Posterior trunk	13	13	13	13
Right buttock	2.5	2.5	2.5	2.5
Left buttock	2.5	2.5	2.5	2.5
Genitalia	1	1	1	1
Right upper arm	4	4	4	4
Left upper arm	4	4	4	4
Right lower arm	3	3	3	3
Left lower arm	3	3	3	3
Right hand	2.5	2.5	2.5	2.5
Left hand	2.5	2.5	2.5	2.5
Right thigh	5.5	6.5	8.5	9.5
Left thigh	5.5	6.5	8.5	9.5
Right leg	5	5	5.5	7
Left leg	5	5	5.5	7
Right foot	3.5	3.5	3.5	3.5
Left foot	3.5	3.5	3.5	3.5

Figure 7.3 Lund Browder chart for estimating total body surface area of burn injuries.

Table 7.2 Burn center referral criteria

American Burn Association criteria for referral to a burn center
Partial thickness burns >10% TBSA
Burns to the face, hands, feet, genitalia, perineum, or major joints
Full-thickness burns (any)
Electrical or chemical burns
Burns associated with inhalational injury
Presence of comorbid conditions that may affect resuscitation and treatment
Significant associated injuries (major trauma, such as motor vehicle crashes and explosions)
Burn injuries that exceed specialist or institutional capacity
Burn injuries with special long-term social, emotional, or rehabilitative needs
Suspected intentional injury

Source: Adapted from Committee on Trauma of the American College of Surgeons. *Resources for Optimal Care of the Injured Patient 2006.* Chicago, IL: American College of Surgeons, 2006.

third space fluid loss for small burns has minimal physiological consequences, larger burns can lead to loss of a significant proportion of the circulating blood volume and additional tissue damage remote from the site of injury can occur. After extensive burn injury, early and accurate fluid administration optimizes outcomes, including reducing acute renal failure, multiple organ dysfunction, and mortality [7].

Oral hydration should first be attempted for children with burn injuries affecting less than 10% TBSA, keeping in mind that this recommendation is a guideline and not a substitute for clinical judgment [45]. Although an enteral route is often sufficient for managing fluid losses in this setting, younger children with even small burn injuries and those with significant burn injury on the head and neck cannot maintain adequate hydration by the oral route. Children with less extensive injuries associated with inadequate oral intake benefit from early placement of a nasoenteric tube for enteral nutritional support and hydration.

Among patients with larger burns, initial hydration by either an oral route or enteral tube is not as rapid or effective as intravenous hydration. The Parkland formula bases resuscitation on the TBSA of burn injury and the child's weight (4 mL/kg/% TBSA injured) and is a useful guide for initiating resuscitation. Children have additional maintenance requirements that are better accounted for using the Shriners Burns Hospital–Galveston formula, which estimates maintenance and resuscitation requirements (5000 mL/m^2 TBSA burn + 2000 mL/m^2 TBSA). Although the Parkland and Galveston formulas are useful in children, the Galveston formula correlates better with the fluid requirements in patients under 23 kg [46]. No randomized controlled studies, however, have compared these two approaches in children. An initial estimate can be made to administer half of the estimated volume estimated using each formula within 8 hours of the burn injury and the second half over the next 16 hours. The resuscitation volume estimated by the Parkland formula for smaller burns can be easily administered by either oral or enteral hydration or administration of maintenance intravenous fluid. Calculations of burn size at the injury scene or at nonspecialty centers often overestimate TBSA. For this reason, an initial strategy of hydration at 1.5 maintenance rate is appropriate to avoid overhydration when anticipated transport time is short.

Lactated Ringers is the initial resuscitative fluid of choice for burn patients. For children less than 30 kg or less than 5 years old, dextrose should be added to maintenance fluids to protect from hypoglycemia. With a severe hypermetabolic response, younger pediatric patients can quickly deplete their hepatic glycogen stores resulting in hypoglycemia. The Parkland and Galveston formulas serve as only guides for initially estimating fluid resuscitation volume and tend to underestimate resuscitation volumes in smaller burn injuries and overestimate volumes in larger burn injuries [47–49]. Once an evaluation of burn size and depth has been performed, one of these formulas can be used to calculate fluid volume needed over the first 24 hours after injury.

Given the wide variation in burn depth, individual response to injury, and concomitant tissue injuries (i.e., inhalation injury), resuscitation should be guided by a frequent assessment of end organ perfusion. Urine output remains the most useful means for monitoring the effectiveness of resuscitation in children. Actual fluid volume should be directed by frequent titration based on hourly urine output goals (typically 1 mL/kg/h for pediatric patients) [50,51]. An indwelling urinary catheter may be required to accurately measure urine production during the initial resuscitation period.

The deleterious effects of over-resuscitation have been increasingly recognized. In the 20 years after the Parkland formula became standard practice, typical volumes of crystalloid administered after burn injury greatly exceeded the amount recommended in the original formula, and the use of colloid in the second 24-hour period was abandoned [52–54]. This rise in resuscitation volume has been termed "fluid creep." Over-resuscitation has now been shown to be associated with systemic complications. These complications include abdominal compartment syndrome, extremity edema requiring escharotomies or fasciotomies, pericardial effusion, pleural effusions, prolonged intubation, acute respiratory distress syndrome, multiple organ dysfunction, and even death.

Decreasing crystalloid fluid administration while maintaining adequate perfusion and not exacerbating the tissue damage related to hypoperfusion is the current focus in burn resuscitation. Careful titration of fluid administration requires specific resuscitation titration endpoints. Among children, urine output remains the endpoint of choice. The use of other approaches for monitoring resuscitation have been studied, including vital sign monitoring, assessment of cardiac output and index and central venous pressure, the use of echocardiography to assess ejection fraction and stroke volume, and gastric tonometry. These monitoring methods, however, require knowledge of oxygen consumption, cardiac index, and myocardial function, and therefore also require invasive procedures such as the use of pulmonary artery catheters and transesophageal echocardiograms [50]. Invasive procedures (e.g., transesophageal echocardiograms, Swan–Ganz catheters, and central venous catheters) are not recommended for monitoring the endpoint of resuscitation in children unless there is an additional indication for the procedure. A recent review of studies in adults and children found only limited evidence supporting the use of hemodynamic monitoring for assessing burn resuscitation endpoints. No large prospective trials have assessed endpoint alternatives to urine output [50].

The original Parkland formula included the use of colloid infusion at 24 hours after injury [52]. The crystalloid components of this regimen in the first 24 hours initially gained popularity and became a standard approach for predicting fluid requirements while the use of colloids in the second 24 hours after injury has fallen out of favor [54]. Studies showing an increase in mortality with colloid use and concerns over viral hepatitis transmission from blood products led to an increase in the use of crystalloid resuscitation without colloid supplementation in the late 1970s and 1980s [54–56]. With increasing concern over “fluid creep,” the use of colloid resuscitation has reemerged and has recently been shown to improve outcomes, including decreasing fluid requirements [55–58]. Although most studies assessing the role of colloids have been performed in adults [59–63], a recent randomized controlled study in children showed that colloids given in the first 8–12 hours after injury decreased the volume of crystalloid required for postburn resuscitation, reduced fluid creep, and decreased length of stay in patients receiving colloids [56]. This study used 5% albumin providing 0.5 g of albumin/kg daily for 3 days starting up to 12 hours after injury. Although albumin may improve outcomes when used for burn shock resuscitation, the quality of the current data is insufficient for definitive conclusions [55]. Two small studies have also found that ascorbic acid (vitamin C) can safely reduce fluid requirements and decrease pulmonary complications when administered at high doses after burn injury [64,65]. The efficacy and safety of vitamin C have not, however, been tested in children with burn injuries. Using the Parkland or Galveston formula for resuscitation can be time consuming and error prone [66,67]. Accurate initial calculation of required fluid may avoid the complications of over- and under-resuscitation of the burn-injured patient. The use of computerized decision support to guide resuscitation has been found to be beneficial in adult burn patients [68], but this approach has yet to be reported in pediatric burn patients.

Wound management

Burn wound management is determined by wound size, depth, and location. Superficial partial-thickness burns can be treated with debridement followed by serial dressing changes. Burns of this depth heal within 3 weeks without additional intervention. The practice of debriding burn blisters has been debated [69]. While burn blister fluid has been shown to be detrimental by suppressing lymphocyte and neutrophil function, intact blisters are associated with less bacterial colonization [70,71]. Although blister fluid may slow keratinocyte replication, reepithelialization is 40% faster when blisters are left in place [69,72]. Debridement is associated with increased pain levels but also provides a uniform wound base which may improve healing [73].

Daily dressing changes and debridement along with the use of topical antimicrobials have become standard treatment for burn wounds. Although silver compounds are in common use as topical antimicrobials in this setting, including silver sulfadiazine cream and mafenide acetate, evidence that these agents reduce wound infection or promote healing is lacking [74]. Procedural pain is an important disadvantage of daily dressing changes, especially when used for large burn injuries. To reduce the need for dressing changes, several products have been developed that use silver as the antimicrobial agent that can remain in place for several days. In addition to reducing pain, long-acting silver dressings may improve the rates of reepithelialization when compared to the use of silver sulfadiazine dressing [75].

Although silver-based dressings are commonly used for managing pediatric burns, a variety of nonsilver-based dressings are available. Biosynthetic dressings such as Biobrane™, Suprathel™, and Omniderm™ are semipermeable dressings designed to adhere to the wound and decrease the need for frequent dressing changes. Similar to long-acting silver dressings, dressings in this category have similar or improved reepithelization rates and decreased pain in comparison to dressings using silver sulfadiazine [75]. These dressings, however, have no antimicrobial activity and may not be appropriate when wound infection is already present or when first used more than 24 hours after injury.

Biological dressings are another category that has been used for the management of pediatric burn wounds. These dressings include natural biological dressings (allograft, xenograft, and human amnion), dressings derived from a biological source (Alloderm™), and synthetic dressings designed to substitute for biological dressings (Integra™). Allograft has had limited use as a primary dressing for pediatric partial-thickness burns but it is frequently used as an adjunct dressing among children undergoing surgical treatment [76]. A reduction in scar formation has been described when using allograft compared to silver sulfadiazine [77]. Allograft can be used on contaminated wound beds while other biological dressings may only be placed on clean wound beds [77,78]. Xenograft has been reported to have an improved infection risk and decreased need for narcotics and number of dressing changes when compared to conventional dressings in children [79]. The impact of xenograft on the rate and quality of wound healing has yet to be compared with more commonly used silver dressings. Human amnion for temporary coverage of partial-thickness burns results in improved healing and fewer dressing changes [80,81]. Alloderm (LifeCell Corporation, Branchburg, NJ) is allograft made from acellular cadaveric dermis and works by a similar mechanism. Alloderm is immunogenic and is rejected after several weeks of underlying dermal regeneration [77]. Integra (Integra LifeSciences Corporation, Plainsboro, NJ) is made from bovine collagen and glucosaminoglycans. It provides a scaffolding for fibrovascular ingrowth and sloughs off as autologous epithelialization occurs beneath it [77].

Surgical treatment

Early excision and coverage of deep partial-thickness and full-thickness burns have become standard care for pediatric burn injuries. This technique has been shown to improve outcomes after severe burns and results in decreased infection risk, length of stay, and scar formation in children [7,8,82]. By excising devitalized tissue, early infection risk is reduced and the release of inflammatory mediators is slowed. The subsequent systemic inflammatory response syndrome, sepsis, and multiple organ dysfunction resulting from systemic response to inflammation are attenuated [10,83]. The objective of excision is to obtain a viable tissue base while minimizing tissue loss, as the preservation of elements of the dermis reduces scar formation and improves wound appearance [84]. After initial excision, wound coverage is achieved using autologous skin grafts or a temporary coverage with nonautologous tissue depending on the patient's physiological status as well as the location and depth of the wound.

Split-thickness skin grafts (STSG) are harvested to the level of the superficial dermis, allowing for healing with minimal or no scar formation. STSG can be meshed to varying degrees to cover larger defects and prevent fluid accumulation under the graft. STSGs can, however, be less cosmetic and can undergo secondary contraction. STSG donor sites heal within 7–10 days and can be reused if additional coverage is needed. Full-thickness grafts are excised to the level of the hypodermis. The donor sites require closure because the entire thickness of the skin has been removed. Full-thickness grafts are advantageous for managing burn injuries in areas where wound contraction is problematic such as the neck or where wound durability is needed such as the palmar surface of the hand. Coverage using autologous STSG is generally feasible for injuries up to about 40% of TBSA. Immediate coverage with autologous STSG is not always possible in larger burns because of the availability or location of donor sites, the presence of infection, or patient status. In these cases, excision can be performed, and temporary coverage can be achieved using a biological or biosynthetic dressing and staged autografting can be performed at subsequent procedures.

Escharotomy

Circumferential full-thickness injuries can lead to constrictive physiology. In the extremities, full-thickness wounds can swell, compromising arterial and venous blood flow. This decreased blood flow can lead to tissue ischemia and tissue loss. Full-thickness burns to the chest can lead to a restrictive pulmonary physiology, resulting in hypercapnia, hypoxia, and respiratory failure. Escharotomy or linear division of the burn wound can improve vascular flow and mobility and limit tissue loss. Escharotomy incisions are made to the level of the hypodermis to span the length of the affected region, generally on opposite sides of the affected area. Because of the depth of the injury requiring escharotomy, this procedure can be performed with minimal additional analgesics using conventional diathermy.

Pain management

Pain management is an integral part of the acute management of children with burn injuries. Although the mechanisms remain to be defined, growing evidence supports that appropriate pain management may be associated with the rate of reepithelialization of partial-thickness burn wounds in children [85]. Pain management for the child with a burn injury is unique because of the amount of pain associated with the burn wound and dressing changes and the number and duration of dressing changes often needed. Although approaches used for other painful procedures can be used, several strategies for managing pain among children with burn injuries have been proposed.

Strategies for pain management can be described according to the intent and setting: management of procedural pain versus background pain between procedures, and inpatient versus outpatient settings. The optimal pain medications for wound debridement and dressing changes are potent but short acting. In the emergency department, intranasal fentanyl meets these requirements and avoids the additional pain associated with placement of an intravenous catheter. These features make its use ideal for debridement of small wound or smaller dressing changes. For more extensive procedures, ketamine is frequently used in children, often in combination with a benzodiazepine, propofol, or a narcotic [86–88]. Ketamine provides an analgesia effect at low doses and dissociative anesthesia at higher doses. Ketamine can be administered orally, obviating the need for an intravenous catheter. A strategy based on the use of ketamine is associated with a low incidence of the respiratory depression that can be associated with narcotic use [88]. Nitrous oxide is increasingly being used in settings outside of the operating room, including the emergency department and specialized outpatient clinic settings [89]. The use of this agent for pediatric burn patients has been reported to be safe and effective [90].

Between burn procedures and dressing changes, the goal is to provide adequate pain relief that will allow activity and physical or occupational therapy when needed. The World Health Organization (WHO) recommends treating pain in children at consistent intervals with a two-step approach starting with acetaminophen or nonsteroidal anti-inflammatories (NSAIDs), such as ibuprofen, as a base for mild to moderate pain, and augmenting with opioids, such as morphine, for severe or persistent pain [91]. Use of continuous infusion of acetaminophen is associated with decreased need for opioids [92]. The administration of acetaminophen at presentation to referring hospitals improves pain control during the subsequent hospitalization for definitive care [93]. The use of NSAIDs decreases opioid use in children with burn injuries [94] and does not appear to significantly increase the risk of procedure-related bleeding when administered perioperatively [95]. The use of oral analgesics is recommended whenever possible, but intravenous administration is acceptable if oral administration is not available, feasible, or an intravenous route is preferred. Nonopioid analgesics and opioids can be used as the initial treatment and as maintenance treatment of burn-related pain. Because of the risk of opioid dependence, the lowest effective doses should be given, and pain should be regularly reevaluated with appropriate adjustments in medication dosing.

Nutrition

After severe burn injury, patients experience a hypermetabolic state. The metabolic derangement includes elevated oxygen consumption, metabolic rate, urinary nitrogen excretion, lipolysis, insulin resistance, and weight loss [96]. Hypermetabolism in burn patients is a unique pathophysiologic response that leads to protein wasting, loss of lean body mass, and fat accumulation. Because of proportionally less body fat and muscle mass than adults, children are at increased risk for the consequences of burn hypermetabolism. Effects of burn hypermetabolism include impaired wound healing, multiple organ dysfunction, susceptibility to infection, heart failure, and even death. Hypermetabolism can lead to metabolic derangements and to loss of lean body mass. The metabolic stress associated with burn injuries can persist for years [97].

In combination with early excision and coverage, early and aggressive enteral feeding has been found to decrease the effects of hypermetabolism in pediatric burn patients [98,99]. Initiation of feeds within 48 hours is important because early initiation of enteral nutrition may reduce the hypermetabolic response to burn injury [75]. Catecholamines are the primary mediators of hypermetabolism and insulin resistance in burn patients [100,101]. Several studies support that propranolol, a nonselective beta-blocker, is an efficacious therapy for hypermetabolism in the severely burned child [100]. Propranolol decreases tachycardia, cardiac oxygen use, and resting energy expenditure and improves glucose metabolism, lessening the negative effects of the hypermetabolic state after burn injury [10].

Accurate caloric intake based on body surface area can attenuate the catabolic response associated with hypermetabolism after burn injury [101,102]. As in other settings, caloric requirements are calculated based on patient age and extent of the burn injury (Figure 7.4). Children with smaller burns can be encouraged to have a high-protein, high-calorie diet monitored with a calorie count. For burn injuries affecting large areas, tube feeding is almost always needed, particularly for younger children [103]. Not all children will tolerate sufficient calories via an enteral route, in which case parenteral nutrition can be used until full enteral nutrition can be given. Burn patients should be given an age-appropriate multivitamin or, for moderate-to-severe burns, micronutrient supplements. Ensuring adequate nutrition delivery is an important goal for children undergoing multiple surgical procedures. If enteral feeds are frequently stopped preoperatively, patients may not be receiving optimal nutrition because of these gaps. Strategies for managing this challenge include increasing enteral feedings outside of the immediate postoperative period or continuation of tube feedings

Although successful delivery of nutrition can be challenging, no gold standard for monitoring nutritional status after pediatric burn injury has been established. Due to the risks associated with underfeeding and malnutrition in burned children, monitoring is recommended to ensure that the elevated metabolic demands are met. Prealbumin, C-reactive protein, transferrin, and indirect calorimetry have all been suggested as markers but have not shown a consistent association with nutrition status [103,104]. Monitoring of laboratory trends over time is preferred over reliance on a single value. Indirect calorimetry can be used to estimate energy expenditures by evaluating oxygen consumption or carbon dioxide production. When available, indirect calorimetry has been recommended for monitoring energy requirements after burn injury [105,106]. Indirect calorimetry, however, can be influenced by metabolic derangements often seen in critically ill patients, limiting its usefulness in these settings [106]. The combined use of laboratory trends and indirect calorimetry monitoring is an ideal approach for evaluation of nutritional status in the burn-injured child requiring nutritional support.

Long-term outcomes

Many burn-injured children have significant challenges that continue for months or after injury, including limitation of function, pruritus, pain control, body image, and posttraumatic stress. Although these sequelae are more common among children with significant injuries, consequences of the burn injury can follow a wide range of injury types and severity [107].

Enteral nutrition support decision chart: Use to initiate tube feeds prior to dietitian seeing patient

<12 months of age:

Burn size	Tube feeds	Diet order
<5%	No	Continue home diet
5%–9%	Consider	Continue home diet
≥10%	Yes: Initiate home formula or breast milk at 2 mL/kg/h, advance by 2 mL/kg/h q 4 h as tolerated until reach goal × 24 h; if intolerance, return to previously tolerated rate; if volume is intolerable, concentrate to 24 kcal/oz	Continue home diet

1–4 years of age:

Burn size	Tube feeds	Diet order
<5%	No	High calorie, high protein diet and calorie count
5%–9%	Consider	High calorie, high protein diet and calorie count
≥10%	Yes: Initiate Nutren Jr® at 1 mL/kg/h, advance by 1 mL/kg/h q 4 h as tolerated until reach goal × 24 h; if intolerance, return to previously tolerated rate; if volume is intolerable, concentrate formula (Boost® Kid Essentials1.5)	High calorie, high protein diet and calorie count

5–9 years of age:

Burn size	Tube feeds	Diet order
1%	No	Regular diet
2–9%	No	High calorie, high protein diet and calorie count
≥10%	Yes: Initiate Nutren Jr at 1 mL/kg/h, advance by 1 mL/kg/h q 4 h as tolerated until reach goal × 24 h; if intolerance, return to previously tolerated rate; if volume is intolerable, switch to concentrate formula (Boost Kid Essentials1.5)	High calorie, high protein diet and calorie count

≥10 years of age:

Burn size	Tube feeds	Diet order
1%	No	Regular diet
2%–9%	No	High calorie, high protein diet and calorie count
≥10%	Yes: Initiate Nutren 1.0 at 1 mL/kg/h, advance by 1 mL/kg/h q 4 h as tolerated until reach goal × 24 h; if patient experience intolerance, return to previously tolerated rate	High calorie, high protein diet and calorie count

Enteral feeding adjustments; enter as a communication order:

- If patient experiences emesis, return to previously tolerated rate and continue to advance as tolerated
- Enteral nutrition support can be decreased as patient's PO intake increases; consider decreasing when patient is consuming at least 50% of estimated needs PO; consult nutrition to determine if patient is ready to wean enteral nutrition support

Figure 7.4 Nutrition guidelines for pediatric burn patients.

Scarring

Deep dermal and full-thickness burns can result in significant scarring. Burns that take more than 3 weeks to heal have a higher likelihood of healing with hypertrophic scar [108]. A contracture is a condition in which excessive scar forms after injury and then contracts, limiting the range of motion when associated with joints. To prevent functional limitations associated with contracture formation, splinting of the affected area has been proposed [108]. Support of splinting, however, is weak, and there is some evidence that splinting may worsen rather than prevent scar contracture [108]. Other treatments for excessive scarring include intralesional injection of steroids and pressure therapy. Intralesional steroids reduce inflammation, collagen deposition, and fibroblast proliferation, all implicated in excessive scar growth [109]. The side effects of localized administration of steroids include skin atrophy, telangiectasia, and hypopigmentation, but it avoids the more severe systemic effects of steroids such as Cushing's syndrome. Pressure garments should only be used in wounds after the acute healing phase. The minimal effective pressure provided by compression garments is 15 mm Hg. This pressure works by decreasing blood flow to injured areas, resulting in decreased collagen synthesis and promotion of realignment of already present collagen [110,111]. The efficacy of pressure garments appears to be limited to patients with moderate to severe scarring [110].

Surgical treatment for scars with cosmetic or functional limitations is often deferred until more than 1 year after injury. This interval allows sufficient time for the scar to mature and for the use of nonsurgical management. Healed burn wounds with contractures can cause significant functional limitations or cosmetic concerns. Options for reconstruction in the setting of contractures include burn excision, tissue expansion, skin grafting, z-plasty release, and skin flaps (local or distant) [33,112].

Physical function and rehabilitation

During and after recovery, mobility among burn patients may be limited by weakness, deconditioning, pain, and contracture. Physical limitations after burn injury can persist for years. As many as 20% of children who survived massive burns have serious long-term functional limitations, including decreased physical functioning [112]. Rehabilitative exercise has been shown to improve muscle mass and physiological function among pediatric burn pediatrics [113,114]. Follow-up with a multidisciplinary burn teams has been associated with improved physical function [113].

Electrical injury

Many pediatric electrical injuries result from low-voltage (<240 V) electrical shock after contact with household outlets. A child without a cardiac history who suffers a witnessed low-voltage injury can be discharged home without further evaluation if only a minimal burn wound is present, tetany did not occur, and there was no loss of consciousness [115]. An electrocardiogram is required if the injury was unwitnessed, produced tetany or if more than a minor burn wound is present. Although no specific ECG abnormalities are known to be associated with electrical injury, any new abnormality should be monitored [116]. Serum creatine phosphokinase and urinary myoglobin evaluations should be performed only after high-voltage injury to evaluate for significant muscle necrosis. Low-voltage injuries only require monitoring and testing if the child has a history of cardiac disease or had loss of consciousness associated with the injury. Twenty-four hours of cardiac monitoring, creatine phosphokinase, and urine myoglobin evaluations are required for assessing the impact of high-voltage injuries (>240 V) or lightning.

High-voltage electrical injuries can be associated with significant muscle damage and myonecrosis. If myoglobinuria is detected on urinalysis, the patient is at risk for acute tubular necrosis and renal failure. Urine output in these patients should be maintained at more than 2 mL/kg/h. Mannitol and bicarbonate containing infusions have been used as adjuncts in this setting, but data supporting their effectiveness are lacking. When muscle damage is severe, the combination of myonecrosis and fluid resuscitation can lead to significant edema and compartment syndrome necessitating fasciotomies of affected limbs [117–120]. Technicium-99 pyrophosphate scans can be used to assess the extent of muscle damage after an electrical burn [118].

Chemical burns

Initial treatment consists of removal of any exposed clothing, dusting off of skin if the chemical agent is a powder, and copious irrigation of skin with room temperature water. Eye burns require prolonged lavage and an ophthalmologic consult. Rundown of contaminated water onto unaffected skin should be avoided. Alkaline chemicals cause liquefactive necrosis, which results in deeper penetration and damage than the coagulation necrosis caused by acid burns.

Directed treatment of chemical burns based on the specific chemical involved is important for optimizing treatment. Different chemical skin exposures require specific treatment strategies. Hydrofluoric acid should be initially treated with water irrigation and then neutralized with topical calcium gluconate gel. If calcium gluconate gel is not available, it can be made by combining an ampule of calcium gluconate with 100 g of lubricating jelly. Injuries related to phenols (e.g., carbolic acid) are of particular concern because of a risk of absorption and systemic toxicity. Immediate and rapid irrigation with large volumes of water is mandatory because irrigation with smaller amounts of water will dilute the phenol and enlarge the affected area. Children should have liver function tests performed 24 hours after phenol exposure and should be monitored for systemic effects including pulmonary insufficiency, hepatic failure, and renal failure. Tar should initially be solidified with cooling water. Once the tar has hardened, it can be removed with petroleum jelly, a surfactant surface mixture, or a product containing polyoxyethylene sorbitan.

Conclusion

The successful treatment of burns in children requires aggressive initial assessment and treatment in addition to long-term management of functional outcomes. Prompt directed care and multidisciplinary follow-up now contribute to excellent outcomes in children even after the most severe of burn injuries.

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8

Trauma from child abuse

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Introduction

Caffey and Kempe first focused the medical community's attention on the problem of child abuse by identifying an association between long-bone fractures and subdural hematomas in children. Further work led to Kempe's symposium and article "The Battered Child Syndrome" [1–3]. As awareness increased, it became clear that a constellation of injuries is associated with child abuse and that these injuries occur in patterns. Because the history is often unreliable or deliberately deceptive, the recognition of known patterns of injury and the judicious use of diagnostic imaging are important in the evaluation of these patients. Unfortunately, prospective randomized controlled trial data on child abuse are unavailable. Since the treatment of most of the injuries associated with child abuse is well described elsewhere in this and other texts, this chapter will not review the treatment of specific injuries. Instead, it will attempt to assist the practitioner in deciding whether identified injuries could be caused by the reported mechanism and in recognizing the unique associations that have been previously identified.

Literature-based guidelines

In this updated second edition, the authors examined the literature pertaining to nonaccidental trauma obtained from MEDLINE and SCOPUS from 1990 to 2015 and classic articles from earlier time periods. There were no class I papers. Thus, standards of care cannot be developed according to the definitions of evidence-based medicine. Although a few papers fit into class II (prospectively collected data submitted to retrospective analysis), most were class III. There is a vast amount of empirically derived information that is supported by class III data.

Epidemiology

The U.S. Department of Health and Human Services estimates that 702,000 children were victims of child abuse and neglect in 2014, with a rate of 9.4 victims of all ages per 1000 children. Three-quarters (75%) of victims were neglected, 17% were physically abused, 8% were sexually abused, and 14% of victims suffered two or more types of maltreatment. Children < 1 year of age account for the largest percentage of child abuse victims with an incidence of 24 abused babies per 1000 children. The most common injury is head trauma. The rate falls as age increases to a rate of 3.5 victims per 1000 children by age 17. The rate of abuse in the < 1-year age group has risen since 2010 while rates from all other age groups have remained consistent [4]. When compared to all pediatric trauma patients, child abuse victims are more likely to have higher injury severity scores at presentation (mainly due to severe head injury) and higher mortality rates than accidentally injured children [5]. Boys < 1 year were more likely to be victimized than girls, but older girls were more likely to be victimized than boys of the same age. Caregiver risk factors for abuse included alcohol abuse (9% of victims) and drug abuse (26% of victims). Perpetrators were most likely to be a parent, 41% mothers, 21% fathers, and 21% both mother and father. Eighty-three percent of perpetrators were in the age group 18–44, with the age group of 25–34 having the highest rate; this is contrary to popular belief that young adults or teenage parents are the largest group of perpetrators of child abuse and neglect [4]. Within abusive head trauma, perpetrators are most likely to be identified as the patient's father or father figure, accounting for 50%–70% of cases [6–10]. Notably, when infants are excluded abusive head trauma has been shown to be the result of a nonparental caregiver in approximately 3 out of 4 cases [9].

Fatality rates from maltreatment are also higher for the very young, with 71% of fatalities in children younger than 3 years. The rate decreases with age. Boys have a higher fatality rate than girls at 2.48 versus 1.82 fatalities per 100,000 children. Population data show that while the highest percentage of child fatalities is among White children (43%), the rate of African American child fatalities is 4.36 per 100,000 African American children, almost three times the rates of White or Hispanic children (1.79 per 100,000 White children and 1.54 per 100,000 Hispanic children) [4].

Initial evaluation and treatment

History

The history of presenting illness or injury is a critical component of the initial evaluation of inflicted injury in children. The typical finding is a discrepant history that is modified over time as the caretaker adapts the history to developing medical information. Therefore, documentation of each interaction is important to catalog the evolution of the history during the hospitalization. Because the history is often unreliable, most injuries are discovered by physical exam and imaging studies.

Clinical presentation

Unexplained loss of consciousness or shock

Seriously abused children are often evaluated for an unexplained loss of consciousness or shock. As with any life-threatening injury or clinical situation with hemodynamic instability, standard resuscitative interventions are employed. When the history is not consistent with the clinical scenario, or there are external signs of abuse, the evaluation should focus on imaging studies to define the injury. Typically, computed tomography (CT) scanning of the head and of the abdomen and pelvis during the same radiographic session are useful for demonstrating intra- and extracranial pathology as well as visceral injury. The imaging studies help classify the mechanism and timing of injury. The evaluation of these children also includes retinal examination by an ophthalmologist and soft tissue examination to evaluate for patterned bruising or burns, as well as careful palpation for point tenderness, suggesting acute fractures. All children suspected of nonaccidental injury should also undergo a skeletal survey to evaluate for occult bony injuries.

External and soft tissue trauma

Injuries to the skin and soft tissue include burns (contact and immersion), bruises, and patterned marks and scars. Patterns and locations of burns and bruises are often self-explanatory, for example, clothing iron imprint directly on the back or thigh or hand-shaped bruise on the cheek. All of these physical findings can be correlated with the history. Pathologic bruising can be a source of confusion. This can usually be eliminated by routine coagulation studies. Bruises of the buttocks, perineum, or abdomen, or multiple bruises of varying ages, are suspicious for inflicted injury. Inflicted burns are usually either immersion or pattern-type injuries due to a hot object. Immersion burns often occur in a stocking/glove distribution or on the buttocks and posterior surfaces of the thighs, legs, and feet. Pattern burns, such as those caused by an iron, are rarely unintentional.

Fractures

Fractures are brought to the attention of the physician in three ways: (1) acute evaluation for fracture-related signs and symptoms, (2) incidental discovery of old fractures on another radiographic study, and (3) by skeletal survey. The most critical step in determining the etiology of the fracture is the correlation of the injury with the age and development of the child. Fracture patterns and their associations with intentional injury are discussed below.

Imaging studies

Skeletal survey

All infants and children with suspected abuse should undergo a skeletal survey. Postmortem skeletal surveys should be performed on all children who die when abuse is suspected. High-detail systems with specific images should be performed, avoiding the "baby-gram" technique. Lateral spine and pelvic films have traditionally been included in the skeletal survey; however, these studies carry a high radiation exposure and low diagnostic yield. In the absence of clinical findings of peripheral neurologic, spinal, or pelvic injury these studies may be omitted from the survey [11]. Repeat imaging in one to two weeks may show injuries not readily apparent on the initial survey due to the development of fracture calluses. However, as with the initial survey radiation, exposure to the child may be reduced by omitting the skull, spine, and pelvis views unless specifically indicated. Neurological injuries will most likely already be documented with a more sensitive CT or magnetic resonance imaging (MRI). This limited survey will reduce radiation exposure by approximately 90% without impact on the diagnosis of skeletal fractures [12,13].

Nuclear medicine

Bone scintigraphy has been suggested as an alternative or complementary imaging method to plain radiographs for occult fractures associated with child abuse [14–16]. There have been no definitive studies demonstrating the superiority of one over the other. The major value of radionuclide scintigraphy is its increased sensitivity for periosteal trauma of the extremities and trauma of complex anatomic structures such as the spine, ribs, and scapula. Thus, scintigraphy can further characterize or rule out multiple injuries in the child with a suspected mechanism of abuse.

Neuroradiology

CT of the brain is critical in the management of traumatic brain injury (TBI). MRI is less readily available in the acute setting. Thus CT is the primary imaging modality for central nervous system (CNS) trauma in most institutions. Occasionally a definite diagnosis is difficult because of the small and incompletely myelinated pediatric brain. Three-dimensional reconstructions of head CT images can be helpful in differentiating fractures from normal variants [17]. MRI can be useful in the less acute setting to more precisely define chronic abnormalities. A class II study compared two groups of patients with similar Glasgow Coma Scores and perinatal histories, categorizing the TBI as either accidental or inflicted [18]. Patients with inflicted TBI had higher rates of subdural, interhemispheric, and convexity hemorrhages and signs of pre-existing abnormalities such as cerebral atrophy, subdural hygroma, and ex vacuo ventriculomegaly. Subdural hygroma occurred exclusively in patients with inflicted TBI with atrophy, suggesting a previously undetected TBI. Intraparenchymal hemorrhage, shear injury, and skull fractures were more frequent after accidental TBI.

CNS injury

Abusive head trauma

Caffey first postulated a link between shaking infants and intracranial and intraocular hemorrhage without evidence of external trauma, which he termed "whiplash shaken baby syndrome" [1,2]. This entity has also been referred to as shaken-infant syndrome or shaken-baby syndrome. Many infants with this syndrome also show signs of impact injury to the head, ranging from skull fractures to soft tissue injury. When these findings are present it is often referred to as the ''shaken-impact syndrome." Abusive head trauma in children is sometimes further classified under the domain of "battered child syndrome" when more distant injury is present [19–20]. The various terminology used to describe these injuries has also been shaped by exploration into the underlying biomechanics and detection of occult blunt trauma. Some authors have argued that shaking alone is insufficient to produce the rotational force necessary to create subdural bleeding [21,22]. Additionally, neurophathologic examinations following abusive head trauma reveal high incidences of hypoxic ischemic insult and relatively few cases of diffuse axonal injury when fatal [23–25]. In light of these controversies, the term "abusive head trauma" has gained the support of the American Academy of Pediatrics as the proper term for describing these injuries [26].

Infants with abusive head trauma often present with sudden infant death syndrome (SIDS), seizures, coma, or apnea. The most common lesion on imaging is a subdural hematoma not associated with signs of external trauma [27–29]. The cause of the subdural hematoma is avulsion of the venous bridges between the brain and dura due to the rapid acceleration and deceleration that occurs with violent shaking or impacts [2]. There may also be associated skull fractures. Accidental subdural hematoma is rare in infants, and is not typically related to low-level falls (<4 feet). In the absence of a high-energy mechanism of injury, such as a motor vehicle crash or fall from a significant height, child abuse must be considered in every case of subdural hematoma in children. In the clinical scenario of reported minimal trauma in infants, the presence of a skull fracture without intracranial injury suggests accidental trauma, whereas skull fractures and intracranial bleeding or intracranial bleeding alone are highly suggestive of child abuse [30].

Fundoscopic examination is critical when assessing for abusive head trauma. Ocular findings must be evaluated and rigorously documented by an ophthalmologist. The validity of clinical information and diagnostic studies in abusive head trauma cases is dependent on the completeness of the retinal examination. A full assessment includes indirect ophthalmoscopy to examine the peripheral retina. One study demonstrated that 29% of patients with retinal hemorrhages were not detected by nonophthalmologists [31]. Complete postmortem ocular evaluation (including the optic nerve) is the gold standard for the diagnosis of retinal hemorrhage [32]. The mechanism that produces retinal hemorrhage is the subject of debate in the literature. One theory postulates that an abrupt increase in intracranial pressure results in venous obstruction and retinal hemorrhage. This may be augmented by abrupt increases in intrathoracic pressure due to thoracic compression. A second theory holds that acceleration/deceleration forces result in traction of the vitreous on the retina with hemorrhagic retinoschisis cavities. Numerous class II and class III studies show that retinal hemorrhages occur only rarely (up to 6%) with severe head trauma and not at all with moderate or mild head trauma [33–35]. In comparison, a retrospective analysis of the National Pediatric Trauma Registry found that retinal hemorrhages were reported in 28% of child abuse cases in children under 5 years of age [36]. Clinically, evidence of retinal hemorrhage is reported to have an approximately 74% sensitivity and 94% specificity for abusive head trauma. This review reports a superior sensitivity for retinal hemorrhage when compared to retinal folds, traumatic retinoschisis, and optic nerve sheath hemorrhage [35]. Other causes of retinal hemorrhage in infants include birth trauma, cardiopulmonary resuscitation (CPR), hematological diseases, and ruptured vascular malformations. With rare exceptions, CPR does not cause retinal hemorrhage [32,37–39]. Bacon et al. and Kirschner and Stein each reported a case of retinal hemorrhage in an infant after vigorous resuscitation [40,41]. Purtscher retinopathy, a lesion of diverse pathophysiologic origin, is a rare cause of retinal hemorrhage. However, this is rarely the cause of retinal hemorrhage and should be interpreted in the context of the clinical presentation.

Abusive head trauma has been found to result in significant increases in long-term debility when compared to noninflicted injuries. In a prospective study of patients presenting with moderate to severe TBI, 80% of patients with inflicted injuries had moderate to severe disability at 1 month following injury as compared to 45% of noninflicted head-injured patients [42]. Another study showed that cognitive and behavioral deficits were more severe and more prevalent in the inflicted injury group for years after injury [43].

Abdominal injury

Although the true incidence of abdominal trauma as a result of child abuse is unknown, it is less common than burns, head injuries, and musculoskeletal injuries [44], and represents less than 1% of all pediatric trauma admissions [45]. The most common mechanism is a direct blow to the mid-epigastrum. This compresses the abdominal viscera against the thoracolumbar spine, which can in turn produce a burst injury to the intestine, pancreatic contusion or transection, duodenal hematoma or perforation, or mesenteric laceration (Figures 8.1 and 8.2) [46,47]. As with any blunt abdominal trauma, bleeding from a solid organ injury can also occur. Children with abdominal injuries tend to be older than those with shaken-infant/shaken-impact syndrome, 14–15 months versus 11 months [45,48]. The level II study in 2005 found similar mortalities between children with abdominal injury and the rest of the nonaccidental trauma population. Children with abdominal injury were most likely to die from concomitant head injury, and no children in their cohort died directly from their abdominal injuries. However, children with intra-abdominal injuries did have higher injury severity scores at presentation and were more likely to need emergent operation. In addition, patients with visceral injuries had more associated intrathoracic trauma [45].

Patients with abdominal injuries secondary to abuse often present in shock late after their injuries. The cornerstones of the diagnosis of these injuries are the physical exam and CT scan of the abdomen and pelvis. Ultrasound is less helpful. The focused abdominal sonography for trauma (FAST) exam may play a role in the prioritization of injury management in the multisystem injured child, but CT scanning provides more complete anatomic information. Patients with other

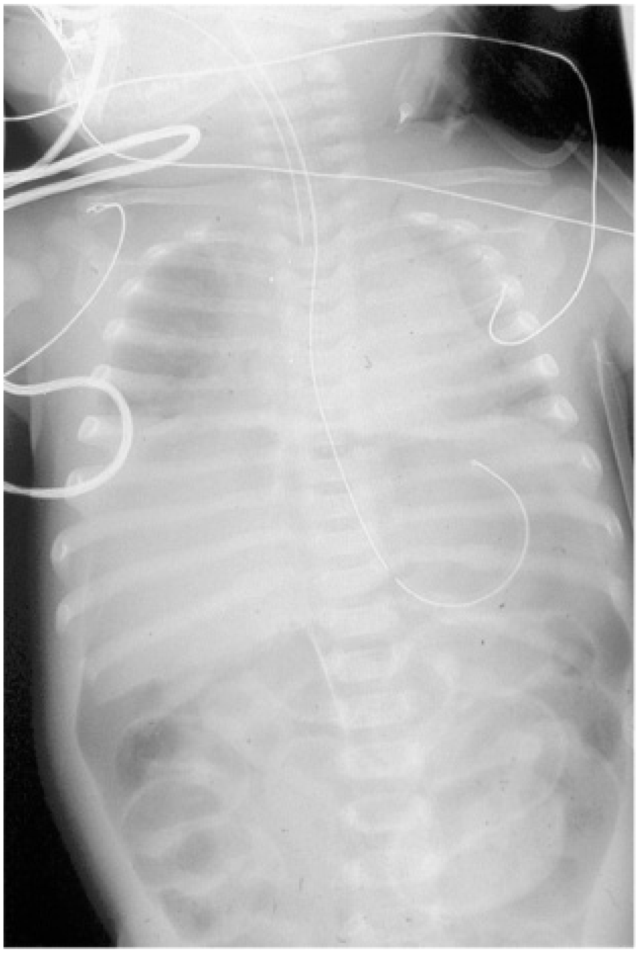

Figure 8.1 Flat abdominal radiograph demonstrating massive free intraperitoneal air. This was due to a jejunal perforation from a direct blow to the midabdomen.

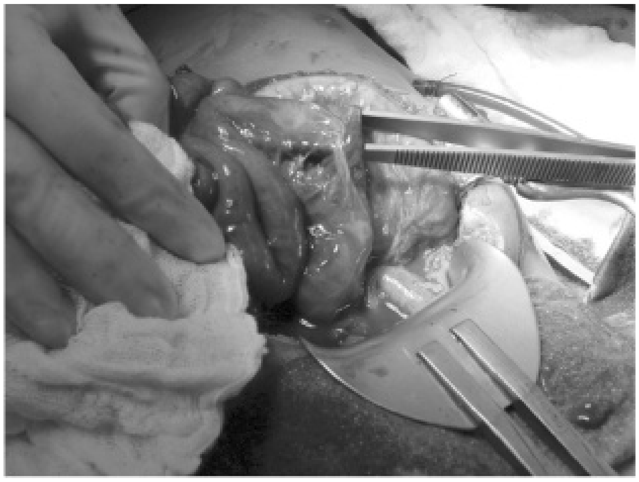

Figure 8.2 Intraoperative photograph of the child whose radiographs are depicted in Figures 8.1 and 8.3. Note the avulsed proximal jejunum with perforation. The forceps are within the lumen of the avulsed segment, demonstrating the perforation. The child was struck in the midabdomen approximately 12–18 hours prior to presentation in hemorrhagic shock.

injuries from nonaccidental mechanisms should undergo CT scanning of the abdomen and pelvis to evaluate for occult intra-abdominal injuries. While minor solid organ injuries in hemodynamically stable patients may be managed nonoperatively, patients with hemoperitoneum often present late after their injuries and in hypovolemic shock. The principles of management of abdominal injury due to blunt abdominal trauma have been applied successfully to these injuries.

Fractures and fracture patterns

Caffey recognized the pattern of fractures and head injury that are indicative of nonaccidental injury [1]. Eighty percent of nonaccidental fractures occur in children less than 18 months of age [49]. In evaluating a child with one or more fractures a careful history and physical exam with particular focus on age and developmental milestones is important. A critical comparison of the history with the physical findings helps determine the likelihood that fractures were intentionally inflicted. The discovery of multiple fractures in different stages of healing or fractures inconsistent with the developmental age of the child or the reported mechanism should raise suspicion of nonaccidental trauma. The presence of a nonaccidental fracture places the child at high risk for subsequent injuries and child protective service (CPS) notifications [50].

Long-bone fractures

Long-bone fractures, without consideration of mechanism, age of the patient, or associated injuries, have a low specificity for child abuse [51]. Spiral fractures have been classically viewed as pathognomonic of abuse in nonwalking children. In a class III study, Scherl et al. noted that the majority of fractures in children were transverse, and that this was also the most common pattern in cases of confirmed abuse. Because transverse fractures are often not felt to be caused by abuse, they are less frequently the subject of investigation [52]. Perhaps the most important factor in assessing the probability of abuse with femur fractures is age. In children less than 12 months old, 60%–80% of femoral fractures are related to abuse. In contrast, femoral fractures, as well as lower extremity fractures in general, are rarely determined to be the result of abuse in children older than two years of age [53–56].

The location of the humeral fracture is the most important distinguishing feature to delineate between accidental and nonaccidental fractures. In infants and toddlers, midshaft and metaphyseal fractures are more likely to be related to abuse, whereas supracondylar fractures are usually due to accidental falls [49,53].

Rib fractures

Rib fractures are uncommon in childhood, mainly because it requires a high-energy impact to break a child's rib. Rib fractures are believed to result from anterior–posterior thoracic compression during violent shaking (Figure 8.3). It has been estimated that 85%–100% of rib fractures in infants are due to abuse [53,57]. These fractures have been reported as the most frequently detected occult fracture in suspected cases of child abuse [58]. Most reports state that fractures due to abuse occur in the posterior part of the rib near the costovertebral junction where the rib articulates with the transverse process [59]. However, some studies claim that fractures caused by abuse can also occur in the anterior and lateral aspects of the rib [14]. A postmortem radiologic–histopathologic study using high-resolution radiographic techniques demonstrated that the majority of rib fractures are not detected by routine skeletal surveys [60]. CPR is often implicated as a cause of rib fractures in children. This arose from reports of rib fractures in adults after CPR [61]. However, as is true for retinal hemorrhages from CPR, this association is either nonexistent or extremely rare in children and infants. Class II and class III data report that 0%–3% of pediatric rib fractures result from CPR [14,15,62]. Regardless of location, rib fractures are a marker for severe thoracic injury. If rib fractures are not explainable by a high-energy impact (motor vehicle crash or

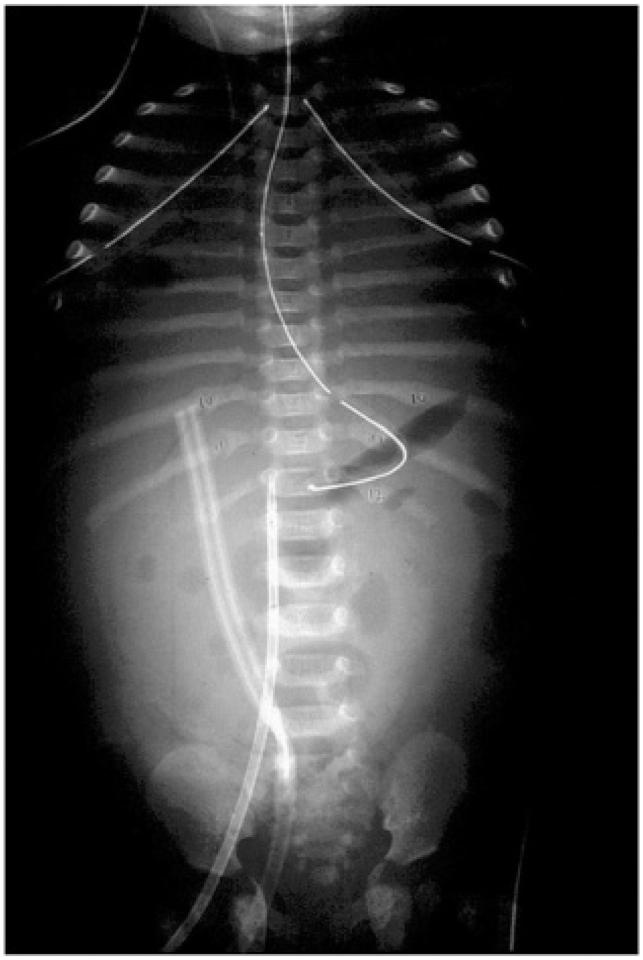

Figure 8.3 Skeletal survey demonstrating rib fractures with fracture calluses noted. These findings were detected on the skeletal survey of the child whose injuries are shown in Figures 8.1 and 8.2. These old fractures and new injuries are pathognomonic of abuse.

auto–pedestrian injury) or intrinsic bone disease, then child abuse should be considered as a possible cause. Suspicion for undiagnosed osteogenesis imperfecta should be low when rib fractures are diagnosed in infancy without evidence or documentation of perinatal/birth trauma [63].

Stairway injuries and low-level falls

Stairway falls are common during childhood, but have a low risk of mortality with a reported yearly rate of less than 1 per million child years [64]. As opposed to falls from a height, stairway falls are discretely quantifiable without the confounding variable of hitting another object. Falls down stairways are often implicated as the mechanism of injury by caregivers after nonaccidental trauma. Knowledge of the expected injury patterns and injury severity may provide a more objective basis for the diagnosis of nonaccidental trauma. Two class-II studies have specifically addressed the issue of injury pattern after stairway-related injury [65,66]. Both studies concluded that truncal injuries were rare (2%–3%) and that head, neck, and distal extremity injuries were common (70%–90%). Importantly, multiple injuries involving more than one body region were rare. While extremity injuries are common, femur fractures appear to occur rarely in stairway or low-level falls [65,67]. Intestinal perforation as a result of stairway falls has never been reported. A 29-year review of all English language publications demonstrated no intestinal perforations due to an unobstructed stairway fall [68]. Therefore, intestinal perforation after a reported stairway fall should be viewed as highly suspicious.

Physician responsibilities

It is the duty of the examining physician to report all suspected cases of child abuse to CPS. It is not the duty of the physician to be absolutely certain that suspicious injuries or circumstances are related to abuse. Most large children's facilities have child protection teams that consist of social workers, nurses, and physicians with expertise in this area. Following CPS notification, a written physician's statement is required to document the basis for the reasonable suspicion, the probable mechanism of injury, its severity, and the actual and anticipated medical consequences. The physician who prepares this statement must be prepared to testify about his or her findings in court. Many physicians and CPS teams find that medical photographs of the described injuries assist in communicating and memorializing the physical findings in their report.

Diseases such as osteogenesis imperfecta, Menkes syndrome (sex-linked recessive copper deficiency), temporary brittle bone disease, and congenital syphilis can cause bony abnormalities that mimic the effects of child abuse [69,70]. Hemophilia, purpura fulminans, or other disorders of coagulation may present with bruising and frank bleeding, suggesting trauma. The history may appear inconsistent with the physical exam if the examiner is unfamiliar with these diseases. Hermansky–Pudlak syndrome (functional platelet disorder) has presented with both subdural hematoma and retinal hemorrhage in an infant [71]. Mongolian spots may be mistaken for contusions.

Physicians accustomed to evaluating children for suspected abuse learn to recognize most of these diagnoses. In fatal cases, autopsy results can clarify the diagnosis. In nonfatal cases a pediatric specialist trained in the evaluation of child abuse should assess all children with suspected abuse to minimize the possibility of a mistaken diagnosis. The risk of repeat abuse in patients presenting with nonaccidental trauma is high with estimates of 26% of cases presenting with a second episode of abuse at 1 year and 40% at 2 years [72]. Delays in diagnosis are not without ramification and can lead to increased morbidity and even mortality [73].

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9

Imaging the injured child

PATRICK MCGOVERN and MICHAEL L. NANCE

Introduction

In an age of rapid technological advances and exponential growth in the number of tools available to clinicians, it has become increasingly important to determine when and how to use differing imaging modalities. Delivering high-quality care to injured patients requires rapid, accurate diagnoses, a need that has come to depend on radiologic studies. The pediatric population is no different, but presents additional challenges, including the potential long-term consequences of radiation exposure and logistical challenges such as patient size and cooperation. Taken with other difficulties faced when treating pediatric patients, such as short opportunity windows and the inability of many to verbalize their concerns, selection of the optimal imaging modality is critical. Here, we discuss clinical algorithms and guidelines developed to maximize patient benefit while also limiting failures in timely and accurate diagnosis, excessive exposure to potentially harmful procedures, and unnecessary medical costs.

One of the most important considerations regarding choice of imaging modality is the relative risk of radiation exposure each imaging technique delivers. As described below, the modality chosen is heavily guided by clinical presentation, injury location, and other factors that necessitate certain studies. For example, vascular compromise often requires immediate angiographic evaluation in the absence of other more life-threatening injuries, and few other studies can provide the information needed for proper management. In contrast, stable adult patients with concern for abdominal injury often receive computed tomography (CT) scans, even though free-air visualized under the diaphragm on an upright chest x-ray is reason enough to perform a laparotomy in many cases. The vast majority of ionizing radiation exposure related to imaging is due to CT scans, particularly in the head and neck region; single CT scans not only deliver more radiation than multiple plain-film studies, but also the relative risk of developing malignancy (due to radiosensitivity of the tissues in the head and neck) is higher [1]. Averaged in mSv over total studies per patient, CT scans are associated with the highest level of radiation delivered, followed by plain radiographs, and all other study types [2]. Although diagnostic studies can produce a great deal of data relatively quickly, good clinical judgment must be used to determine what imaging study (if any) is necessary to care for the patient, and what study is best suited to provide this information at the lowest reasonable dose of radiation. “As low as reasonably achievable,” or the ALARA principle, has become an important mantra for clinicians given the very real risk of mutagenesis and cancer from excessive radiation exposure in childhood. Although the benefits of indicated CT scans generally far outweigh the risks of cancer, many are still performed in the absence of a true clinical indication [3].

Imaging of the head and neck

CT remains the standard of care for imaging of most cranial and cervical injuries due to its relatively rapid scan acquisition time and the breadth of information provided. The main drawback of CT continues to be the associated ionizing radiation. CT usage within the general population (all ages) has been steadily rising; the number of pediatric emergency room visits that included CT scans jumped from 330,000 in 2005 to 1.7 million in 2008 [4]. This is not without consequence, especially with regard to head CT scans. A retrospective cohort study in 2012 found that exposure to childhood CT scans was linked to an increase in cases of both brain neoplasms and leukemia [5]. Attempts to develop and put into practice other imaging modalities such as rapid magnetic resonance imaging (MRI) have some promise [6], but have not yet gained widespread clinical use. Greater than 470,000 visits to emergency departments (EDs) annually are associated with some form of traumatic brain injury [7], and 10%–15% of all head injuries can be classified as severe [6], necessitating the use of imaging to define the extent of injury and track progression. For less severe injuries, it can be difficult to determine when CT scans are truly warranted. An algorithm-based approach was proposed in order to limit the number of unnecessary head CTs being performed for children without clinically important traumatic brain injury (ciTBI) (Figure 9.1). Briefly, patients are considered in two groups based on age (greater than or less than 2 years of age). Of all the signs and symptoms evaluated for both children less than and older than 2 years of age, loss of consciousness, skull fractures, significant mechanism of injury, and Glasgow Coma Scale (GCS) < 14 warrant CT scan evaluation (Figure 9.2) [8]. For children less than 2 years of age, observation may be used in certain circumstances, such as the presence of scalp hematomas, loss of consciousness greater than 5 seconds, or odd behavior according to the parents or caretakers. For patients greater than 2 years, loss of consciousness, vomiting, severe mechanism of injury, or severe headache may warrant extended observation. In both sets of patients, clinical factors such as the presence of multiple findings, physician experience, worsening symptoms, and even parental preference can be used in deciding between observation and CT scans [8]. Taken with the other criteria mentioned, this algorithm obviates the need for CT evaluation in almost 60% of the patients evaluated in the ED for traumatic brain injuries, without increases in failure to diagnose life-threatening and morbid injuries. Other imaging modalities that yield results less rapidly (e.g., MRI) may be considered at the discretion of consultants, if warranted and only after the patient is stabilized with all emergent issues addressed.

Clinically Important Traumatic Brain Injury (ciTBI)

- Neurosurgical Intervention for Traumatic Brain Injury (TBI)
  - Death from TBI
  - Intracranial pressure monitoring
  - Elevation of depressed skull fracture
  - Ventriculostomy
  - Hematoma evacuation
  - Lobectomy
  - Tissue debridement
  - Dura repair
  - Other neurosurgical interventions
- Intubation for more than 24 h for TBI*
- Hospital admission of 2 nights or more for the TBI in association with TBI on CT†‡
  - Hospital admission for TBI defined by admission for persistent neurological symptoms or signs such as persistent alteration in mental status, recurrent emesis due to head injury, persistent severe headache, or ongoing seizure management

* The 24-h period of endotracheal intubation for TBI was used to avoid misclassification of patients who might need brief intubation for airway protection for CT imaging, transfer between hospitals, or altered consciousness caused by anticonvulsant medication use.

† The 2-night definition was created to exclude those children routinely admitted for overnight observation because of minor CT findings that do not need any specific intervention.

‡ Skull fractures were not regarded as traumatic brain injuries on CT unless the fracture was depressed by at least the width of the skull.

Figure 9.1 Clinically important traumatic brain injury. (Reproduced from Kuppermann N. et al., *Lancet*, 374, 1160–1170, 2009. With permission.)

Blunt cervical injuries are rare in the pediatric population, accounting for less than 1% of all evaluations for traumatic injury [9]. While guidelines for adult cervical imaging have been well established, the infrequency of cervical spine injuries in the pediatric population makes development of protocols challenging. Nevertheless, a 2011 study found that altered mental status, focal neurologic deficits, complaint of neck pain (not posterior neck tenderness), torticollis, substantial torso injury, predisposing conditions, diving, and high-risk motor vehicle crashes were all associated with cervical spine injury, and may serve as a starting point when determining which children require additional imaging [9]. Though sensitivity is close to 100% when using the adult National Emergency X-radiography Utilization Study (NEXUS) criteria for pediatric patients, a majority of children receiving cervical CT scans can be classified as low risk, and many of them are scanned without any prior imaging—making it likely that unnecessary exposure to ionizing radiation happens frequently in centers applying adult criteria to children [9]. For children with significant injuries or findings, prompt consultation with a spine surgeon can ensure that either the initial and/or subsequent imaging obtained can be properly used to rule out or plan for operative intervention, all while reducing unnecessary exposure.

The NEXUS group [10] included in its study a pediatric cohort made up of 3065 patients younger than the age of 18, none of whom had missed injuries when the criteria were applied; caution is warranted, however, because of the small number of patients in early childhood included in the study [11]. In an effort to provide guidance, the Trauma Association of Canada released recommendations regarding cervical spine clearance in children; their recommendations are reproduced in Figure 9.3 [12]. Notably, they indicate that odontoid view radiographs are useful in cooperative patients, maintain that plain films should be used as an initial assessment, flexion-extension radiographs are indicated for persistent spinal tenderness, and that all patients with abnormal neurologic exams should undergo MRI [11]. Figure 9.4 reproduces a suggested algorithm for determining appropriate imaging of the pediatric cervical spine. In general, stable children who can undergo clinical examination do not need imaging except in the presence of abnormal physical findings. If unable to clear based on initial clinical presentation anterior/posterior (A/P) and lateral films, with odontoid films if the patient can cooperate

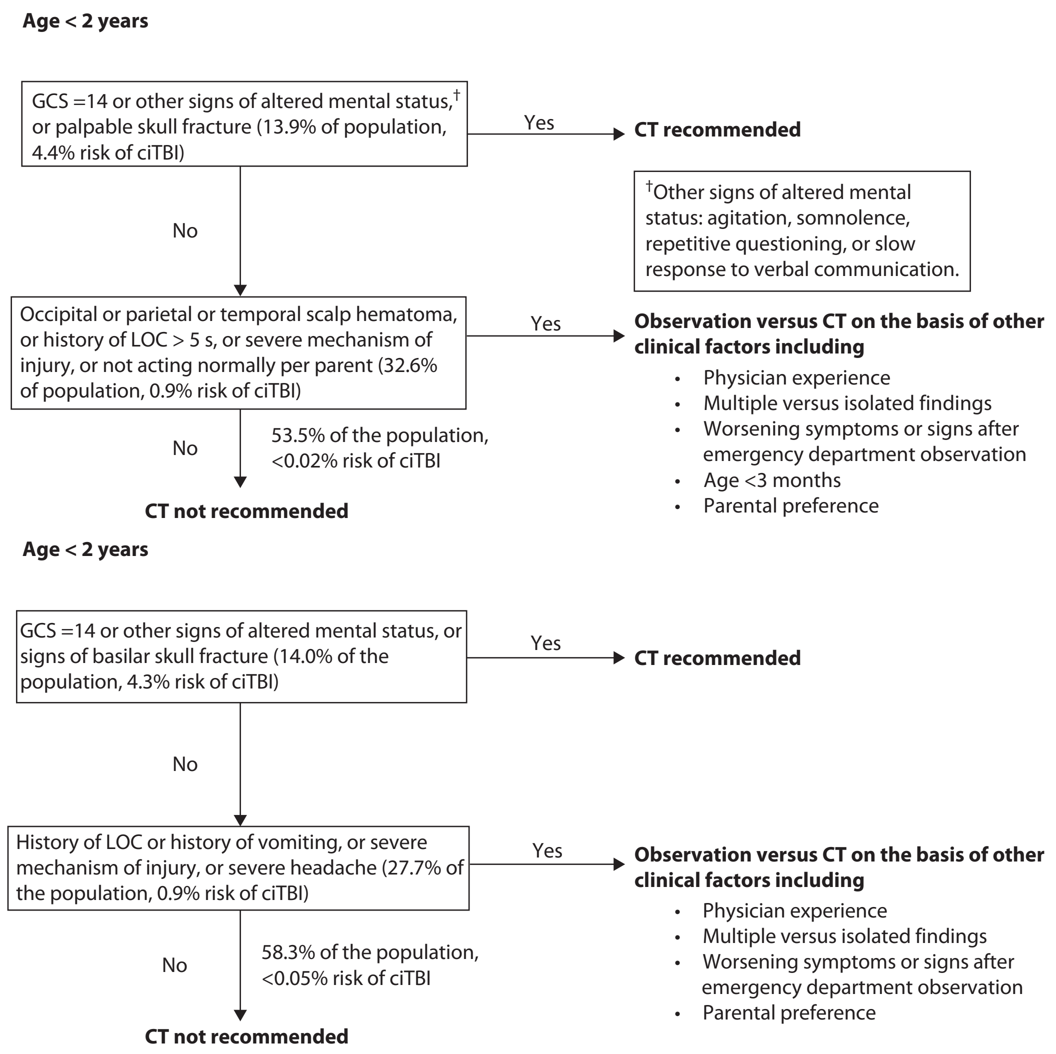

Figure 9.2 Suggested CT algorithm for children younger than 2 years and for those aged 2 years and older with GCS scores of 14–15 after head trauma. (Reproduced from Kuppermann N. et al., *Lancet*, 374, 1160–1170, 2009. With permission.)

1. It is possible to clinically clear the pediatric C-spine.
2. Pediatric patients should be managed with the lowest possible radiation exposure caused by the potential risk of radiation-induced malignancy.
3. The odontoid view radiograph may be beneficial in clearing the C-spine of cooperative patients.
4. Plain radiographs should still be the initial assessment tool of choice with CT scan reserved for patients where more diagnostic certainty is required or when suspected injuries require further investigation.
5. The flexion-extension radiographs may be indicated for evaluation of the neurologically intact patient with normal initial x-rays but a persistence of spinal tenderness.
6. MRI is recommended for all patients with an abnormal neurologic examination as well as for patients requiring special investigation of their soft tissues and spinal cord.
7. Pediatric patients with an unreliable clinical examination should be managed with a conservative and cautious approach.

Figure 9.3 TAC National pediatric C-spine clearance guidelines—summary of recommendations. (Reproduced from Chung S. et al., *J. Trauma-Injury, Infect. Crit. Care*, 70, 2011. With permission.)

are indicated. The NEXUS criteria for imaging include focal neurologic deficits, midline spinal tenderness, altered loss of consciousness, patient intoxication, and the presence of distracting injuries. Patients with any of these factors should undergo further imaging [11]. For many pediatric patients, tincture of time will resolve the inability to clear the cervical spine. For patients who are stable and are being admitted to the hospital, consideration should be given to leaving the child

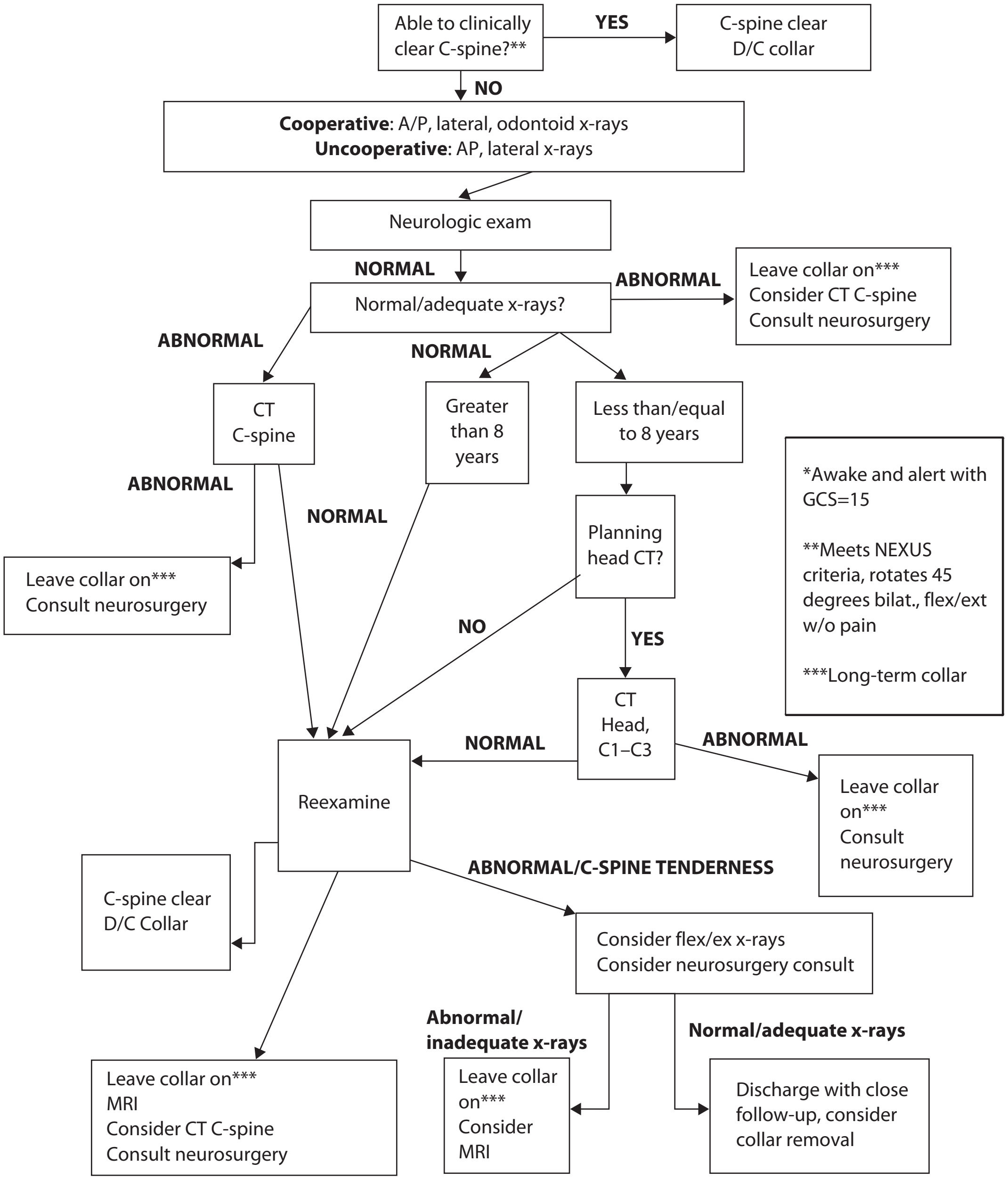

FIGURE 9.4 TAC C-spine evaluation: patient with reliable clinical exam (*see description in legend in figure). (Reproduced from Chung S. et al., *J. Trauma-Injury, Infect. Crit. Care*, 70, 2011. With permission.)

in an age/size appropriate padded hard collar and reexamination at a later time (e.g., next morning) to determine if the spine can be cleared without advanced imaging.

In addition to a relative lack of available data, children's cervical spines differ from adults and can have normal radiologic findings that would be considered pathologic in older patients. These include pseudosubluxation, variable ossification, and even nonvisible vertebral bodies on lateral plate studies [13]. In addition to highlighting the importance of having experienced radiologists available for interpretation, these differences may also lead to more radiation exposure–heavy studies such as CT scans, given the limitations of other studies. MRI, however, plays a much larger role in evaluation of the cervical spine than many other body regions, particularly because of the importance of resolution and the detail needed for determining spinal cord/canal integrity [13]. Vascular studies and their value (such as magnetic resonance angiography) must also be given consideration when concern exists for arterial compromise, as they avoid the risks of radiation and contrast exposure while providing excellent anatomic detail. These injuries are rare, and much reliance will remain on CT until newer and faster methods can be put into practice. Many of the principles of pediatric cervical spine evaluation can be generalized to the rest of the spinal column, as children's spines tend to be much more lax and mobile, which can have a protective effect against injury when compared to the more rigid and immobile adult spine [14]. Cerebrovascular injury in children also occurs less frequently than in adults (possibly due to increased vessel elasticity) resulting in a lack of clearly delineated imaging algorithms specific to the pediatric population [15].

Thoracic injuries

As in the head and neck, special considerations regarding thoracic radiographic findings exist for the pediatric population. Softer, less ossified rib cages in children may result in transmission of energy to underlying structures without fracture of the adjacent rib; as many as 52% of significant thoracic trauma occur in the absence of rib fractures [16,17]. When fractures are present, they are commonly located posteriorly (as opposed to laterally as in adults) [17,18]. In addition, because of the pliability of the pediatric chest wall, when multiple rib fractures are present, the suspicion of child abuse should be raised. Fractures of the first rib especially are concerning, given the amount of energy needed to cause such injuries. Typically, they can result from high-impact forces, compressive forces, shaking, or acute axial loads [19]. Due to a lack of fixation of the central mediastinal structures, children are particularly susceptible to the consequences of tension pneumothorax and thus such injuries should be treated expeditiously [20]. In addition to noninvasive monitoring, cardiac evaluation can be supplemented with sonography from focused abdominal sonography for trauma (FAST) exams performed as part of the resuscitation workup. The FAST exam can provide quick information regarding the presence of pericardial fluid and even myocardial contractility. Transthoracic and transesophageal echocardiography have also been used to identify both myocardial and aortic injury, even prior to CT scanning [21]. Given the acuity that chest trauma can present, the physician must formulate a diagnosis and treatment plan rapidly, with support from the aforementioned studies as indicated.

As in injured adults, the chest x-ray remains the mainstay for the initial evaluation of thoracic injuries in children. Most clinically relevant injuries in the chest (pulmonary contusion, pneumothorax, hemothorax, and rib fractures) [17] are visible on plain radiographs. Despite the obvious superior sensitivity of CT scans, plain-film studies also have been found to yield valuable clinical information at reduced cost and radiation exposure, validating their use as initial studies [22]. A 2008 retrospective study showed only 17% of findings seen on CT but not plain films resulted in changes in management or intervention [22]. As an example, CT scans identified more than six times the number of pneumo/hemothoraces than plain chest films, yet only 4 out of 47 of these patients required thoracostomy tubes, and only 2 of those 4 patients had injuries that could not be identified on plain films [23]. This, of course, is in stark contrast to the head and neck, where more radiation heavy imaging may be required to confirm common and life-threatening injuries. Chest radiographs do have their limitations, as serious injuries like diaphragmatic rupture can be obscured by concurrent parenchymal injuries within the chest (atelectasis, contusion, hemothorax, etc.) and clinical suspicion of such damage can be lacking [17]. In order to define more complicated injuries as well as missile trajectories, multidetector CT is most often used, though even in these cases it is important to limit exam time as much as possible. MRI is often too time-consuming for routine use in chest evaluation, as thoracic trauma can frequently require emergent intervention without any radiographic diagnosis. Decompensation is often rapid and unexpected in the pediatric population, and waiting for a chest x-ray before emergent decompression or placement of thoracostomy tubes can be detrimental. Along with clinical judgment, ultrasonography can serve as an adjunctive study to detect and quantify pneumo/hemothorax and other pleural processes. In addition, bedside ultrasonography may facilitate placement of an appropriate catheter. Chest radiographs may miss small collections (air or fluid), nondisplaced rib fractures, or contusions; however, the clinical significance of these occult findings must be questioned [17,24]. It has been recommended that high dosage of multidetector CT scans should be reserved for those with high likelihood of chest injury that may require intervention such as patients requiring positive pressure ventilation, tracheobronchial compromise, or suspected vascular or aortic injury [17]. Factors predisposing patients to significant thoracic injuries have been identified and include hypotension, elevated respiratory rate, abnormal results on chest exam findings including abnormal auscultation, femur fracture, and a GCS score of less than 15 [25]. The presence of these findings can help point the clinician in the correct direction regarding the use of CT and other potentially harmful studies in the absence of definitive management algorithms although initial plain radiographs are still indicated in most of these cases.

Aortic angiography, CT angiography, and other imaging modalities should be employed if there is evidence of central chest pathology (e.g., mediastinal widening on chest x-rays). In cases of suspected aortic injury, CT angiography is the study of choice given the brevity of the study and finer resolution in comparison to MR-based angiographic studies [26]. Large vessel injury in the chest poses a significant threat to life, and the risks of radiation exposure and contrast use are far outweighed by the need to define and diagnose these injuries in the appropriate clinical setting.

Abdomen and pelvis

Aside from providing valuable information regarding the chest, plain-film studies of the thorax can also yield some information regarding the abdomen, including "air-under the diaphragm" (indicating hollow viscus injury) and the locations of any retained missiles. Abdominopelvic radiographs, however, except for the aforementioned findings, rarely provide additional information outside of pelvic skeletal integrity [27]. Management of intra-abdominal injuries is based on the location, severity, and hemodynamic status for children with solid organ injuries. Thus, CT scan has been the gold standard due to the rapid scan acquisition time and reliable characterization of solid visceral injury. Although ultrasonography (as part of a FAST exam) has become a mainstay in the initial evaluation of abdominal trauma in the adult patient, its role in the assessment of the pediatric patient is less clear. Many consider FAST insensitive in children, and lacking information regarding the grade of solid organ injury [28]. Like other regions of the body, CT has become the preferred method for defining the extent and nature of injury; in the absence of convincing physical exam findings, it can help determine the need for operative intervention. As in adults, even relatively rapid studies such as CT scans should be reserved for hemodynamically stable patients, and should be deferred in the presence of hard indications for immediate surgery. Though solid viscus injury is typically easy to identify by CT scan, hollow viscus injury can be more difficult to detect [29] and more frequently requires operative intervention. Free extravasation of air or oral contrast has limited usefulness in identifying hollow viscus injuries; free unexplained fluid within the peritoneal cavity, however, is present in at least 50% of children with bowel perforation [29,30]. Other studies have indicated that free air is the only radiologic finding that is an automatic indication for laparotomy, and then only in the absence of bronchial, pleural, or chest pathology [31]. Oral contrast does not increase the sensitivity for finding such injuries, though specificity may be slightly improved [32].

The abdomen and pelvis make up a significant portion of the child's central body mass, thus many organs are exposed to ionizing radiation with CT scanning. In order to reduce this number, the Pediatric Emergency Care Applied Research Network (PECARN) established seven clinical historical items that greatly increased the risk of an injury needing significant intervention or operation (and thus warrant CT scan): abdominal wall bruising, GCS score < 14, abdominal tenderness, thoracic trauma, abdominal pain, decreased breath sounds, and vomiting [33]. It was recommended that patients with these findings undergo CT scanning if otherwise clinically appropriate. There are data to support that children presenting with blunt trauma due to nonmotorized force along with normal GCS scores and normal SIPA (shock index, pediatric adjusted) [34] are unlikely to need intervention and can safely undergo observation instead of a CT scan [34]. For penetrating injuries (where violation of the peritoneum is assumed to have occurred), CT scan may be useful in determining trajectory and identifying organs injured. CT scanning should not, however, delay operative intervention when there is an indication for laparotomy.

Adjunctive studies fill the gaps left by plain films and ordinary CT scans in identifying serious injuries requiring repair. Contrast-based exams and retrograde cystography can help identify active hemorrhage from solid organ injury and hollow-viscus damage, as well as genitourinary injuries, respectively. Rectal contrast enhanced pelvic CT scan for penetrating lower abdominal and pelvic injuries can be quite valuable in confirming the presence and extent of injuries [35]. CT is a more sensitive method for visualizing bony injuries to the pelvis, though plain films are sometimes all that can be obtained due to patient instability or the rapid need for intervention [36]; a CT should be performed any time a pelvic fracture is identified as the situation permits.

Angiographic studies (both diagnostic and interventional) play a critical role in abdominal and pelvic injuries; they allow for precise localization of injury and can obviate the need for morbid interventions such as open vessel repairs and laparotomies. Although identification is important, nonoperative management of bleeding injuries in the stable pediatric patient is still indicated in most cases. For example, active extravasation or "blushes" seen on studies in patients with splenic injuries do not mandate interventions such as angioembolization [37]. Such measures should be reserved for unstable patients or those failing conservative management. Most (60%) of hemorrhages stemming from pelvic injuries can be treated with pelvic fixation alone, and 75% of the others can be adequately visualized and treated with angioembolization [38]. Liver injuries behave similarly, requiring operative intervention only in severe cases. Delayed CT angiographic studies can also be used to identify urinary tract injury, with extravasation of urine or blood [29]. Kidney injuries also rarely require operative intervention in the setting of trauma.

Peripheral and musculoskeletal studies

Fractures and dislocations in children do not require nearly as much imaging and radiation dosage to diagnose compared to traumatic injuries in other body regions, and in some cases they require none at all. Any fracture associated with concerning signs (lack of pulse distal to fracture, neurologic compromise, severe mottling or discoloration of skin, missile or crush injuries, etc.) will require more extensive imaging (including CT or angiography). Information needed to save limbs should be obtained so long as an immediate threat to the patient's life does not exist. Uncomplicated skeletal injuries can generally be managed with plain-film studies, which should be performed when evidence of a fracture or dislocation exists; this includes gross deformity, open fractures, and other criteria based on the particular limb and body region. It is generally a good rule of thumb to image each of the joints surrounding ("above and below") any identified musculoskeletal deformities in order to fully define the extent of injury and rule out further joint involvement. Fractures across growth plates and other areas can have long-term consequences affecting growth and maturation, making it important to properly define such injuries; MRI has improved resolution over other modalities and should be used for such purposes, if concern exists [39]. In selected cases, CT scanning may provide information necessary to appropriately triage orthopedic injuries for transfer or operative planning. The decision to obtain advanced imaging in the evaluation of musculoskeletal injury should be done in conjunction with the orthopedic surgeon.

The role of imaging in pediatric trauma resuscitation

Modern pediatric hospitals and trauma centers have become very efficient in the initial management of critically injured patients, and many tasks are performed simultaneously. In addition to steps routinely performed (vascular access, laboratory draws, primary and secondary surveys) the need for imaging and intervention depends greatly on the initial clinical findings. Though the patient's airway, ability to breathe, and circulatory status should always remain a priority, portable chest x-rays can be performed after the primary survey if deemed necessary by the medical team. Close attention should also be paid to neurologic status and any evidence of spinal compromise, as posterior tenderness, deformity, and loss of rectal tone may indicate the need to evaluate spinal integrity. Head CT can be prioritized if necessary. In patients with suspected abdominal injuries, FAST exams can be performed as part of or after the secondary survey; in unstable patients, it may be the last imaging performed prior to operative intervention. It is also important to identify all penetrating injuries, urethral bleeding, and rectal bleeding, as this will dictate which areas require imaging with or without oral, rectal, and other contrast agents. Any pelvic injury or instability warrants bedside radiography to identify potentially life-threatening injuries, for example, open book fractures. If pulseless limbs or other evidence of vascular compromise are identified, the medical team should prepare for angiographic intervention or CT angiography. Plain films of extremities and other fractures (clavicle, shoulder) can be deferred until the second phase or afterward depending on whether or not the patient requires intervention. The tertiary survey (usually performed the day after admission) can include any newly identified or evolving injuries/traumatic processes.

If the patient does not proceed directly to the operating room or another interventional procedure, further imaging (including CT) should be considered. "Exam-based imaging" or the practice of focusing radiographic studies on clinical areas of concern rather than relying on broad studies should be the standard approach. CT scans should be limited only to the area of concern. Routine use of "pan scans" (whole body CT scanning) should be condemned. Keeping in mind the need to keep radiation exposure as low as possible, children frequently can be observed or even sent home, if clinically appropriate. As sedation is required in some patients to obtain advanced imaging, this must be factored when considering the type of imaging and need for sedative [40].

Summary and conclusions

Children can present with a wide variety of injuries, including multisystem trauma and other serious conditions; the tendency to image as much as possible can be a strong one, especially in the face of major, multisystem injuries [41–44]. It is important to remember that along with increasing the number of misleading or unhelpful findings, many advanced imaging studies carry with them the added risk of radiation exposure and often the need to sedate or anesthetize the patient. Caring for injured children requires striking a balance between maximizing the amount of useful information available to help direct management and unnecessary harm and resource utilization. As technology improves, our ability to diagnose and treat will also improve, but an exam-based imaging strategy will stand the test of time.

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10

Transfusion therapy in injured children

LISA HENSCH and JUN TERUYA

Introduction

Historical perspective

The practice of transfusion medicine has evolved over the years as we develop a deeper understanding of the effects of anemia, how particular patients tolerate anemia, coagulation, and the risks associated with transfusion. At first, the utility of transfusion was limited by both our understanding of the ABO system and red blood cell (RBC) antigens, leading to both acute and delayed hemolytic transfusion reactions. In addition, blood was collected from unscreened donors and carried a much greater risk for the development of transfusion-transmitted infections including hepatitis B virus (HBV), hepatitis C virus (HCV), human immunodeficiency virus (HIV), and human T-cell lymphotropic virus. Today, our knowledge of these systems and enhanced testing methods for infection allow us to transfuse patients more safely. However, emerging infections such as West Nile virus, Zika virus, and the risk of prion disease still threaten our blood supply. Transfusion of blood products is also still associated with a number of adverse reactions including acute and delayed hemolysis, transfusion-related acute lung injury (TRALI), transfusion-associated circulatory overload (TACO), and transfusion-related immunomodulation. Clinicians should therefore remain mindful that transfusion is not without risk and should only occur in the appropriate setting.

During transfusion medicine's infancy, whole blood, collected in glass bottles, was all that was available for transfusion. As one can imagine, there were problems associated with both compatibility and mobility of the blood supply. As better methods became available, we have moved to component-based therapy. Differential centrifugation and apheresis techniques now provide individual products: RBCs, plasma, platelets, and cryoprecipitate. In addition, we now have a multitude of hemostatic agents to choose from to help better control active bleeding.

Epidemiology

An audit of blood component use in the United States showed that an estimated 13.8 million RBC units, 2.17 million platelet units, 3.9 million plasma units, and over 1 million cryoprecipitate units were transfused in 2011 [1]. The pediatric population accounted for 265,000 RBC units, 127,000 platelet units, and 58,000 plasma units, which represented a significant decline in pediatric transfusion overall since 2008 [1]. Trauma is the leading cause of mortality in children ages 1–18 years, and the majority are motor vehicle related [2]. Review of the National Pediatric Trauma Registry (NPTR, October 2000) demonstrates that, of the 39,681 children in the database, 3453 (0.9%) received blood component therapy. This low incidence of transfusion is likely due, in part, to the mild (Injury Severity Score [ISS] 1–9) to moderate (ISS 10–19) injury severity, which comprises 90% of the children within the NPTR. In pediatric patients suffering from blunt or penetrating trauma, a study of 748,347 patients reveals that only 13,859 patients received a transfusion. Of these, a higher percentage of patients with penetrating trauma received transfusions (6% vs. 2%) [3].

Selected injured children with multiple injury or severe solid organ injury will require blood transfusion. In a population of severely injured children, ISS > 25, Glasgow Coma Scale (GCS) < 7, immediate blood transfusion > 20 mL/kg, and Pediatric Trauma Score < 4 were all independent risk factors for death. The probability of death was 0.63 in those children with all threshold values [4]. Nonoperative management is now the accepted treatment of solid organ injury in the hemodynamically stable child [5,6]. The fear of excessive transfusion has led some to question this form of management. Using decision analysis, Feliciano et al. concluded that the nonoperative management of splenic injuries was associated with an increased mortality from transfusion-related deaths [7]. These concerns seem unfounded in children, since a number of studies demonstrate that the operative management of splenic and liver injuries is associated with a greater transfusion requirement than nonoperative management [8–10]. Moreover, the tendency to transfuse children with solid organ injury appears to be declining [11]. Isolated orthopedic injuries rarely require transfusion in children unless other injuries are present or they involve major disruption of the pelvic ring [12–14]. Among children admitted with trauma, children eventually admitted to the pediatric intensive care unit (PICU) are more likely to be transfused after reaching the PICU (67% of those transfused) rather than before reaching the PICU [15]. These children are also more likely to require mechanical ventilation and have a higher risk of mortality [15]. In summary, while it appears that the need for transfusion in children is low, severely and multiply injured children are more likely to require blood component therapy.

Pathophysiology

Hypovolemic shock due to acute blood loss is the most common form of shock observed in injured children. By definition, shock represents a state of inadequate tissue perfusion to maintain normal cellular and organ function. The maintenance or restoration of normal oxygen delivery (DO_2) to tissues, not an arbitrary hemoglobin value, should be the primary therapeutic goal of RBC transfusion. The DO_2 is defined as the product of blood flow (cardiac output) and arterial oxygen content (CaO_2). At or near the critical DO_2 point, two parameters that reflect tissue perfusion begin to change: (1) lactate level increases and (2) the oxygen extraction ratio (OER), defined as oxygen consumption/DO_2, increases. Increases in the OER and lactate below the critical DO_2 point represent a physiologic transfusion trigger [16].

Interventions to improve DO_2 are directed to maximize carbon monoxide (CO) and O_2 carrying capacity. In the setting of traumatic shock, cardiac output is optimized first by increasing preload with fluid resuscitation. Reducing afterload or supplementing cardiac contractility may become necessary if fluid resuscitation alone fails. If efforts to improve cardiac output are insufficient to improve DO_2, then oxygen content may be targeted. Oxygen-carrying capacity depends on several variables [CaO_2 = 1.36 × hemoglobin × saturation (%) + 0.0034 PaO_2], but hemoglobin concentration is the principal determinant. An acute decrease in hemoglobin produces a drop in DO_2 unless there is a compensatory increase in cardiac output (Figure 10.1). A healthy individual may tolerate up to a 40% decrease in blood volume by increasing heart rate, redistributing fluid from the extravascular space to the intravascular space, reducing blood viscosity, and increasing oxygen extraction. Ensuring complete oxygen saturation with the augmentation of inspired oxygen is easily accomplished with the addition of supplemental oxygen. In general, the healthy patient can compensate as hemoglobin falls to 5 g/dL, but below this level compensatory responses begin to fail. They become inadequate at levels below 3.5 g/dL. The mortality rate exceeds 50% for hemoglobin concentration less than 3 g/dL [17]. In the setting of refractory shock and maximized cardiac output, increasing the hemoglobin concentration with blood transfusion becomes necessary.

The actual utilization of oxygen by tissues is oxygen consumption. When oxygen consumption exceeds oxygen availability, anaerobic metabolism begins and lactate production increases. In hemorrhagic shock, reduced O_2-carrying capacity and blood volume contraction exist at the same time. Restoration of blood volume by crystalloid infusion can reestablish cardiac output. Current experience suggests that otherwise healthy patients with hemoglobin values of less than 10 g/dL rarely require transfusion. Studies in Jehovah's Witness patients who refuse blood transfusion demonstrate that extremely low hemoglobin levels can be tolerated [18]. In surgical patients who refuse blood, Carson found that no deaths occurred among patients with hemoglobin levels >6 g/dL and blood loss less than 500 mL [19].

The critical principle in the management of the trauma patient is the restoration of DO_2 and correction or avoidance of tissue hypoxia. The decision to augment DO_2 in the setting of hemorrhagic shock with the administration of blood depends upon the severity of preexisting blood loss, the degree of ongoing blood loss, and the individual's compensatory ability to maintain the balance of DO_2 to consumption. The optimal transfusion trigger remains elusive, but healthy patients tolerate hemoglobin as low as 7 g/dL if adequately resuscitated and without ongoing blood loss. In a study of healthy volunteers, acute isovolemic reduction of

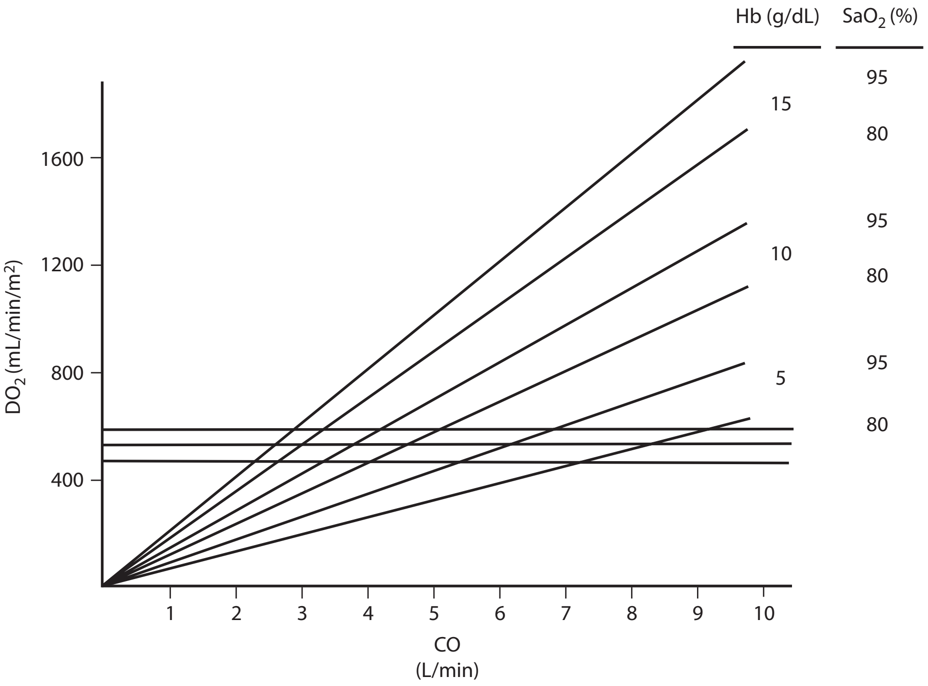

Figure 10.1 Changes in oxygen delivery (DO$_2$) with changes in hemoglobin (Hb) concentration and oxygen saturation (SaO$_2$). Note the effect of decreased SaO$_2$ on the need to increase cardiac output (CO) to maintain normal global DO$_2$. Correction of SaO$_2$ will measurably decrease CO. (From Greenburg AG, *Am J Surg*, 170, 44S–48S, 1995.)

hemoglobin to 5 g/dL results in increased heart rate, stroke volume, and cardiac index and a slight increase in oxygen consumption, but does not produce evidence of inadequate systemic DO$_2$ or increased lactate production [20]. The same is true of euvolemic patients undergoing elective surgical procedures [19]. In an elderly population undergoing surgical repair of hip fracture, a hemoglobin concentration of >8 g/dL had no apparent effect upon 30- or 90-day mortality [21]. Together these studies demonstrate that in diverse populations of patients, low hemoglobin is well tolerated, even in patients undergoing surgery, if intravascular volume is maintained and cardiac function is satisfactory.

In the setting of trauma, the adequacy of resuscitation is guided by the restoration of normal vital signs and organ perfusion. The use of lactate measurements to detect inadequate tissue perfusion and, therefore, inadequate resuscitation is helpful in selected situations. Minimally invasive measures of tissue oxygenation, skeletal muscle oximetry, or gastric tonometry, as well as the more invasive techniques of central vascular monitoring, have been used in an attempt to identify the endpoints of resuscitation. Yet, no single parameter exists to define the optimal transfusion trigger, and the decision to transfuse must be made on a case-by-case basis.

Component therapy

At the time of collection, blood is typically fractionated into its constitutive components of RBC, platelets, plasma, cryoprecipitate, and concentrated clotting factors. Component therapy allows the more efficient use of donated blood and avoids the undesirable effects of whole blood due to antibody–antigen reactions. In combat settings and some trauma centers, whole blood use is making a resurgence.

Whole blood

Use of whole blood is often restricted by ABO blood types, and when used should generally be an exact match for the recipient. Group O whole blood, traditionally considered to be the universal donor of RBCs, has plasma that contains both anti-A and anti-B. However, group O whole blood with low titers of anti-A and anti-B has been used in military conflicts when appropriate component therapy is unavailable and is considered to be "safe" when type-specific products cannot be obtained [22]. While the transfusion of 2 units of group O whole blood appears to be safe, additional studies are needed to determine the efficacy of these products [23]. As such, these products are unlikely to be routinely available, but may find increasing popularity in trauma resuscitation in the civilian population in the future.

Red blood cells

RBCs are obtained by removing the supernatant plasma from 450 mL of whole blood after centrifugation and anticoagulation. The average volume of 1 unit of RBCs in additive solution (AS-1 or AS-3) is approximately 250–300 mL with a hematocrit of 55%–65%. Small amounts of clotting factors and platelets are present but are essentially nonfunctional. RBC transfusion is indicated to increase RBC mass and therefore oxygen transport. Blood volume varies with age, ranging from 90 to 100 mL/kg in the premature infant to 70 mL/kg in children over 3 months of age [24]. Therefore, blood should be administered in boluses of 10–15 mL/kg in infants and small children.

Consensus Guidelines for Transfusion of RBCs

1. The use of a single hemoglobin trigger for all patients and other approaches that fail to consider all-important physiologic and surgical factors affecting oxygenation are not recommended.
2. Transfusion is rarely indicated when hemoglobin is >10 g/dL but generally indicated when the hemoglobin is <6 g/dL or the anemia is acute.
3. The determination of whether intermediate hemoglobin concentrations (6–10 g/dL) justify or require RBC transfusion should be based on the patient's risk for complications of inadequate oxygenation [25–27].

The storage lesion. It has been well established in the literature that as red cells age 2,3-diphosphoglycerate (2,3-DPG) and adenosine triphosphate (ATP) decrease. The pH becomes more acidic due to ongoing glycolysis and there is an increase in extracellular potassium. RBCs themselves suffer membrane vesiculation and loss of RBC deformability. Several studies have explored the relationship between age of storage and clinical outcomes. In a study of 455 patients assigned to both liberal and restrictive transfusion strategies, investigators found an association between prolonged storage (>2–3 weeks) and the development of multiple organ dysfunction syndrome in pediatric patients [28]. Other studies have suggested that there is no increase in mortality [29,30] but found an association between older RBC age and increased length of hospital admission [30] as well as postoperative infection [31]. Currently, an international study of mortality and hospital stay on fresh (<14 days old) versus standard age RBC units among pediatric patients in ICU is ongoing.

Special indications

There are a variety of modifications that can be made to cellular products (RBCs and platelets). These include leukoreduction, irradiation, washing, and volume reduction. Leukocyte reduction has become a nearly universal practice in large blood centers and reduces the risk of febrile nonhemolytic transfusion reactions (FNHTRs) and human leukocyte antigen (HLA)-alloimmunization. Leukocyte-reduced units are considered to be cytomegalovirus (CMV) safe. Irradiation is indicated in selected populations to prevent transfusion-associated graft versus host disease, an early universally lethal complication of blood transfusion that may occur in immunocompromised patients or in patients receiving products from HLA-matched or related donors. Washing and volume reduction can be used in volume-sensitive patients, and may be beneficial in those with repeated transfusion reactions. In addition, certain patient populations, such as sickle cell or thalassemia patients, are issued blood products that are matched for RBC antigens, commonly Rh (D, C, c, E, and e) and K antigens. Each of these modifications requires additional time for product preparation and release from the transfusion service. In patients requiring blood products urgently, it is unlikely that there will be adequate time for modification or matching. Immediate transfusion therapy should therefore take precedence in the setting of hemorrhagic shock and should not be delayed. This may require that emergency-release units be used.

Platelets

A unit of platelet concentrate is extracted from the platelet-rich plasma of 1 unit of whole blood to yield 5.5 × 10^{10} platelets in approximately 50–60 mL of plasma. Today however, most platelets used for transfusion are apheresis units derived from a single donor. They contain greater than 3 × 10^{11} platelets in 200–400 mL of plasma. Platelets are stored up to 5 days and may be stored up to 7 days with additional bacterial testing. The product will retain 70% of platelet viability and 80% of the original clotting factor activity with exception of labile coagulation factors, i.e., factors V and VIII. Platelet transfusion is indicated to correct clinically significant thrombocytopenia or platelet dysfunction. Platelet concentrates contain white cells and may cause febrile reactions due to white cell antigens. Since platelets are stored near room temperature, the risk of bacterial infection due to contamination should be considered. In children, transfusion of one dose of platelets increases the platelet count 30–60,000/mm^3, with an average platelet survival of 6–7 days. The usual dosage is 5–10 mL/kg.

Consensus Guidelines for the Transfusion of Platelets

1. Surgical patients with microvascular bleeding usually require platelet transfusion if the platelet count is less than 50,000/mm^3 and rarely require therapy if it is greater than 100,000/mm^3; with intermediate platelet counts, the determination should be based on the patient's risk for more significant bleeding.
2. Platelet transfusion may be indicated despite an apparently adequate platelet count if there is known platelet dysfunction and microvascular bleeding [26,27,32].

In patients with central nervous system or ophthalmic hemorrhage/procedure, as well as in those with pulmonary hemorrhage, the platelet count should be maintained above 100,000/mm^3. Patients can present with platelet dysfunction due to cardiac bypass, uremia, congenital platelet disorder, or medication and may require platelet transfusion regardless of the platelet count. Remember, platelet counts may drop rapidly in the setting of disseminated intravascular coagulation (DIC), frequently seen in children with traumatic brain injuries.

Fresh frozen plasma

When a unit of whole blood is fractionated, the plasma components are frozen. Coagulation factors are present in the levels obtained from fresh whole blood. Frozen storage preserves clotting factor activity. The time to prepare and thaw fresh frozen plasma (FFP) for transfusion is 30–45 minutes. For this reason, many transfusion services, particularly those in trauma centers, maintain a supply of thawed and/or liquid plasma. The benefit of these units is that they are more readily available for transfusion. However, both liquid and thawed plasma have reduced levels of the labile clotting factors, V and VIII. Gosselin et al. demonstrated that liquid plasma maintains at least 50% of clotting factor activity at up to 15 days of storage [33]. The availability of liquid plasma can improve the RBC-to-plasma ratio early in massive transfusion situations [34] while FFP is being thawed for use.

Plasma transfusion is indicated for the management of acquired multiple factor deficiency. This may result from massive hemorrhage, DIC, dilutional coagulopathy, liver disease, vitamin K deficiency, and warfarin therapy. It should be noted that a four-factor prothrombin complex concentrate, Kcentra™, is now Food and Drug Administration (FDA) approved for urgent warfarin reversal and should be used over plasma when available. In the setting of trauma, plasma is regularly used as part of the massive transfusion protocol (MTP). In infants and small children, plasma is administered in 10–15 mL/kg boluses.

Consensus Guidelines for the Transfusion of FFP

1. Correction of known coagulation factor deficiencies for which specific concentrates are unavailable.
2. Correction of microvascular bleeding in the presence of elevated (>1.5 times normal) prothrombin time (PT) or activated partial thromboplastin time (PTT).
3. Correction of microvascular bleeding secondary to coagulation factor deficiency in patients transfused with more than one blood volume and when PT/PTT measurements cannot be obtained in a timely fashion.
4. FFP is contraindicated for augmentation of plasma volume or albumin concentration [26,27,35].

Cryoprecipitate

Cryoprecipitate is prepared from individual donors and contains concentrated factor VIII, von Willebrand factor (vWF), factor XIII, and fibrinogen. Freezing of plasma at −18°C and then thawing at 1°C–6°C allows separation of the precipitate, which contains approximately 250 mg of fibrinogen, 150 units of factor VIII/vWF, and 100 units of factor VIII. Cryoprecipitate is indicated for patients with dysfibrinogenemia, hypofibrinogenemia, or consumptive coagulopathy. In the past, cryoprecipitate was used for patients with hemophilia A, congenital factor XIII deficiency, and von Willebrand disease, but today specific factor replacement is available for these patients. Cryoprecipitate may also be used for fibrin glue, but commercial fibrin glue preparations are now available.

Consensus Guidelines for the Transfusion of Cryoprecipitate

1. Correction of microvascular bleeding in massively transfused patients with fibrinogen concentrations less than 80–100 mg/dL or when fibrinogen concentrations cannot be measured in a timely fashion [26,27].

Emergency management

Hemorrhagic shock is the most common form of shock observed in injured children. Rapid identification and treatment of hemorrhagic shock are the core principles in the ABCs of trauma resuscitation. In the acute phase of resuscitation, the recognition of acute blood loss and shock is dependent upon an accurate assessment of clinical indices of organ function and perfusion. The American College of Surgeons Committee on Trauma has developed a useful classification of hemorrhagic shock based on systemic signs (Table 10.1) [36]. Estimates of blood loss are based on parameters of cardiovascular, respiratory, central nervous system, and renal function. Furthermore, the response to initial fluid resuscitation suggests the degree of blood loss, the rate of ongoing bleeding, and the likelihood of the need for blood transfusion. A rapid response to fluid administration suggests minimal blood loss (class I) and a low probability of blood transfusion. A transient response suggests moderate and ongoing blood loss (classes II and III) and a moderate to high need for blood. If no response to initial fluid resuscitation is observed, then severe blood loss (class IV) is likely and immediate transfusion is indicated.

If signs and symptoms of shock are present, a bolus of 20 mL/kg of crystalloid solution is rapidly administered and assessment repeated. If signs of shock continue, another crystalloid bolus is given. Resuscitation with >60 mL/kg of crystalloid solutions is associated with increased length of stay, rate of mechanical ventilation, and in-hospital mortality in pediatric trauma patients [36]. External hemorrhage should be controlled with pressure and fractures splinted to reduce ongoing blood loss. Minimal or no response to crystalloid administration and the absence of obvious bleeding suggest internal hemorrhage. In this setting, acute blood transfusion is indicated. Group O Rh-negative, uncrossmatched RBCs are administered in 10–20 mL/kg boluses and preparation may be made for prompt operative intervention to control further blood loss. The use of O-negative or noncrossmatched type-specific blood is almost as safe as crossmatched RBCs for emergency volume resuscitation but should be reserved only for these situations. Fully crossmatched blood is associated with the lowest risk of unexpected hemolytic reactions but generally requires 45 minutes to prepare. Crossmatch may take longer if unexpected antibodies are present. In life-threatening situations, blood resuscitation should not be delayed while awaiting crossmatch. It must be kept in mind that the use of greater than one-half blood volume of O-negative blood complicates later ABO typing and crossmatching. In addition, recent TRALI mitigation strategies

Table 10.1 Classification of hemorrhagic shock in the injured child and the probability of blood transfusion based on clinical assessment

	Class I	Class II	Class III	Class IV
Blood loss [blood volume (%)]	<15	15–30	30–40	>40
Clinical findings				
Heart rate (beats per minute)	<100	>100	>120	>140
Blood pressure	Normal	Normal	Hypotension	Severe hypotension
Respirations (tachypnea)	No	Mild	Moderate	Severe
Mentation	Anxious	Combative	Confused	Lethargic
Skin	Warm	Cool	Mottled	Pallor
Capillary refill (sec)	<5	5–10	10–15	>20
Urine output (mL/kg)	1–3	0.5–1	<0.5	Negligible
Resuscitation				
Response to initial fluids	Rapid	Transient	None	
Vital signs	Return to normal	Improvement, then recurrent tachycardia, hypotension	Remain abnormal	
Blood preparations	Type and crossmatch	Type-specific	O-negative	
Blood transfusion risk	Low	Moderate–high	Immediate	

Source: American College of Surgeons, Committee on Trauma. *Advanced Trauma Life Support Student Manual*, American College of Surgeons, Chicago, IL, 1997.

(male donors and nulliparous females) have limited the availability of "universal" AB plasma. In some situations, group A plasma, containing varying degrees of anti-B, may be used to increase the supply of available plasma. In a study of 254 patients, those who received incompatible group A plasma (14%) had no reported hemolytic transfusion reactions or significant difference in outcomes [37].

Traumatic coagulopathy occurs less frequently in children than adults. In a study of pediatric trauma patients showed that 6% of children were found to have coagulopathy, defined as INR ≥ 1.5 or PTT > 36 seconds or platelets $< 100,000/\text{mm}^3$. These patients had a two- to fourfold increase in mortality over noncoagulopathic patients [38]. Pediatric patients who have suffered a traumatic brain injury have been reported to have coagulopathy in over 40% of cases [39]. For this reason, laboratory testing to determine the extent of coagulopathy should be performed as soon as possible.

Massive transfusion

In the adult population, massive transfusion has been frequently defined by the number of RBCs used in a certain time (i.e., >10 RBC units in 24 hours [40] or >4 RBC units in 1 hour with continued need for blood components [41]). These definitions do not have as much value in the pediatric population due to the small blood volume of patients. For this reason, transfusion of >50% of total blood volume over 24 hours is most frequently used [42]. The principle of massive transfusion is to provide balanced resuscitation to the bleeding patient. Damage control resuscitation includes rapid control of bleeding, permissive hypotension (to prevent disruption of thrombus), and prevention of metabolic and physiologic consequences of transfusion (acidosis, hypocalcemia, and hypothermia) [43]. Though initially used in combat-related trauma, many institutions have now developed MTPs for applications in civilian settings. While there is still some debate about the appropriate ratio of FFP to platelets (whole blood derived units) to RBCs in MTPs, most trauma services aim for 1:1:1 or 1:1:2. In the pragmatic randomized optimal platelet and plasma ratios (PROPPR) trial of a 1:1:1 versus 1:1:2 transfusion strategy, authors found that a 1:1:1 ratio improved survival related to exsanguination at 24 hours, but did not improve overall mortality at 24 hours and 30 days [44].

Pediatric MTPs are the subject of increasing research. Dehmer et al. suggest strategies for the development of an MTP in pediatric patients that include initiation after 40 mL/kg of crystalloid infusion in patients with ongoing hemodynamic instability; a ratio of 1:1:1 in those >30 kg and a weight-based protocol for those <30 kg; maintenance of temperature, pH, and avoidance of hypocalcemia; and the consideration of recombinant factor VIIa in severe cases (off-label use) [45]. In a study of 102 patients, Hendrickson et al. examined the implementation of a pediatric MTP and found that it did not improve mortality, suggesting that additional large trials are warranted in this area [46].

Laboratory testing in trauma

Recent data highlight the importance and utility of coagulation data in pediatric trauma and resuscitation. Hemoglobin/hematocrit (H/H) and platelet counts are imperative in the assessment of the bleeding patient to help assess the extent of hemorrhage. Admission hematocrit of <35% in pediatric blunt trauma patients has been shown to be an effective screening test to help predict the need for blood transfusion and can be used to help guide resuscitation efforts [47]. The BIG score (base deficit + [2.5 × international normalized ratio] + [15 – GCS]) is now being used to help evaluate illness severity and predict mortality in pediatric populations [48,49]. In addition to the prognostic use of laboratory data, values obtained from the laboratory can be utilized in goal-directed hemostatic resuscitation. The PT, PTT, fibrinogen level, and platelet count can be used to determine if transfusion with FFP, cryoprecipitate, and/or platelets is indicated. Slow turnaround times can make physicians hesitant to collect samples since the data may be largely useless by the time results are reported. At our institution, we have found that the use of an MTP "Stat Pack" can provide actionable coagulation data in less than 15 minutes from specimen collection. The "Stat Pack" includes one citrated tube, one ethylenediaminetetraacetic acid (EDTA) tube, and a heparinized syringe that allows us to receive information on PT, PTT, fibrinogen, H/H, platelet count, blood gases, and electrolytes. The rapid turnaround time allows clinicians to make appropriate decisions about resuscitation in a timely manner.

Thromboelastography (TEG) or rotational thromboelastograms (ROTEM) are also frequently used in the setting of massive transfusion to help guide therapy. Rapid TEG (using tissue factor and kaolin) can be used as a point of care device with initial data reporting occurring within minutes [50,51]. An added benefit of using these assays versus conventional coagulation testing is that they are able to detect hyperfibrinolysis and allow for directed support with tranexamic acid (TXA) when needed. In a comparison of rapid TEG to conventional coagulation assays, therapy guided by rapid TEG led to increased overall survival (particularly survival at <6 hours from admission) and less initial plasma and platelet use [51]. TEG and ROTEM may also be used to guide therapy with hemostatic agents, such as fibrinogen concentrates, and avoid transfusion of plasma altogether in selected patients [52].

Hemostatic agents

Recombinant factor VIIa

Recombinant factor VIIa (rVIIa) is a source of activated factor VII that acts via the extrinsic pathway of coagulation to help achieve the formation of a fibrin–platelet hemostatic plug. This drug is FDA approved for the treatment and prevention of bleeding in patients with hemophilia A or B with inhibitors, as well as in congenital factor VII deficiency. Off-label use of this hemostatic agent in the pediatric population has been described in the literature in the setting of intracranial hemorrhage, gastrointestinal hemorrhage, DIC, patients receiving extracorporeal membrane oxygenation therapy, and in pediatric patients undergoing cardiac surgery [45,53–55]. Doses of rVIIa prescribed in the literature vary widely. A large retrospective study of 388 pediatric patients receiving off-label rVIIa (approximately 10% trauma cases) reported decreased overall blood use and a median initial dose of 114 mcg/kg. This study also found that thromboembolic adverse events were reported in 5% of patients, which did not correlate with the amount of rVIIa received at initial dose [56]. In a second study of pediatric patients (135 total) receiving rVIIa, it was reported that three patients had thromboembolic events, resulting in two deaths and one limb amputation, though these events could not definitively be attributed to rVIIa administration [53]. Further investigation is needed into the appropriate utilization and dosing of rVIIa in the setting of pediatric trauma.

Tranexamic acid

TXA is an antifibrinolytic that functions by displacing plasmin from fibrinogen, resulting in the inhibition of fibrinolysis. The CRASH-2 trial of over 20,000 patients examined the use of TXA in the trauma setting and suggested that TXA should be given to bleeding trauma patients soon after injury [57]. Similarly, the pediatric trauma and tranexamic acid (PED-TRAX) study looked at 766 pediatric combat trauma patients, of which 10% received TXA [58]. They concluded that TXA use in this setting was associated with decreased mortality and was not associated with an increase in thrombotic complications [58]. It is recommended that TXA, if used, should be given within 3 hours of injury.

Fibrinogen concentrates

Fibrinogen concentrates are produced from pooled human plasma and are available as a powder that is reconstituted for intravenous infusion. Cryoprecipitate has traditionally been used for fibrinogen replacement, but takes time to thaw, whereas fibrinogen concentrates are readily available to be used for rapid replacement without determination of ABO group. There is currently limited few data on its use in pediatric trauma; however, use of this product should be considered in patients with demonstrated hypofibrinogenemia or dysfibrinogenemia when cryoprecipitate is unavailable.

Definitive management

Operative intervention

Perhaps the most effective measure to limit blood transfusion therapy is the elimination of further bleeding by surgical intervention. Any child with suspected thoracic, abdominal, or vascular injury who is refractory to resuscitation should be taken promptly to the operating room. Given the success of nonoperative management of solid organ injury in children, one must be vigilant in recognizing the child who is continuing to bleed and requires operative therapy. In general, any child with a known solid organ injury in the abdomen who remains hemodynamically unstable despite adequate fluid resuscitation, or requires >1/2 blood volume replacement within the first 24 hours, has continuing bleeding and requires a laparotomy. Clinical variables in patients with splenic injury suggesting the need for surgical intervention include hypotension in the field or emergency department (ED), tachycardia in the ED, initial hematocrit less than 30, multiple injuries, or the need for blood transfusion in the ED [59].

Once operative control is achieved, additional measures can be employed to reduce the need for blood transfusion. The use of fluid warmers, heated ventilatory circuits, and active warming devices reduces the risk of hypothermia and the coagulopathy associated with decreased body temperature. Further surgical measures and techniques such as argon beam coagulation, collagen hemostatic agents, fibrin sealant, abdominal packing, vascular isolation, or arteriography with embolization have all been effectively employed in the management of surgical bleeding. The basis for deciding to transfuse the patient intraoperatively is less clear. Remember, elective surgical procedures have been safely performed in adults with severe anemia (hemoglobin <7 g/dL) who refuse blood on religious grounds, provided normovolemia is maintained [21]. The decision to transfuse should be based on an assessment of the patient's condition, estimate of blood loss prior to surgical control, and ongoing blood loss.

Endpoints of resuscitation

The conventional endpoints of resuscitation—return of normal heart rate, blood pressure, and urine output—may be all that are necessary in the previously healthy injured child with normal cardiopulmonary function. Base deficit (BD) and lactate appear to accurately reflect the hemodynamic and tissue perfusion changes associated with hemorrhagic shock. Other indicators include increases in BD parallel oxygen transport parameters such as a-v O_2 difference, DO_2, and oxygen consumption. Similarly, lactate levels and BD can be used to guide resuscitation [60,61]. Injury survivors with moderate to severe BD improve their BD within 4 hours and normalize their BD by 16 hours. Nonsurvivors fail to improve their BD to 6 or better, despite ongoing resuscitation [61]. Moreover, transfusion requirements appear increased with more severe BD. In severely injured patients, transfusions were required within 24 hours of admission in 72% of patients with a BD ≤ -6 versus 18% of patients with a BD ≥ -6 [60]. Endpoints of resuscitation should not rely solely on the BD or lactate level. Mikulaschek et al. demonstrated that if treatment decisions were guided by BD or anion gap, incorrect treatment would occur in up to one-half of patients [62]. Persistent lactic acidosis suggests occult hypoperfusion. In a prospective study of trauma patients with two consecutive lactic acid levels >2.5 mmol/L who underwent invasive monitoring and resuscitation, Blow et al. found a correlation between lactic acidosis and poor cardiac performance. Patients with persistent hypoperfusion despite resuscitative efforts demonstrated 43% mortality [63]. The normalization of end organ and tissue perfusion as measured by serum lactate is perhaps the most reliable perfusion marker available [64].

Recovery

The recovery phase of injury until the time of discharge is the period when the greatest reduction in transfusion can be accomplished without compromising the patient. In the absence of ongoing blood loss, equilibration of the fluid compartments rarely produces significant changes in the hematocrit. Critically ill patients with hemoglobin concentrations less than 9 g/dL, randomized to a restrictive strategy in which transfusion was administered only for hemoglobin less than 7 g/dL or to a liberal transfusion strategy in which hemoglobin concentrations were maintained greater than 10 g/dL, demonstrated that a restrictive strategy of red cell transfusion results in a lower 30-day mortality in patients who are <55 years of age, less acutely ill, and without significant cardiac disease [65]. Similarly, the Transfusion Requirements in PICU (TRIPICU) study of 637 stable, critically ill pediatric patients found that a restrictive strategy (<7 g/dL) could be used safely in most patients [66]. During the recovery period, the decision to transfuse should be made only on the basis of symptoms or signs of ischemia. In general, children are not at risk for myocardial ischemia and rarely manifest signs of anemia (dyspnea, fatigue, and tachycardia). Blood draws should be minimized or eliminated, particularly if the patient is afebrile, asymptomatic, and tolerating a diet. In children with isolated splenic injury, Shafi et al. found that after an initial drop in hematocrit within the first 24 hours post-injury, the hematocrit remained stable and returned to baseline by day 6 [11].

Complications of transfusion

Transfusion reactions

Adverse events related to transfusion are not uncommon, and are likely underreported. The National Healthcare Safety Network reported an overall adverse reactions rate of 0.24% [67]. Transfusion reactions may be broadly classified into nonhemolytic and hemolytic reactions. Nonhemolytic reactions are far more common and most often occur as the result of interactions with plasma proteins or cytokines within the blood component. Of these, allergic and FNHTRs are the most common. Allergic reactions usually include rash, pruritus, urticaria, or localized angioedema mediated by IgE and histamine release [68]. However, these reactions may have more severe manifestations including bronchospasm and anaphylaxis. Patients who have had mild reactions previously may develop more severe reactions over time and should always be carefully monitored for signs of respiratory distress. When an allergic transfusion reaction is suspected, the transfusion should be discontinued and the symptoms managed with antihistamines, epinephrine, and steroids, as indicated. FNHTRs are also common and include the development of fever and/or chills and rigors during the transfusion or shortly thereafter.

Life-threatening nonhemolytic transfusion reactions include TRALI and TACO. TRALI is the rapid (<6 hours from transfusion) onset of acute lung injury. This adverse reaction may be either immune or nonimmune mediated and is most commonly associated with the transfusion of plasma-containing components. It was the most common cause of transfusion-related fatalities (41%) reported to the FDA between 2010 and 2014 [69]. TACO is the second most common cause of fatality in the same timeframe at 22% [69]. Risk factors for TACO include larger volume and faster rate of transfusion [70]. Signs and symptoms include dyspnea, orthopnea, pulmonary edema, elevated brain natriuretic peptide (BNP), and evidence of left heart failure.

Hemolytic transfusion reactions may be acute or delayed. In the emergency setting, where blood is released prior to completing a type and screen, it is particularly important to be cognizant of the signs and symptoms associated with each. Hemolysis occurs when recipient antibodies react with donor RBC antigens. Acute hemolytic transfusion reactions (AHTRs) are caused primarily by ABO incompatibility and most often result from either clerical or administration errors. In the emergency setting, AHTRs may also result from the use of emergency release (uncrossmatched) blood due to preformed recipient antibodies from previous transfusion or pregnancy. AHTR is characterized by the rapid onset of fever, chills, rigors, chest or abdominal pain progressing to respiratory distress, and circulatory shock. Hemoglobin is present in the plasma and urine. Renal failure may ensue. Once recognized, the transfusion should immediately be discontinued. Aggressive resuscitation should be instituted to support the circulation and achieve a urine output of >2 mL/kg/hr. Other reasons for AHTR include improper storage or transfusion temperature (such as transfusion using a malfunctioning blood warmer), transfusion in the same line as medications, mechanical lysis resulting from rapid transfusion through small bore needles, and transfusion with incompatible fluids [71]. Delayed transfusion reactions take place in the days to weeks following transfusion. There is serologic evidence of a new RBC antibody in the plasma and possible fall of hemoglobin back to pretransfusion values. Laboratory confirmation of suspected hemolysis includes increased lactate dehydrogenase (LDH), increased plasma free hemoglobin, decreased haptoglobin, increased unconjugated bilirubin and hemoglobin in the urine.

Transfusion-transmitted disease

Viral infection is one of the most feared complications of transfusion. The first descriptions of transfusion-associated HIV infection occurred in late 1982. Improved screening and detection have reduced the current frequency of HIV infection to approximately 1/1,500,000 units [72]. The risk of HCV transmission by transfusion is estimated to occur in 1/1,100,000 units [72]. HBV infection now has the highest residual risk and is estimated to occur in 1/850,000–1/1,200,000 units [73].

Bacterial infection due to contamination is reported to occur as a result of 1:100,000 platelet transfusions and 1:5,000,000 red cell transfusions [74]. The difference in frequency is attributed to storage of platelets at 20°C–24°C, which facilitate bacterial growth, while RBCs are generally stored at 1°C–6°C temperatures. *Yersinia enterocolitica* infection is associated with RBC transfusion [74]. *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Serratia marcescens*, and *Staphylococcus epidermidis* infections are most frequently observed in platelet-associated infections. *Babesia microti* is now the most commonly reported cause of transfusion-transmitted infection with subsequent fatalities [69,75].

Metabolic complications

Children may be more susceptible than adults to metabolic complications with rapid transfusion because of the higher ratio of transfused blood to TBV. Children are prone to hypothermia and may become profoundly hypothermic with the infusion of cold fluids and blood products. Hypothermia not only increases metabolic demand but also worsens coagulopathy. For this reason, a blood warmer should always be used when blood components are going to be administered rapidly.

Rapid transfusion can also produce severe electrolyte disturbances. Blood components contain citrate which chelates calcium and prevents clotting within the unit. When large volumes are transfused, the patient's own calcium may drop rapidly. Low serum calcium results in alterations in the coagulation cascade and depressed circulatory function [76]. When possible, ionized calcium level should be monitored, particularly in the setting of massive transfusion. Replacement with calcium gluconate is recommended when values become low due to citrate toxicity. Additionally, hyperkalemia may arise after large- or rapid-volume infusion. Hyperkalemia has been reported to occur in up to 39% of transfused trauma patients [77]. Children, especially neonates and infants, are more susceptible to development of hyperkalemia. Consequences include cardiac arrest during massive transfusion [78]. Therefore, serum electrolytes should be monitored in the setting of transfusion.

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11

Pediatric ICU management

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Introduction

Pediatric trauma patients with severe injuries will require admission to an intensive-care unit (ICU) for close monitoring and/or ongoing resuscitation and support. ICU management is complex and requires the active participation of pediatric surgeons, intensivists, and subspecialists to fully address patients' injuries. This chapter focuses on the principles of critical care and management techniques that are most applicable to the critically injured trauma patient.

Monitoring

Close monitoring is required for all trauma patients in the ICU. That includes measurement of heart rate, electrocardiography, fluid balance, blood pressure, temperature, and respiratory rate. Additional modalities may be used to either invasively or noninvasively follow cardiac output (CO) and function, end-tidal CO_2, sedation levels, neural activity, and intracranial pressures, among others, depending on the patients' injuries and clinical status.

Cardiovascular monitoring

Noninvasive monitoring is commonly used to assess blood pressure. Accurate blood pressure measurement in children requires an appropriately sized cuff. Interpretation requires consideration of the child's age, sex, and height. Age-based guidelines for normal and abnormal vitals are detailed in Table 11.1. Pitfalls of noninvasive monitoring include the fact that diastolic pressures tend to be slightly higher than with invasive monitoring and the lack of continuous measurements.

Invasive blood pressure monitoring may be obtained through either percutaneous arterial cannulation or cutdown techniques, with the radial and femoral arteries being the most common sites for access. Advantages to a functioning arterial line include continuous waveform assessment of arterial blood pressure and convenient access for arterial

Table 11.1 Pediatric advanced life support vital sign guidelines

Normal heart rate by age (beats/min)		
Age	**Awake rate**	**Sleeping rate**
Newborn to 3 months	85–205	80–160
3 months–2 years	100–190	75–160
2–10 years	60–140	60–90
>10 years	60–100	50–90
Normal respiratory rate by age (breaths/min)		
Infants (<12 months)	30–60	
Toddler (1–3 years)	24–40	
Preschool (4–5 years)	22–34	
School age (6–12 years)	18–30	
Adolescence (13–18 years)	12–16	
Systolic blood pressure hypotension reference ranges (mmHg)		
Term neonates (0–28 days)	<60	
Infants (1–12 months)	<70	
Children 1–10 years	<70 + (age in years × 2)	
Children >10 years	<90	

blood gas sampling. However, arterial lines are prone to kinking and compression and may lead to clot formation or limb ischemia.

Continuous monitoring of heart rate and rhythm via electrocardiography is almost universal in the ICU. In trauma patients, ventricular tachycardia is associated with subarachnoid hemorrhage; persistent sinus bradycardia is associated with cerebral hypoxia, cardiac arrest, airway obstruction, tracheal disruption, increased intracranial pressure, and hypothermia; and sinus tachycardia is associated with hypovolemic shock. Moreover, some trauma patients may have taken arrhythmogenic drugs including tricyclic antidepressants, cocaine, opiates, and amphetamines.

The gold standard for cardiac monitoring hemodynamic shock is the Swan–Ganz catheter, which is a balloon-tipped catheter that is floated through the central venous circulation, right atrium, and right ventricle (RV) to terminate in a pulmonary artery branch. A thermister on the catheter monitors CO and permits calculation of cardiac index, stroke volume index, left-ventricular stroke work index, indices of right-ventricular function, systemic vascular resistance (SVR) index, pulmonary vascular resistance index, oxygen delivery (DO_2), oxygen uptake (VO_2), and oxygen-extraction ratio (O_2ER). The pulmonary capillary wedge pressure is a surrogate for the left atrial pressure and equivalent to the left-ventricular end-diastolic pressure, assuming the absence of mitral valvular disease and pulmonary hypertension. Pulmonary artery catheters should not be routinely used, but may provide a survival benefit to critically injured trauma patients in select situations [1,2]. Any benefit provided hinges on a thorough understanding and interpretation of the data provided from the catheter.

Less invasive methods of monitoring CO have been developed. One such product is the pulse index continuous cardiac output (PiCCO™) device, which integrates a wide array of both static and dynamic hemodynamic data through a combination of trans-cardiopulmonary thermodilution and pulse contour analysis from central venous and intra-arterial catheterization alone [3]. Several other products also exist to measure CO, including those that employ esophageal dopplers (e.g., CardioQ™ and HemoSonic™), partial carbon dioxide rebreathing (e.g., noninvasive partial CO_2 rebreathing [NICO™]), and bioimpedence (e.g., PhysioFlow™), among several others. The role for these devices is still being defined but may be important as Swan–Ganz catheter use declines.

Oxygen saturation

Arterial oxygen saturations may be continuously and noninvasively measured by pulse oximetry using the spectrophotometric properties of oxygenated hemoglobin (Hb). The pulse oximeter probe has two light-emitting diodes that pass light through perfused tissue to a photodetector that compares the fraction of infrared, red, and ambient light and calculates oxygen saturation. Probes are small and may be placed on the finger, toe, earlobe, forehead, or other convenient location. Of note, accuracy decreases at low saturations (i.e., SaO_2 <70%), and traditional pulse oximeters cannot distinguish carboxyhemoglobin from oxygenated Hb. Therefore, measurement of SaO_2 via pulse oximetry is unreliable in the setting of carbon monoxide poisoning.

Ventilation

End-tidal carbon dioxide ($EtCO_2$) monitoring, known as capnometry, is a noninvasive method for measuring the $PaCO_2$ in expired gas. The principle is similar to pulse oximetry in that a sampling chamber contains a light source on one side and a photodetector on the other measures the carbon dioxide (CO_2) content of exhaled gas that passes through it. Since CO_2 absorbs light at the infrared wavelength (940 nm), the CO_2 present in the gas may be calculated from the amount of infrared light that reaches the photodetector. $EtCO_2$ is a reflection of alveolar ventilation, metabolic rate, and the pulmonary circulation. It is also useful for confirmation of endotracheal tube placement and may be helpful for early detection of endotracheal tube dislodgement.

Neurologic monitoring

Several modalities are available to monitor both intracranial pressure and level of sedation/neurological activity. These are varied and may be invasive or noninvasive. Patients with major head trauma may require ventriculostomy with placement of an external ventricular drain for continuous intracranial pressure (ICP) monitoring and therapeutic cerebrospinal fluid drainage. The bispectral index (BIS) monitor is an electroencephalographic recording device that generates a single numeric value and may be used to titrate sedation/anesthesia depth during mechanical ventilation, barbiturate coma, or procedural sedation. Similarly, near-infrared spectroscopy (NIRS) and related technology may be used to assess cerebral perfusion.

Oxygen delivery and extraction

Aerobic metabolism consumes oxygen and results in the generation of carbon dioxide. The transport of oxygen from the lungs to the tissues can be described in terms of (1) the oxygen content in arterial blood (CaO_2), (2) the delivery of oxygen in the blood to the tissues (CO), and (3) the rate and efficiency of VO_2 from the capillaries into the tissues.

The arterial oxygen content is a sum of the Hb-bound O_2 and the dissolved O_2 in the plasma and is described by the following equation: $CaO_2 = (1.34 \times Hb \times SaO_2) + (0.003 \times PaO_2)$. The first part of the equation describes Hb-bound oxygen, where 1.34 mL O_2/1 g Hb is the oxygen-binding capacity of Hb and SaO_2 is the percentage of oxygenated Hb in the blood. The second part of the equation reflects the dissolved O_2 in blood. Hb is the principal determinant of oxygen content in the blood, and so, practically speaking, one may ignore the contributions of dissolved oxygen.

DO_2 is the product of CO and CaO_2, where CO is affected by heart rate, volume status (preload), SVR (afterload), and contractility. Each of these factors can be manipulated. VO_2 is calculated as a product of the CO and the arteriovenous oxygen content difference (CaO_2–CvO_2) and describes the rate at which oxygen dissociates from Hb and moves into the tissues. The O_2ER describes the fraction of delivered oxygen that is taken up into the tissues (VO_2/DO_2). Under normal conditions, decreases in DO_2 result in an increase in O_2ER up to a maximum level of 50%–60% extraction (normal is between 25% and 30%) without any observed changes in VO_2. However, once this limit is reached, the VO_2 becomes supply dependent and further decreases in DO_2 result in proportional decreases in VO_2. In other words, shock and cell death occur when anemia or poor oxygenation are present and compensatory mechanisms are inadequate to supply enough oxygen to the tissues to meet metabolic demands. Critically ill patients may have several other metabolic derangements that favor the release of oxygen from Hb molecules. Additional factors that are known to shift the oxygen dissociation curve to the right include increased heart rate, 2,3-diphosphoglycerate (DPG), and carbon dioxide and decreased pH.

The mixed-venous oxygen saturation (SvO_2), measured from the pulmonary artery, is a useful way to assess the balance between systemic DO_2 and systemic VO_2. Central venous O_2 saturation ($ScvO_2$) provides a suitable alternative that may be measured from the superior vena cava. Agreement between SvO_2 and $ScvO_2$ values should be within 5% of each other assuming that multiple $ScvO_2$ measurements are averaged, so the most useful information is garnered by following trends [4]. Assuming arterial saturations >90%, measurements below 65% reflect conditions of impaired oxygenation where maintenance of VO_2 requires increased oxygen extraction by the tissues. $ScvO_2$ >80% may be seen with microcirculatory shunting (such as in sepsis or liver failure), left to right shunts, or with cytotoxic dysoxia from mitochondrial disease or cyanide poisoning.

Shock and cardiovascular support

Shock occurs when tissue perfusion is inadequate to maintain aerobic metabolism. Shock may be classified as (1) hemorrhagic/hypovolemic, due to lack of circulatory volume; (2) distributive/neurogenic, characterized by lack of vascular tone; or (3) cardiogenic, secondary to pump failure. Often, as is the case with septic shock, there may be a significant amount of overlap. Shock is common in severe traumatic injuries, and data show that shock on admission is independently associated with a high mortality (16.8%) [5]. Close monitoring and early, goal-directed therapy is essential to improving outcomes in these children.

Hemorrhagic shock and transfusion

The incidence of hemorrhagic shock is lower in children. Precisely because it is uncommon, presentations in children may be misleading and protocols for management of massive transfusion in children may not be in place at all hospitals. Additionally, the cardiovascular response to shock in children is age dependent. Younger children have an extended period of compensation with elevated CO and increased peripheral vascular resistance, so they may lose a significant volume of blood before demonstrating major

Table 11.2 Pediatric blood volume

Age	Estimated blood volume (mL/kg)
Premature infant	90–100
Term infant to 3 months	80–90
Children older than 3 months	70
Obese children	65

hemodynamic instability. Shock in these patients most commonly presents with tachycardia, whereas adolescents are more likely to manifest hypotension [6].

Management of hemorrhagic shock in the pediatric population depends on an accurate assessment of blood loss and size-appropriate goals for resuscitation. Estimated blood volumes by age are detailed in Table 11.2. Rapid blood loss may not initially be reflected in Hb or hematocrit levels, and guidelines that suggest initiating transfusion for Hb levels <7 g/dL [7] do not apply to actively bleeding trauma patients. Resuscitative efforts are based on assessment of vital signs (heart rate, blood pressure, central venous pressure, etc.), measures of end organ perfusion (urine output and mental status), laboratory data (base deficit and lactate), and real-time imaging (echocardiography). Current guidelines advocate damage control resuscitation (DCR) techniques including (1) permissive hypotension to avoid disruption of thrombus formation, (2) rapid control of bleeding, (3) limitation of crystalloid and blood replacement products, and (4) prevention of hypothermia, coagulopathy, hypocalcemia, and acidosis [8].

Experience with adult patients has demonstrated a benefit to whole blood or balanced transfusion, as well as implementation of massive transfusion protocols (MTP) [9,10]. Many adult MTPs utilize a ratio of 1:1:1 (units of red blood cells [RBCs] to fresh frozen plasma [FFP] to platelets) to address the acute coagulopathy of trauma as well as hemorrhage. Protocols based on this strategy have been adapted for children [8]; however, data on the benefit of MTPs and balanced transfusion in this population are less clear [11–14].

Lastly, it is important to recognize that even though transfusion increases blood oxygen content and may improve hemodynamics and CO, it does not necessarily normalize DO_2 to tissue [15]. RBCs that are stored for prolonged durations commonly display reduced deformability and increased aggregation, which together decrease their ability to offload oxygen. Additionally, native RBCs typically export nitric oxide in hypoxic tissue to cause vasodilation, resulting in increased regional flow and augmented DO_2. Stored blood often suffers from abnormal vascular signaling that increases vascular resistance and diminishes regional perfusion. Several other negative effects of transfusion, including immunosuppression, coagulopathy (typically with >40 mL/kg RBCs in children), and transfusion reactions, among others, must be considered.

Septic shock

Septic shock may complicate trauma as a result of infection during treatment in the ICU. Among all 20,000 children who develop septic shock annually, in hospital mortality is 10% [16]. Those who survive may experience adverse neurocognitive outcome and functional decline [17,18]. Prompt recognition and initiation of guideline-based therapy of both severe sepsis and septic shock are critical to providing patients the best chance of survival and recovery [19,20].

Guidelines from the American College of Critical Care Medicine and, more recently, the Surviving Sepsis Campaign recommend goal-directed resuscitation with infusion of crystalloids and initiation of pressors and appropriate antibiotic therapy within the first hour of presentation, as well as source control, when appropriate, within 12 hours [19,21]. Each hour delay in antibiotic administration has been shown to decrease survival by 8% [22]. Goals of therapy include reversal of hypotension, increasing urine output, normal capillary refill, full peripheral pulses, and adequate level of consciousness without inducing hepatomegaly or rales. For $ScvO_2 < 70\%$, Hb levels of 10 g/dL should be targeted, although a lower target of >7 g/dL is appropriate after stabilization. Hydrocortisone therapy should be given to children with fluid-refractory, catecholamine - resistant shock and/or absolute adrenal insufficiency. Extracorporeal membrane oxygenation (ECMO) should be considered for refractory septic shock and/or data suggest improved survival (up to 74%) in patients treated with veno-arterial (VA) ECMO [23].

Cardiogenic shock

Pure cardiogenic shock is an uncommon result of pediatric trauma. As part of the initial assessment of a child with suspected acute heart failure, it is important to question whether an alternative diagnosis such as sepsis is possible. In the trauma patient, precipitating causes such as myocardial contusion, pericardial tamponade, tension pneumothorax, or arrhythmias must be identified and treated. An acute decline in cardiac function in previously healthy children is poorly tolerated and may place them at risk for imminent cardiovascular collapse.

Patients with cardiogenic shock are at risk of cardiac arrest during intubation [24]. Sedation and analgesia may blunt endogenous catecholamines, increase systemic venous capacitance and preload, cause peripheral vasodilation, and have direct myocardial depressant effects. Additionally, the increased intrathoracic pressure from positive pressure ventilation may further reduce right-ventricular preload. Any precipitating factors should be treated and possible precautions include administration of additional fluid, preemptive catecholamine infusions, judicious use of induction agents that are associated with vasodilation and myocardial depression, and readiness to place the patient on ECMO in the case of refractory cardiac arrest.

Management of heart failure targets preload, afterload, and contractility in order to augment stroke volume/CO. Patients with heart failure see increases in left-ventricular end-diastolic volume, decreased stroke volume, and increased left-ventricular end-systolic volume. These factors, along with increased preload and ventricular end-systolic pressure, result in progressive left atrial hypertension, pulmonary edema, increased work of breathing, and shock. Careful monitoring should be used to optimize ventricular filling pressures to maximize stroke volume while limiting pulmonary and peripheral edema. Trauma may compromise preload via reduction in diastolic filling time with excessive tachycardia, tamponade, or loss of atrioventricular synchrony. Therapy may involve volume administration, heart rate control, or administration of diuretics and fluid restriction, although the latter is uncommon during initial phases of trauma resuscitation and management. Additional strategies may attempt to reduce oxygen demand (VO_2) by managing core temperature, pain/anxiety, work-of-breathing, and catabolic stress.

Afterload is influenced by ventricular transmural wall pressure, the thickness of the ventricular wall, and resistance at the aortic outflow tract from either valvular stenosis or systemic arterial pressure. Assuming adequate blood pressure, SVR may be reduced by using vasodilators. Drugs such as nitroglycerin or nitroprusside may be used. Milrinone has the dual effect of lowering SVR while improving contractility. Caution should be taken to maintain an adequate diastolic pressure to ensure stable coronary artery perfusion pressures and prevent subendocardial ischemia.

Inotropic therapy may be added to increase myocardial contractility in patients with severe heart failure. The goal of therapy is to augment stroke volume at the same or lower ventricular end-diastolic pressure. Characteristics of common agents are detailed in Table 11.3.

Neurogenic shock

Head injury is an important cause of hypotension and shock in pediatric trauma, particularly among young children [25–27]. One study reported that isolated head injury was seen in 31% of children ≥6 years old and 61% of children 0–5 years old who presented with systolic hypotension following trauma [27]. A more recent study supported these findings in that among patients with severe shock following trauma, isolated head injury was found in 29% of children age 0–15 years and in 50% of children younger than 5 years old [25]. These data challenge traditional teachings regarding resuscitation for shock in trauma, as current practices originate primarily from managing hemorrhage. Further study is warranted to identify best practices for treating these children.

Adrenal insufficiency

During periods of significant stress, cortisol levels are increased through activation of the hypothalamic–pituitary–adrenal (HPA) axis in order to maintain homeostasis. Cortisol increases the availability of energy substrates; maintains cardiovascular tone, endothelial integrity, and distribution of fluids within the vascular compartments; potentiates vasoconstriction; and counteracts the inflammatory cascade modulating immune responses [28]. Despite the fact that many critically ill patients have elevated plasma cortisol concentrations, these levels often reflect production that is inadequate to meet the body's increased demand. This "functional" or "relative" adrenal insufficiency is termed critical illness-related corticosteroid insufficiency (CIRCI) and may result from a decrease in adrenal steroid production, tissue resistance to glucocorticoids, or structural damage to the adrenal gland, hypothalamus, or pituitary gland from either hemorrhage or infarction. Secondary adrenal insufficiency may also occur following long-term therapy with exogenous glucocorticoids. While reported prevalence varies by population, rates as high as 60%–90% have been seen in patients with septic shock, and a large multicenter, prospective study of critically ill children (comprising trauma, sepsis, and surgery) identified an incidence of

Table 11.3 Characteristics of selected inotropic agents

Inotrope	Receptor/mechanism	Cardiac output	Heart rate	SBP	PCWP	Half-life	Myocardial oxygen consumption
Dopamine	$\beta_1 > \beta$	↑	↑	↑	↔	2–20 minutes	↑
Dobutamine	$\beta_1 > \beta_2$	↑	↑	↔	↓	2–3 minutes	↑
Epinephrine	$\beta_1 > \beta_2$, α_1	↑	↑	↑	↔	2–7 minutes	↑
Milrinone	Phosphodiesterase-III inhibition	↑	↔	↓	↓	1–4 hours	↔
Levosimendan	Stabilises calcium–troponin interaction opens K_{ATP} channel	↑	↑	↓	↓	1–1.5 hours	↔

Source: Costello JM, et al. *Cardiol Young* 2015;25 (Suppl 2):74-86.

α_1 = alpha-1 adrenergic receptor; β_1 = beta-1 adrenergic receptor; β_2 = beta-2 adrenergic receptor; DA = dopamine receptor 1; K_{ATP} = adenosine triphosphate sensitive potassium; PCWP = pulmonary capillary wedge pressure; SBP = systolic blood pressure.

adrenal insufficiency of 30% [28,29]. When there is no structural damage to the HPA axis, CIRCI is reversible in most patients. In the pediatric population, there is some disagreement on diagnostic criteria, although delay in diagnosis and treatment may be fatal.

Clinical features of CIRCI are often nonspecific, but may include abdominal pain, mental status changes, hyponatremia, hyperkalemia, neutropenia, eosinophilia, fever, hypoglycemia, and hemodynamic instability with dependence on catecholamine therapy despite control of other potential etiologies.

Diagnostic tests for adrenal insufficiency have several limitations. The adrenocorticotropic hormone (ACTH) stimulation test measures the ability of the adrenal gland to increase production of cortisol in response to ACTH, but it does not test the integrity of the HPA axis, the response to other stressors such as hypotension or hypoglycemia, or the adequacy of stress cortisol concentrations. It may also be poorly reproducible in patients with septic shock. Adult consensus guidelines recommend use of the high-dose ACTH stimulation test (250 μg cosyntropin) rather than the low-dose (1 μg) test due to limited data and poor reproducibility of the latter, as well as the fact that there is no premade pharmacological preparation of the low-dose solution. However, the low-dose (1 μg) test may be more physiologic and has been used in critically ill children with 100% sensitivity and 84% specificity [28]. A diagnostic approach in children can be found in Figure 11.1.

There are six randomized controlled trials regarding use of hydrocortisone for adrenal insufficiency in adults that disagree on whether or not there is a mortality benefit [28]. Significantly less work has been performed in pediatric populations and efficacy data are not well established. However, current pediatric and neonatal septic shock guidelines from the American College of Critical Care Medicine recommend administration of hydrocortisone if the patient is at risk for adrenal insufficiency and remains in shock despite vasopressor infusion [19]. Studies in children with systemic inflammatory response syndrome have shown that vasopressor dosages are reduced within 4 hours of corticosteroid administration in 92% of children with CIRCI [30], and the addition of fludrocortisone to the treatment protocol for patients with septic shock, specifically, is associated with a shorter duration of norepinephrine support [31]. Further studies are needed to determine the best management strategies in the pediatric population.

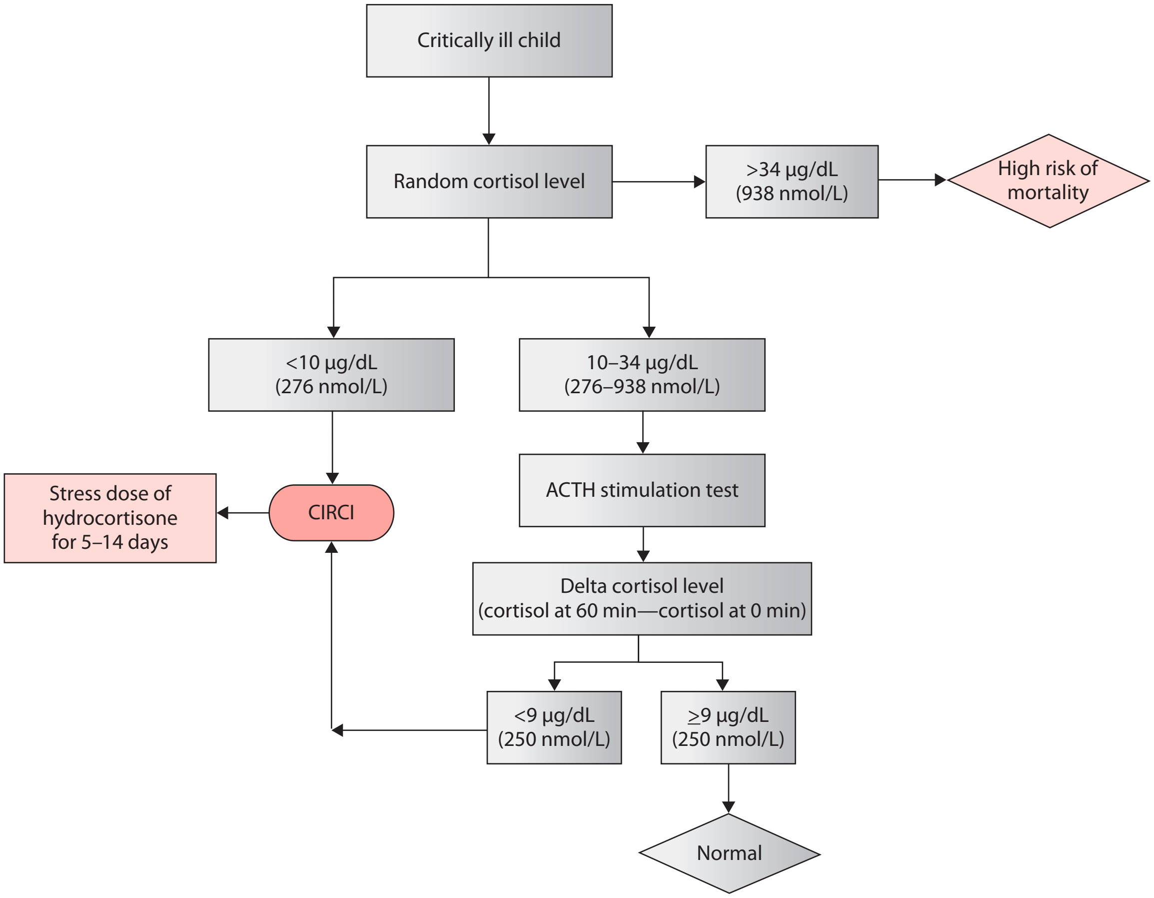

Figure 11.1 Decision tree for the investigation and management of adrenal function in critically ill children. (From Levy-Shraga, Y. and Pinhas-Hamiel, O., *Horm Res Paediatr.*, 80, 309–317, 2013. With permission from Karger Publishers.)

Acute respiratory distress syndrome

Incidence and pathophysiology

Acute lung injury and respiratory insufficiency are common in the pediatric trauma patient and may result from etiologies such as pulmonary contusion, atelectasis, aspiration, infection, acute respiratory distress syndrome (ARDS), and others. The most serious of these, ARDS, occurs in children with an incidence between 2.0 and 12.8 per 100,000 person years. It is observed in 8.3% of all mechanically ventilated children in the pediatric intensive care unit (PICU), and carries with it a mortality of 18%–27% [32,33].

In trauma patients, pulmonary injuries preceding ARDS may be direct (e.g., pulmonary contusion or smoke inhalation) or indirect (e.g., shock and sepsis). These initial injuries lead to ARDS through a common, diffuse inflammatory process. The initiating event appears to be activation of circulating neutrophils that infiltrate the pulmonary capillaries and result in endothelial damage. Enhanced permeability of both the microvasculature and airways leads to accumulation of a protein-rich exudate in the alveoli [34]. Compromised barrier function allows migration of leukocytes, erythrocytes, and platelets into the airspaces, which augment inflammation by secreting pro-inflammatory mediators. This results in a vicious cycle wherein lung damage promotes further inflammation and leads to progressive respiratory insufficiency. Furthermore, fibrin is deposited in the lungs and may result in pulmonary fibrosis. These processes occur rapidly: 29% of those who develop ARDS following trauma do so within 24 hours of injury, and all others meet criteria within 7 days of their initial insult [32].

The end result is decreased pulmonary compliance, increased work of breathing, and worsening oxygenation. Hypoxemia results from impaired oxygen diffusion across the alveoli and ventilation perfusion mismatch. The inflammatory exudate in the lungs collects to a greater extent in dependent portions of the lung. It leads to inactivation of surfactant and consequently contributes to atelectasis and intrapulmonary shunting [34]. The lower pulmonary and chest wall compliance, as well as reduced functional residual capacity, seen in children may also compound alveolar hypoventilation and derecruitment. This may be further complicated by reductions in compliance from chest wall trauma.

Age-related considerations in pathogenesis

There are several pediatric-specific factors and comorbidities that must be considered when managing ARDS. The first is the progression of postnatal lung and immune system development across ages. It is thought that alveolarization adds roughly 250 million alveoli from birth to adulthood, but the process may be almost complete by 18 months of age [32]. Subsequent lung maturation includes a rapid increase in alveolar surface area, slowing of cellular proliferation, decreased mesenchymal and interstitial tissue mass, and changes to the alveolar capillary network. These processes continue until adult height is reached, and along with immune development, are likely to affect age-related incidence of infections, inflammation, and pulmonary apoptotic and repair mechanisms. Data do not suggest a clear dichotomy in terms of incidence or mortality at any particular age, but, certainly, acute hypoxia in the perinatal period from surfactant deficiency or congenital abnormalities should not be treated as ARDS.

Diagnostic criteria

Several of the criteria commonly accepted to define ARDS in adults are translatable to the pediatric population [35], but departures from these measures have been described to better define and risk stratify the disease in children. Criteria for pediatric acute respiratory distress syndrome (PARDS) have been published in consensus guidelines [32] (Figure 11.2). Pediatric-specific guidelines discuss criteria for risk stratification and disease severity that use SaO_2 when PaO_2 is unavailable, that account for the increasing use of noninvasive respiratory support, and that rely heavily on oxygenation index ($OI = [FiO_2 \times \text{mean airway pressure} \times 100]/PaO_2$). The OI is not affected by variability in ventilator management and is predictive of outcomes throughout the disease course. For each tier of severity defined by the OI, PARDS mortality doubles: mortality is roughly 12%, 20%, and 41% for the mild, moderate, and severe groups, respectively.

These guidelines also allow for the diagnosis of ARDS in patients with pediatric pulmonary and cardiac anomalies and address the importance of radiographic findings. Specifically, imaging showing bilateral infiltrates is not necessary for the diagnosis of PARDS. The guidelines do not remove imaging findings all together, though, because they may be helpful in distinguishing hypoxia from causes that do not share the pathophysiology of ARDS (i.e., asthma).

Pulmonary critical care

Noninvasive ventilation

Noninvasive positive pressure ventilation (NPPV) may be used as either a preventive strategy in patients at risk for respiratory failure or as primary therapy. NPPV is an attractive alternative to intubation in children with impending respiratory failure and has an overall prevalence of about 8.5% for use in the treatment of mild PARDS [36]. NPPV supports ventilation by reducing atelectasis, improving oxygenation, and offloading fatigued respiratory muscles, all while preserving the airway and airway clearance mechanisms and avoiding sedation [37]. It also minimizes ventilator-associated complications such as pneumonia and barotrauma. Some centers may additionally employ NPPV to bridge to extubation or to support children following extubation.

Several devices are available for delivery of NPPV to children. Currently available technologies include full-face masks, helmet interfaces, short-prong nasal cannulas,

Age	Exclude patients with perinatal-related lung disease			
Timing	Within 7 days of known clinical insult			
Origin of edema	Respiratory failure not fully explained by cardiac failure or fluid overload			
Chest imaging	Chest imaging findings of new infiltrate(s) consistent with acute pulmonary parenchymal disease			
Oxygenation	**Non-invasive mechanical ventilation**	**Invasive mechanical ventilation**		
	PARDS (no severity stratification)	**Mild**	**Moderate**	**Severe**
	Full face-mask bi-level ventilation or CPAP ≥5 cm H_2O	4 ≤ OI < 8	8 ≤ OI < 16	OI ≥ 16
	PF ratio ≤ 300 SF ratio ≤ 264[1]	5 ≤ OSI < 7.5[1]	7.5 ≤ OSI < 12.3[1]	OSI ≥ 12.3[1]
Special populations				
Cyanotic heart disease	Standard criteria above for age, timing, origin of edema, and chest imaging with an acute deterioration in oxygenation not explained by underlying cardiac disease.[2]			
Chronic lung disease	Standard criteria above for age, timing, and origin of edema with chest imaging consistent with new infiltrate and acute deterioration in oxygenation from baseline which meet oxygenation criteria above.[2]			
Left ventricular dysfunction	Standard criteria for age, timing, and origin of edema with chest imaging changes consistent with new infiltrate and acute deterioration in oxygenation which meet criteria above not explained by left ventricular dysfunction.			

Figure 11.2 Pediatric acute respiratory distress syndrome (PARDS) definitions. [1]Use PaO_2-based metric when available. If PaO_2 is not available, wean FiO_2 to maintain SpO_2 ≤97% to calculate oxygen saturation index (OSI =FiO_2 × mean airway pressure × 100]/SpO_2) or SpO_2:FiO_2 (SF) ratio. [2]Acute respiratory distress syndrome severity groups stratified by oxygenation index (OI; [FiO_2 × mean airway pressure × 100]/PaO_2) or OSI should not be applied to children with chronic lung disease who normally receive invasive mechanical ventilation or children with cyanotic congenital heart disease. CPAP = continuous positive airway pressure, PF = PaO_2:FiO_2. (From Khemani, R.G. et al., *Pediatr Crit Care Med.*, 16, S23–S40, 2015. With permission from Wolters Kluwer Health, Inc.)

intermediate size high-flow nasal cannulas (HFNCs), and RAM nasal cannulas. RAM cannulas have larger diameter tubing than HFNCs and thereby reduce resistance in order to allow transmission of greater pressures. Proper fit of these devices is important, as leaks reduce device efficiency and cause patient discomfort with irritation to the eyes and conjunctivitis [37]. All devices should be used with heated humidification to prevent dryness of the airway epithelium, which can cause inflammation that leads to local edema and subsequent increased airway resistance in already small upper airways.

Common modes of noninvasive ventilation

NPPV may be delivered as either continuous positive airway pressure (CPAP) or bilevel positive airway pressure (BiPAP). CPAP is functionally similar to positive end expiratory pressure (PEEP) except that it is delivered throughout the respiratory cycle. With CPAP, patients initiate all breaths. BiPAP delivers both an inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP). While there are no studies directly comparing the two modalities, several nonrandomized trials in both adults and children support the benefit of BiPAP [37]. By providing additional support during inspiration, it improves oxygenation, ventilation, and pulmonary mechanics. However, CPAP still has a role in children who are unable to attain patient–ventilator synchrony or when use of a nasal interface is preferred.

At present, there is no recommended role for HFNC in the treatment of PARDS [37]. HFNC is thought to improve oxygenation and reduce ventilator dead space by "washing out" nasopharyngeal CO_2. It is also thought to generate a modest degree of positive pressure that works to reduce upper airway resistance and work of breathing; although this is likely lower than that provided by NPPV. Further data are needed to define a role for HFNC in the treatment of PARDS.

Use of NPPV in the treatment of chest trauma

Injuries associated with chest trauma include rib fractures, pneumothorax, hemothorax, flail chest, and pulmonary contusions. These injuries may result in direct parenchymal damage and subsequent inflammatory responses that can lead to pulmonary edema, bronchial secretions, airway colonization, alveolar collapse, impaired alveolar fluid clearance, ventilation perfusion mismatch, lung consolidation, mild hypoxemia, or even ARDS. While there are no good data for use of NPPV for chest trauma in children, a recent meta-analysis of use of NPPV in adult chest trauma found significant reductions in intubation rate, respiratory rate, infection, ICU length of stay, hospital length of stay, and mortality (3% vs. 23%) when compared to standard therapies without increased morbidity [38]. CPAP is recommended for management of pulmonary trauma since data suggest patients benefit most from PEEP and because it carries a lesser risk of barotrauma. Additional studies in children are needed in order to make firm recommendations for management.

Use of NPPV in the treatment of PARDS

If NPPV is to be used in the treatment of PARDS, it should be considered early in the course of the disease, and it should be avoided in children with severe PARDS. Certain populations such as those with immunodeficiency may see an even greater benefit from NPPV since they are at greater risk of complications from mechanical ventilation.

Several prospective and retrospective cohort studies describe the use of NPPV in heterogeneous populations of children with respiratory compromise. In a randomized trial that compared NPPV with standard care for 50 children with acute hypoxic respiratory failure, the authors found that the incidence of intubation was significantly reduced with NPPV (28% vs. 60%, $p = 0.045$), as were children's heart and respiratory rates [46]. When only children with mild PARDS were considered, the median frequency of treatment failure with NPPV was 21%; however, that rate increased to 57% for studies that included children with more severe hypoxemia. Given that children with PARDS can deteriorate quickly, NPPV should only be employed with continuous monitoring and where invasive ventilation is also readily available. Available data suggest that children that either worsen or do not show clinical improvement within 4 hours of starting NPPV are likely to require intubation [37,39].

Contraindications

Contraindications to initiating therapy with NPPV are moderate to severe/life-threatening hypoxemia, upper airway obstruction, vomiting, impairment of the cough or gag reflex, facial trauma or deformity, Glasgow Coma Scale score less than 10, hemodynamic instability requiring inotropes/vasopressors, cyanotic congenital heart disease, cardiac arrhythmias, and intolerance of the delivery device. When therapy with NPPV is failing, early conversion to intubation and mechanical ventilation should be considered.

Indications for mechanical ventilation

Mechanical ventilation may be initiated for both respiratory and nonrespiratory problems in trauma patients in the ICU based on a combination of clinical judgment, signs, and symptoms of distress and laboratory values denoting need for support. Indications include (1) hypoxemic or hypercarbic respiratory failure, (2) optimization of $PaCO_2$, as in traumatic brain injury, (3) the need to decrease afterload and work of breathing, (4) airway protection for patients with altered mental status or coma, and (5) central nervous system or neuromuscular dysfunction.

Ventilator-induced lung injury and lung-protective ventilation

Modern protocols for mechanical ventilation have been constructed to minimize ventilator-induced lung injury (VILI). Ventilation with high tidal volumes (V_Ts) or pressures causes lung hyperinflation that can produce stress fractures at the alveolar–capillary interface (volutrauma and barotrauma, respectively). This has several consequences, including accumulation of alveolar gas in the pulmonary parenchyma, mediastinum, or pleural cavity; inflammatory lung injury; and systemic inflammation [40,41]. Conversely, inadequate PEEP may lead to significant stress in dependent lung regions due to repeated alveolar collapse and re-expansion that generates shear forces that damage airway epithelium (atelectrauma). Factors that predispose to lung injury include structural immaturity of the lung and chest wall, surfactant insufficiency or inactivation, and pre-existing lung disease [41].

Lung-protective ventilation describes a strategy to achieve adequate (not necessarily normal) gas exchange by using low V_T to prevent overdistention of the lung, PEEP to reduce atelectasis, and minimal required FiO_2 to avoid oxidative stress. These practices have largely been extrapolated from studies of adult ICU patients with ARDS [42], although there is also significant interest in the neonatal population where lung-protective strategies have been shown to reduce risk for bronchopulmonary dysplasia and retinopathy of prematurity [43]. In general, V_T should be 6 mL/kg of body weight, PEEP should range between 5 and 12 cm H_2O, and FiO_2 should be maintained at the lowest possible level to keep oxygen saturation between 88% and 94%. Plateau pressure should not exceed 30 cm H_2O; however, higher pressures may be tolerated in patients with chest wall trauma that reduces compliance. Permissive hypercapnia, as appropriate, allows us to maintain low V_T ventilation.

Modes of mechanical ventilation

Conventional modes of ventilation

Conventional modes of ventilation differ in three variables: (1) trigger mechanism, (2) pressure versus volume limits, and (3) respiratory cycle timing. A trigger to deliver a positive pressure breath may be either patient effort or elapsed time, and based on how the breath is initiated, one may elect to use a mandatory mode, a support mode, or a combination of both. Volume control (VC) ventilation is limited by a preset V_T, whereas pressure control (PC) ventilation is limited by a preset peak inspiratory pressure (PIP). VC ventilation has the advantage of complete control over minute ventilation and protection against VILI, but the constant flow pattern may lead to greater patient–ventilator dyssynchrony. PC ventilation is characterized by an exponentially decreasing inspiratory flow in order to keep airway pressure at the preselected value. This results in a lower peak pressure for a given V_T, less turbulent flow at the end of inspiration that could lead to improved lung mechanics and gas exchange [44], better patient comfort and potential for greater synchrony. However, PC ventilation leads to variable inflation volumes with changes to the mechanical properties of the lungs and may inadequately ventilate patients with ARDS. Breaths may be cycled based on time, volume, or flow.

Two of the most commonly used conventional modes of ventilation are assist-control (A/C) and synchronized intermittent mandatory ventilation (SIMV) with or without pressure support (PS). In A/C ventilation, the ventilator delivers a preset rate and V_T but will allow for additional breaths to be delivered (at the same level of support) when the patient initiates inspiration. Importantly, the patient cannot breathe independently of the ventilator, and the respiratory cycle may occur at irregular intervals depending on effort. In SIMV, the ventilator delivers preset breaths in coordination with the respiratory effort. If, however, no effort is detected at an interval determined by the preset rate, then a fully supported, mandatory breath will be delivered. This has the advantage of avoiding potential harm to the patient by delivering a mechanical breath when the patient is in mid- or end-inspiration. Spontaneous breathing is allowed between breaths, and the ventilator may be set to provide anywhere from no support to the same amount of support delivered with the mandatory breaths (depending on the set value for PS). Steps to initiate conventional ventilation are detailed in Table 11.4.

Advanced modes of ventilation

Several advanced modes of ventilation exist and the discussion of all of them is beyond the scope of this chapter. Pressure-regulated volume control ventilation (PRVC, also known as volume control plus [VC+]), is a hybrid mode whereby a preset V_T and frequency is delivered with a pressure limit [45]. An adapting, decelerating flow pattern ensures that the V_T is delivered but allows for breath-to-breath changes in pressure, and breaths may be delivered in either a controlled or synchronized fashion. This allows for reductions in PIPs over VC ventilation alone [46].

Airway pressure release ventilation (APRV) can be thought of as delivering two different levels of CPAP, one "high" and one "low", with a set release time. It maintains a high airway pressure for the majority of the cycle and periodically releases to a set PEEP to allow ventilation. Since a greater amount of time is spent in "inspiration," it is a type of inverse ratio ventilation. APRV allows spontaneous breathing throughout the entire cycle and improves alveolar recruitment by increasing the mean airway pressure. As with any PC mode of ventilation, the patient remains at risk for injurious V_Ts or, conversely, ineffective ventilation if lung compliance changes. While there is not much data

Table 11.4 Steps to initiate conventional ventilation

1. Set the *triggering mechanism* (i.e., mandatory breaths, support breaths, or a combination).
2. Set the *control/limit* for the breaths (i.e., PC, VC, or PRVC [also known as VC+]).
3. Set the FiO_2 to 100% and then decrease to lowest level needed to achieve adequate oxygenation (preferably <60%).
4. Set the *respiratory rate* (RR) normal to the child's age.
    a. For infants and small children: 20–30 breaths/min
    b. For adolescents: 15 breaths/min
5. Set the *inspiratory time* (iT).
    a. For infants and small children: 0.4–0.7 seconds
    b. For adolescents: 0.8–1 second
6. Set *PEEP* to exceed alveolar closing pressures and maintain functional residual capacitya. Start at 4–5 and titrate based on oxygenation requirements.
7. For VC/PRVC, set *tidal volume* (V_T).
    a. V_T should range from 6–10 mL/kg ideal body weight. PIP becomes a dependent variable.
8. For PC, set a *pressure* above PEEP to achieve a desired V_T. PIP becomes equal to PC + PEEP.
    a. Start at 20–24 and titrate based on chest rise and desired V_T (as above).
9. *Adjust ventilation* by controlling minute ventilation (=RR x V_T).
10. *Adjust oxygenation* with FiO_2 or PEEP.
11. Troubleshoot by checking endotracheal tube placement/position; evaluating for airleaks; checking a CXR for intraparenchymal problems, pleural effusion, pneumothorax, and so on; evaluating patient synchrony and sedation level; and evaluating if there a more appropriate ventilation mode versus readiness for extubation. Routine monitoring should include ABGs, continuous $ETCO_2$, and continuous SaO_2.
12. If all else fails, consider permissive hypercapnia or hypoxemia.

ABG, arterial blood gas; PC, pressure control; PEEP, positive end expiratory pressure; PRVC, pressure regulated volume control; RR, respiratory rate; VC, volume control.

to advocate use of this mode over others in the pediatric population [47], there is some evidence that it may prevent the development of ARDS in high-risk adult trauma patients [48].

High-frequency oscillatory ventilation (HFOV) uses respiratory rates between 4 and 250 times the normal rate and small V_Ts in an attempt to optimize gas exchange and prevent lung injury. HFOV may be useful in patients with pneumothorax or air leak syndromes. While there is insufficient evidence to suggest that HFOV reduces mortality in these patient populations when compared to conventional ventilation [49], it has been shown in single-center studies to improve oxygenation and lower rates of barotrauma when implemented early in pediatric burn patients with ARDS [50,51]. A protocol for initiating support with HFOV is detailed in Table 11.5. Of note, under-inflation of the lungs may result in elevated pulmonary vascular resistance and higher oxygen requirements, while over-inflation may lead to hemodynamic compromise, hypotension, and hypoxia secondary to decreased CO.

Adjuncts to mechanical ventilation

Several ancillary treatments have been attempted in the management of ARDS, including prone positioning, inhaled nitric oxide (iNO), corticosteroids, helium–oxygen mixtures, plasminogen activators, fibrinolytics or other anticoagulants, inhaled β-adrenergic receptor agonists or ipratropium, inhaled *N*-acetylcysteine for mobilizing secretions, cough assist devices, and exogenous surfactant in non-neonatal patients. The majority of these treatments lack evidence to support their use, but for some therapies, such as prone positioning and iNO, specific patient populations may derive benefit [52].

Prone positioning is utilized to reduce ventilation perfusion mismatch by redistributing blood flow from unventilated areas of the lung and to recruit previously atelectatic lung areas. The schedule for rotation varies and, unless a specialty rotary bed is utilized, the process may be labor intensive and risk dislodgement of lines and endotracheal tubes. While studies have consistently demonstrated improved oxygenation with prone positioning [52], a randomized trial of patients with acute lung injury (PaO_2/FiO_2 ratio of $\leq$300 mmHg) failed to demonstrate any improvement in ventilator-free days, all-cause mortality, and other outcomes. Despite this, a meta-analysis of 10 adult and pediatric studies examining patients with severe ARDS (PaO_2/FiO_2 ratio of $\leq$ 100 mmHg) demonstrated a decreased mortality with prone positioning (risk ratio = 0.84, 95% CI = 0.74–0.96, $p = 0.01$) [53], and a subsequent randomized controlled trial of adults with severe ARDS (PaO_2/FiO_2 ratio of $\leq$150 mmHg) demonstrated a 50% reduction in all-cause mortality at 28 days (16% vs. 33%, $p < 0.001$) [54]. Although prone positioning cannot be recommended as routine therapy for pediatric ARDS patients, it should be considered in cases of severe ARDS.

iNO acts as a pulmonary arterial vasodilator through its effect on vascular smooth muscle relaxation. It is thought to improve ventilation/perfusion mismatch in ARDS by preferentially vasodilating areas that are adequately ventilated, thereby shunting blood away from poorly ventilated areas. Three randomized controlled trials have been performed to study the use of iNO in pediatric patients with ARDS, and while they demonstrate that iNO improves oxygenation, they do not demonstrate any positive effects on outcomes. In fact, iNO may actually be associated with an increased incidence of renal impairment [55,56]. iNO should still be considered in patients with documented pulmonary

Table 11.5 Steps to initiate high-frequency oscillatory ventilation

1. Set the *mean airway pressure (MAP)*.
    a. The ventilator can calculate this value while in conventional modes, and it should generally be increased by 1–2 when transitioning to HFOV.
2. Set the *amplitude* (*ΔP*).
    a. This value is the degree of oscillation around the MAP and is directly related to CO_2 removal.
    b. Keep the MAP and ΔP within a 1:2 or 1:3 ratio. That means you can calculate a starting ΔP by multiplying the MAP by 2 or 3 with the goal of achieving good chest vibration.
3. Set the *number of cycles/second (Hz)*.
4. Typically, premature infants are set to a Hz of 12–15 and term infants are set to a Hz of 8–10.
5. Obtain a CXR within 30–60 minutes of initiating HFOV. The goal is to have 9–10 rib expansion on chest x-ray. An ABG should also be checked within 1 hour of starting HFOV.
6. MAP and/or FiO_2 may be adjusted to *improve oxygenation* (with little effect on ventilation). After a point, high MAPs may compromise cardiac output and could lead to clinical deterioration. However, if the MAP is decreased too rapidly, it may lead to atelectasis and CO_2 retention.
7. ΔP may be adjusted to *change ventilation* (with little effect on oxygenation). An increase in ΔP will cause a decrease in CO_2 and vice versa.
8. If adjustment of ΔP is unsuccessful, the Hz may be altered. An increase in Hz causes a linear decrease in ventilation with a corresponding increase in CO_2 and vice versa.

ABG, arterial blood gas; MAP, mean airway pressure; HFOV, high-frequency oscillatory ventilation.

hypertension or severe right-ventricular dysfunction, and it may be considered as a rescue therapy from—or as a bridge to—extracorporeal life support (ECLS) [52].

Extracorporeal membrane oxygenation

When patients with respiratory failure following trauma fail to improve with the above modalities, consideration of ECMO is warranted. No strict criteria exist to direct the initiation of ECMO, but several predictors of mortality help guide the decision. The most common index employed today is the oxygenation index (OI = [mean airway pressure × FiO_2 × 100]/postductal PaO_2). An OI ≥ 40–45 is used as an indication for ECMO at most centers, but some advocate for more relaxed criteria of an OI ≥ 25. In general, ECMO should only be considered in patients with a likelihood of meaningful survival. Traditional contraindications include irreversible multisystem organ failure, severe irreversible brain damage, ongoing/uncontrolled hemorrhage, pre-ECMO unwitnessed arrest outside of the medical system, and grade III or greater intracranial hemorrhage. Relative contraindications are based on size, weight, and gestational age, as well as comorbidities.

ECMO may be used to support either pulmonary function (veno-venous, VV) or pulmonary and cardiac function (VA). Advantages of VV ECMO include maintenance of cerebral blood flow velocities and cerebral oxygenation, better CNS protection from thrombotic and air emboli, return of pump-arterial blood to the right side of the heart, elimination of increased afterload secondary to blood return to the aorta, maintenance of normal pulsatile blood flow, and easier weaning. Patients on VA ECMO are susceptible to distal venous engorgement and compartment syndrome poor perfusion of the head and heart due to distance of oxygenated blood from the aortic root, and cardiac stun.

Published experience with ECMO in trauma patients is limited. The Extracorporeal Life Support Organization reports a survival rate of 53%–59% for children with PARDS treated with ECMO, including patients treated following trauma. Several small case series of pediatric trauma patients with respiratory failure following blunt injury, near drowning, and severe burns have been published with good results [57–60], but no large, prospective, or randomized trial exists. Initiation later in the course of disease, greater ventilation requirements before ECLS, and concomitant disease such as sepsis or multisystem organ failure were associated with mortality. Although systemic anticoagulation may increase the risk bleeding, trauma patients with intracranial hemorrhages, solid organ injuries, extremity fractures, and other injuries have been successfully managed with ECMO. Clinical judgment is paramount, as current evidence suggests that judicious use of ECMO to support pediatric trauma patients with respiratory failure can salvage some patients who would otherwise die.

Analgesia, sedation, and delerium

Injured children admitted to the ICU are often in pain, frightened, and anxious. Our goal as intensive care providers is to ensure patient comfort and safety by minimizing pain and anxiety. Suboptimal management can lead to increased morbidity including increased duration of mechanical ventilation, infection, intensive care, and length of hospital stay [61]. Strategies combining frequent and consistent assessment of pain, sedation, anxiety, and mental status with goal-directed therapy in the context of a unit-based protocol using the minimal amount of pharmacologic intervention individualized to address unique patient needs are preferred.

Pain scales and assessment tools across developmental stages and age have been developed, identified, validated, and used to monitor pediatric pain. Traditional short- and long-acting narcotic medications (morphine, hydromophone, fentanyl, methadone) in concert with nonopioid medications such as acetaminophen and nonsteroidal anti-inflammatory agents (ibuprofen, ketorolac) may be implemented in unit-based protocols. Regional anesthetic techniques such as epidural anesthesia for multiple rib fractures and extremity nerve blocks for complex fractures may also be utilized in appropriate patients to complement traditional systemic analgesic pharmacotherapy.

Management of mental status, sedation, and anxiety begins with frequent and consistent assessment using tools such as the State Behavioral Scale and the Richmond Agitation-Sedation Scale, among others, that have been developed, validated, and incorporated into sedation assessment and management protocols [61–63]. Short- and long-acting benzodiazepines are often provided as primary sedation therapy. Protocoled management with scheduled, objective assessments helps minimize morbidity and mortality. Daily sedation interruptions, when appropriate, have been shown to decrease duration of mechanical ventilation. Complementary pharmacologic agents such as alpha-2 agonists (deximatomidine and clonidine), typical (Haldol), and atypical antipsychotics (risperdone, olanzapine, ziprasidone) can also be used, in appropriate patients, for the management of sedation and anxiety [62].

Delirium may be defined as fluctuating global cerebral dysfunction [62]. It is a complex and multifactorial disease that arises when normal brain activity is disrupted during critical illness. Delirium may present in children with unique neuropsychiatric disturbances such as issues with the sleep–wake cycle, disorientation, inattention, purposeless actions, labile affect, inconsolability, and autonomic dysregulation. Presenting symptoms may be confounded by the developmental stage of the child. Injured children have multiple risk factors including traumatic brain injury, systemic inflammatory response syndrome, infection, metabolic and electrolyte disorders, pain, anxiety, and complex pharmacology. The recognition and treatment of delirium is essential to improving morbidity and mortality. Pediatric assessment tools such as the pediatric confusion assessment method for the ICU (pCAM-ICU) and the corneal assessment of pediatric delirium (CAP-D) have been developed and validated [64]. These tools include measures of mental status, inattention, level of consciousness, and disorganized thinking.

Treatment incorporates global and multidisciplinary measures including identifying and treating physiologic and metabolic derangements and organ dysfunction, optimizing pharmacologic interventions, appropriately treating pain, identifying appropriate sedation targets, and maintaining a stable and consistent atmosphere that incorporates family members, caregivers, and child-life specialists.

Acute kidney injury and fluid balance

Acute kidney injury (AKI) has been shown to be present in 10%–18% of pediatric intensive care admissions and is an independent predictor of mortality, increased length of stay, and prolonged ventilation [65–67]. The definition of AKI has evolved from RIFLE criteria (risk, injury, failure, loss, and end-stage) to the acute kidney injury network (AKIN) criteria. The most recent Kidney Disease Improving Global Outcomes guidelines incorporate the AKIN and the pediatric-modified RIFLE criteria into three stages of AKI based on the increase of serum creatinine and urine output. Pediatric trauma patients in the ICU are at risk for several conditions that may predispose to AKI including volume overload, hypovolemia, hemorrhage, anemia, cardiac failure, sepsis, direct blunt or penetrating renal trauma, toxins including rhabdomyolysis and myoglobinemia, contrast agents from diagnostic or interventional imaging studies, other medications including antibiotics, and postrenal obstruction from direct trauma or abdominopelvic hematomas.

Fluid overload (FO) has been recognized to play an important role in the outcome of critically ill children [68]. The relationship of FO and AKI is complex and poorly understood. Critically ill patients with FO receiving renal replacement therapy (RRT) have worse morbidity and mortality [69–71]. FO may contribute to cardiac failure, cerebral edema, pulmonary edema, intestinal edema and ileus, body anasarca edema, intra-abdominal hypertension, and abdominal compartment syndrome.

Management of AKI and FO is similar and begins with a complete assessment of cardiovascular and renal pathophysiology including the physical exam, hemodynamic parameters, urine output, and serum and urine chemistries. Although several pharmacologic prophylactic interventions have been proposed (fluid administration, bicarbonate, diuretics, *n*-acetyl cysteine, "renal-dose" dopamine, etc.), none has been shown to prevent AKI in at risk patients [68]. Prevention of FO by careful assessment of resuscitation volumes and fluid balance is paramount. A comprehensive approach to diagnosis and initial management is advised. Care should be taken to optimize intravascular fluid status and CO to maximize renal perfusion. Particular attention should be paid to the composition and volume of infused fluids. Electrolyte and other metabolic abnormalities (i.e., hyperglycemia) should be identified and corrected. Potential offending pharmacologic agents should be removed when possible or dosed appropriately for diminished renal function. When FO is identified, diuretic therapy may be appropriate. Continuous diuretic infusion may lead to a lower dose, fewer hourly fluctuations, and less electrolyte disturbance [72]. Early diuretic therapy in AKI may be associated with improved outcomes [68]. RRT may be appropriate for patients who fail to respond to diuretic therapy. Some studies suggest that early RRT may improve outcome in patients with AKI and FO [68]. RRT encompasses a broad array of interventions including peritoneal dialysis, intermittent hemodialysis, continuous hemodialysis, and ultrafiltration. Continuous renal replacement strategies (CRRT) may be most advantageous to critically ill patients using a slow and steady approach to removing intravascular volume and electrolytes to avoid hemodynamic fluctuations [71]. Pediatric patients with multiorgan dysfunction may benefit from CRRT [73].

Nutrition

The gastrointestinal epithelium serves as a barrier to infection, and this function is maintained through digestion and uptake of nutrients. Progressive atrophy and disruption of the intestinal mucosa occurs during periods of complete bowel rest and may lead to translocation of enteric pathogens into the systemic circulation. Therefore, enteral nutrition may prevent sepsis from these pathogens in critically ill children and is one of the primary reasons why enteral nutrition is preferred to total parenteral nutrition (TPN) in patients who are unable to eat. This has been validated in a prospective randomized trial of patients with major abdominal trauma, and data have shown that early enteral feeding in PICU patients is feasible, well tolerated, and cost-effective without the risk of aspiration or abdominal distention [74,75]. Typically, a nasojejunal tube is the preferred access for enteral feeding, although bolus feeding through a nasogastric tube is an option. In cases where full enteric feeds are not well tolerated, parenteral nutrition should be instituted to meet the caloric needs of the patients. Trickle tube feeds may still be used in these patients to help maintain gut integrity. Choice of formula, additives, and feeding regimens are beyond the scope of this chapter.

Conclusions

In summary, care of the ICU patient is complex with evolving practice guidelines surrounding management of pediatric trauma patients and ever-improving technologies. The best chance of achieving successful outcomes is through a multidisciplinary approach to care. Adept ICU care is capable of supporting children through major trauma and setting them on the path to recovery.

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12

Nutritional support for the pediatric trauma patient

CRISTINE S. VELAZCO and TOM JAKSIC

Trauma is accompanied by a set of metabolic aberrations that are profound but predictable. Over 80 years ago, Sir David Cuthbertson described the fundamental aspects of this metabolic response to injury in adults [1]. Although the metabolic sequelae of trauma in children qualitatively resemble those of adults, marked quantitative differences exist.

An understanding of the metabolic events that accompany trauma is the first step in nutritional support therapy. An individualized determination of nutrient requirements must be made and an appropriate route of delivery selected. Nutritional support of the injured child should be instituted promptly and be designed to limit the deleterious consequences of structural protein loss while facilitating wound healing and the immune response.

Metabolic response to trauma

During the period immediately following severe injury, aggressive fluid, electrolyte, and blood replacement are often required for survival. This period is termed the "ebb phase" of the metabolic response to trauma and is characterized by a decrease in cardiac output and a reduction in metabolic rate. Once the patient has been adequately resuscitated, the "flow phase" of injury is entered. The metabolic response during the flow phase is summarized in Figure 12.1 and consists of an increase in net muscle protein breakdown and the enhanced movement of amino acids through the circulation. This provides the amino acids needed for the rapid synthesis of proteins for the inflammatory response and tissue repair. Those amino acids not used for protein synthesis are channeled through the liver to create glucose from their carbon skeletons by gluconeogenesis. Glucose requirements are effectively met by this mechanism. In a coupled hepatic process, the amino portions of the amino acids are cleaved and detoxified by the urea cycle. There is a marked rise in the circulation of liver-derived acute-phase proteins (i.e., C-reactive protein, fibrinogen, haptoglobin, alpha-1 antitrypsin, and alpha-1 acid glycoprotein) and a concomitant decrease in liver-derived nutrient transport proteins, such as albumin and retinol-binding protein.

The metabolic response to major trauma is associated with a consistent hormonal and cytokine profile regardless of the specific pattern of injury. Traumatized patients demonstrate a very transient decrease in insulin concentrations followed by a persistent elevation. Despite higher insulin levels, which, in theory, should promote anabolism, accelerated net protein breakdown continues. This may be explained, in part, by the elevated concentrations of the catabolic hormones (glucagon, catecholamines, and cortisol) found during the period of acute injury. Increases in the cytokines, interleukin-6 (IL-6) and tumor necrosis factor, both of which are released by activated macrophages, also occur. IL-6 levels are correlated with increased protein turnover, protein catabolism and the synthesis of acute phase proteins, and increased mortality [2,3]. IL-6 also correlates with severity of injury [4]. The release of IL-2, IL-8, gamma interferon, and many growth factors is also known to augment the immunologic and hormonal response to injury.

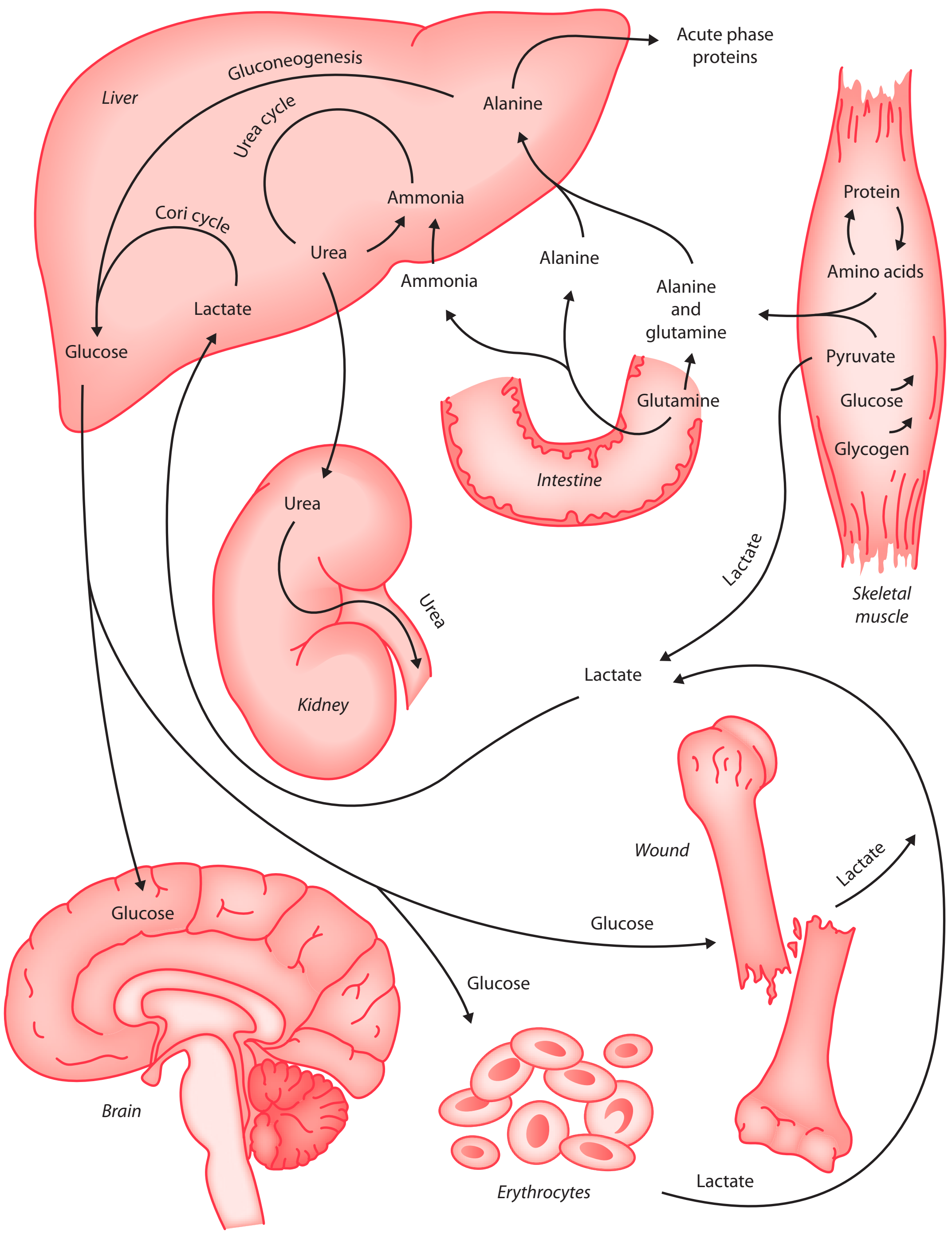

Figure 12.1 Substrate metabolism in patients following major trauma.

The catabolism of skeletal muscle to generate the amino acids needed for wound healing and to produce glucose for energy production is an excellent short-term adaptation in children; however, it cannot be sustained for long periods due to the lack of body protein stores. The progressive loss of skeletal muscle protein leads to respiratory compromise, cardiac dysfunction, increased susceptibility to infection and, ultimately, increased mortality [5]. Hence, minimizing the protein loss associated with trauma is of major clinical importance.

Metabolic reserves

The most striking difference in body composition between the healthy adult and the healthy child is the quantity of protein available at times of injury. As a percentage of body weight, the protein stores of adults are twice those of neonates (Table 12.1) [6–8]. Lipid stores are also decreased in children compared to adults, while carbohydrate reserves are constant across age groups. Not only do neonates and children have reduced stores, but they also have much

Table 12.1 The body composition of neonates, children, and nonobese adults as a percent of total body weight

Age	Protein (%)	Fat (%)	Carbohydrates (%)
Neonates	11	14	0.4
Children (age 10 years)	15	17	0.4
Adults	18	19	0.4

Sources: Forbes, G.B. and Bruining, G.J., *Am J Clin Nutr.* 29, 1359–66, 1976; Fomon, S.J. et al., *Am J Clin Nutr.* 35, 1169–75, 1982; Munro, H.N., *Fed Proc.* 37, 2281–82, 1978.

higher baseline requirements. The resting energy expenditure for neonates is up to three times that for adults, and protein requirements may be 3.5 times the requirement for adults [9]. Thus, critically ill children are more susceptible to the deleterious effects of protracted catabolic stress. The prompt institution of nutritional support, as soon as the patient has been adequately resuscitated, is prudent. In general, any child with significant trauma who will not be eating adequately within 3 days should be considered for nutritional support.

Nutritional needs

Once a decision has been made to commence nutritional support in the injured child, an accurate individualized determination of nutrient requirements is needed. This assessment should include estimates of protein, total energy, carbohydrate, lipid, electrolyte, and micronutrient needs.

Protein requirements

Amino acids are the key building blocks required for growth and tissue repair. The vast majority of amino acids reside in proteins, with the remainder being in the free amino acid pool. Proteins themselves are not static as they are continually degraded and synthesized in a process termed "protein turnover." The reutilization of amino acids released from protein breakdown is extensive. Protein turnover contributes to protein synthesis more than twice the amount of amino acids derived from protein intake. In traumatized children, such as those with severe burn injuries, or in ill children with cardiorespiratory failure requiring extracorporeal membrane oxygenation (ECMO), protein turnover is twice that of normal children [10]. Neonates can lose up to 15% of their lean body mass during a 7-day run of ECMO and may require up to 3 g/kg/day of protein [11]. Generally, in severe illness, amino acids are redistributed away from skeletal muscle to injured tissues, cells involved in the inflammatory response, and the liver. Acutely needed enzymes, serum proteins, and glucose (by way of gluconeogenesis) are thus synthesized. A salient advantage of high-protein turnover is that it allows for the immediate synthesis of proteins needed for the inflammatory response and tissue repair. The process does require energy, hence either an increase in resting energy expenditure or a redistribution of energy normally used for growth is required. Although critically ill children demonstrate both an increase in whole-body protein degradation and whole-body synthesis, it is the former that predominates. Thus, these patients manifest net negative protein balance, which clinically may be noted by weight loss and skeletal muscle wasting.

The catabolism of skeletal muscle to generate glucose is necessary as glucose is the preferred energy source for the brain, red blood cells, and renal medulla. Illness enhances gluconeogenesis in adults, children, and neonates. On a per kilogram body weight basis, gluconeogenesis seems to be particularly elevated in very small children (presumably because of their relatively large brain-to-body-weight ratio) [12]. Interestingly, the provision of dietary glucose is relatively ineffective in quelling endogenous glucose production in the stressed state [13].

Without elimination of the inciting stress for catabolism, the progressive loss of diaphragmatic and intercostal muscle, as well as cardiac muscle, may cause cardiopulmonary failure. Fortunately, amino acid supplementation does improve protein balance. The mechanism for this change in ill patients appears to be an increase in protein synthesis with little change in protein degradation [14].

The amount of protein required to optimally enhance protein accretion is higher in unwell than in healthy children. Infants demonstrate 25% higher protein degradation after surgery, 100% increase in urinary nitrogen excretion with bacterial sepsis, and 100% increase in protein breakdown if they are ill enough to require ECMO [10]. The provision of dietary protein, which is sufficient to optimize protein synthesis, facilitate wound healing and the inflammatory response, and preserve skeletal muscle protein mass, is the single most important nutritional intervention in injured children. The quantity of protein (or amino acid solution) administered in critical illness should be 2–3 g/kg/day for infants up to the age of 1 year and 1.5 g/kg/day for older children. Certain severely stressed states (i.e., severe burn injury) may require additional protein supplementation (2.0–2.5 g/kg/day). Excessive protein administration should be avoided because toxicity, particularly in patients with marginal renal and hepatic function, is possible. Even relatively well neonates fed protein allotments of 6 g/kg/day have developed azotemia, pyrexia, a higher incidence of strabismus, and lower IQ [15,16].

Two important issues regarding the protein metabolism of critically ill children remain to be elucidated. At present, there is no specific recommendation possible regarding any special amino acid composition that may be of specific benefit to severely injured children [17]. The use of enteral glutamine supplementation (with and without other "immune-enhancing" nutrients, such as arginine, omega-3 fatty acids, and nucleotides) has been used in an effort to limit septic complications associated with trauma; however, this approach remains investigational and further larger-scale studies are needed [18–20].

Similarly, quelling the extreme protein catabolism found in children with major injuries utilizing hormonal modulation, particularly insulin administration, is also being actively investigated [21]. Tight glucose control using aggressive insulin therapy has been controversial in adults. Initial prospective studies showed promising results with reducing morbidity and mortality with strict glucose control between 80 and 110 mg/dL [22]. More recent large-scale studies have suggested conventional blood glucose control (180 mg or less per deciliter) results in lower mortality, as well as significantly less-severe hypoglycemia [23]. In the pediatric intensive care unit, tight glycemic control has shown no significant effect on outcomes with higher rates of hypoglycemia seen in the tight glucose control group compared with conventional control [24]. An earlier study showed similar results regarding outcomes, however, without significantly higher rates of hypoglycemia likely due to the use of continuous glucose monitoring [25].

Energy requirements

A careful appraisal of energy requirements in critically ill children is required as both too much and too little energy may have potentially deleterious consequences. Inadequate caloric intake will result in poor protein retention, especially if protein administration is marginal. In contradistinction, the provision of excess glucose calories in critically ill patients results in increased carbon dioxide (CO_2) production rates (hence exacerbating ventilatory failure) and a possible paradoxical increase in net protein degradation [17,26].

The severity and duration of the illness or injury governs the energy needs of critically ill patients. Recent data suggest that energy needs are far less than previously thought for most types of trauma. The resting energy expenditure in the flow phase of injury is increased by 50% in children with severe burns. However, it returns to normal during convalescence though this may be a protracted process in some pediatric patients [27,28]. If illness increases work of breathing, such as in neonates with bronchopulmonary dysplasia, a persistent elevation in energy expenditure up to 25% over expected values is evident [29]. Newborns undergoing major operations have only a transient 20% increase in energy expenditure that returns to baseline levels within 12 hours and remains at baseline unless major complications develop [30,31]. Adequate anesthetic and analgesic management also plays a significant role in muting the stress response, as evidenced by neonates undergoing patent ductus arteriosus (PDA) ligation who do not manifest any discernable increase in resting energy expenditure postoperatively with fentanyl anesthesia and subsequent intravenous analgesia [32]. Adult intensive-care unit patients also do not have an elevation of resting energy expenditure over expected values [33]. Head injury produces a variable elevation in resting energy expenditure, presumably due to a marked rise in circulating catecholamines. Again patients who are sedated, in phenobarbitol coma, or have been given neuromuscular relaxants manifest no such elevation in energy expenditure [34].

Total energy requirements include resting energy expenditure, energy needed for physical activity, and diet-induced thermogenesis. Resting energy expenditure itself includes the caloric requirement for growth. Although critically ill children have increased protein turnover, their growth is often halted during extreme physiologic stress. Additionally, levels of physical activity are typically low following severe injury. The mean energy expenditures of critically ill neonates on ECMO were found to be nearly identical to age- and diet-matched, nonstressed controls [35]. The critically ill cohort did, however, have a greater variability in energy expenditure [35]. Further, a surfeit of calories in critically ill neonates does not necessarily result in improved protein accretion [17]. Thus, for practical purposes the recommended dietary caloric intake for healthy children affords a reasonable starting point for critically injured patients [36]. Table 12.2 outlines safe caloric provisions for injured children at various ages. Enterally fed, traumatized children, as a rule, require a further 10% increment in calories due to obligate malabsorption. In any injured child with protracted illness the actual measurement of resting energy expenditure, by portable indirect calorimetry, is advised due to the high interindividual variability in energy expenditure. Predictive equations used in conjunction with stress factors to account for degree of illness have been shown to be inaccurate in determining individual energy expenditures in intensive-care unit patients and are not recommended [33].

Once protein needs have been met, both carbohydrate and lipid energy sources have similar beneficial effects on net protein synthesis in ill patients [37]. A rational partitioning of these energy-yielding substrates is predicated upon the knowledge of carbohydrate and lipid utilization in trauma.

Table 12.2 Estimated energy requirements for neonates, children, and nonobese adolescents

Age (year)	Estimated energy requirement (kcal/kg/day)
0–4	100
4–6	90
6–8	80
8–10	70
10–12	60
12–18	50

Carbohydrate requirements

Glucose production and availability is a priority in ill children. Injured and septic adults have a threefold increase in glucose turnover and oxidation and an elevation in gluconeogenesis [38,39]. An important feature of the metabolic stress response is that the provision of dietary glucose does not halt gluconeogenesis; consequently, the catabolism of muscle proteins continues [13]. It is clear, however, that a combination of glucose and amino acids effectively improves protein balance in illness primarily by augmenting protein synthesis [40].

In early nutritional support regimens for surgical patients, glucose and amino acid formulations with minimal lipid (the minimum needed to obviate fatty acid deficiency) were often utilized. Energy allotments well over normal dietary requirements were also often given. The excess glucose was converted to fat, resulting in a net generation of CO_2. The synthesis of fat from glucose has a respiratory quotient (RQ), defined as the ratio of CO_2 produced to O_2 consumed, of about 8.7. In clinical situations, this high RQ is not attained, as glucose is never purely used for fatty acid synthesis. Nonetheless, the provision of excess glucose results in an elevated RQ increasing CO_2 production and the ventilatory burden for the child. The mean RQ in postsurgical neonates fed a high glucose diet is approximately 1.0, while comparable neonates fed with less glucose, and lipids at 4.0 g/kg/day, have an RQ of 0.83 [37]. In contrast to glucose metabolism, excess lipids are merely stored as triglycerides and do not result in an augmentation of CO_2 production. Utilizing high glucose total parenteral nutrition (PN), hypermetabolic adult patients fed excess caloric allotments have a 30% increase in CO_2 consumption, a 57% rise in CO_2 production, and 71% elevation in minute ventilation [26]. Thus, avoidance of overfeeding and the utilization of a mixed fuel system of nutrition employing both glucose and lipids to yield energy is theoretically and practically useful in stressed patients, many of whom also have respiratory failure. Such an approach also often obviates problems with hyperglycemia in the relatively insulin-resistant ill child.

Lipid requirements

Lipid metabolism, like protein and carbohydrate metabolism, is generally accelerated by illness and trauma [41]. Initially, during the brief ebb phase following trauma or in early septic shock, lipid utilization is compromised, and triglyceride levels rise as the metabolism of intravenously administered lipids falls. In the flow phase of the injury response, adult patients demonstrate lipid turnover rates that are two- to fourfold higher than comparable controls and proportionate to the degree of injury [41,42]. The increased lipid turnover after injury involves the cycling of free fatty acids and glycerol into the synthesis and hydrolysis of triglycerides. Both metabolic processes result in a stream of substrates through the plasma pool that may be reflected in a modest elevation in the resting metabolic rate. Approximately 30%–40% of the released fatty acids are oxidized for energy, which results in RQ values postinjury in the vicinity of 0.8. This suggests that free fatty acids are, in fact, the prime source of energy in trauma patients. When subjected to uncomplicated abdominal surgery, infants and children have a reduction in RQ and a decline in plasma triglycerides, implying an increased oxidation of free fatty acids [43]. The glycerol, released along with the free fatty acids from triglycerides, may be converted to pyruvate that is then utilized as a glucose precursor. As with other catabolic processes in illness and trauma, the provision of dietary glucose does not decrease glycerol clearance nor diminish lipid recycling.

Normal ketone body metabolism is markedly altered by severe injury. Acetyl coenzyme A (CoA) is the product of incomplete fatty acid and pyruvate oxidation, which through a condensation reaction within the hepatocyte forms the ketone bodies acetoacetate and *B*-hydroxybutyrate. In starved healthy subjects, a major adaptation to preserve skeletal muscle mass is the use of ketone bodies generated by the liver as an energy source for the brain (which cannot directly oxidize free fatty acids); however, in the 3-day period that follows a trauma, there is a negligible elevation in serum ketone body levels when compared to healthy fasting subjects [44]. This observation may be understood in light of serum insulin levels, as ketogenesis is inhibited by even low concentrations of the hormone, a phenomenon evident to physicians in the absence of ketotic problems in type II diabetes. Hence, the high insulin concentrations seen in severe injury ablate the ketotic adaptation to starvation.

The energy needs of the injured patient are met largely by the mobilization and oxidation of free fatty acids; however, ill children have limited lipid stores. Thus, they may evolve biochemical essential fatty acid deficiency within one week if administered a fat-free diet [45,46]. In infants, linoleic acid and linolenic acid are considered essential, with arachidonic acid and docosahexaenoic acid possibly conditionally essential. When there is a lack of dietary linoleic acid, the formation of arachidonic acid (a tetraene) by desaturation and chain elongation cannot occur; the same pathway entrains available oleic acid to form 5,8,11-eicosatrienoic acid (a triene). A triene-to-tetraene ratio of greater than 0.05 suggests mild essential fatty acid deficiency, greater than 0.20 defines moderate essential fatty acid deficiency. Typically essential fatty acid deficiency is not clinically apparent until the triene-to-tetraene ratio is greater than 0.4 with severe deficiency [47–49]. The clinical syndrome consists of dermatitis, alopecia, thrombocytopenia, susceptibility to bacterial infection, and failure to thrive [45,46]. To obviate essential fatty acid deficiency in injured children, a sufficient allotment of linoleic acid and linolenic acid is recommended.

The parenteral provision of commercially available lipid solutions to traumatized children prevents essential fatty acid deficiency and results in improved protein utilization without significantly increasing carbon dioxide production or metabolic rate [50]. These advantages are balanced by some potential risks of excess administration: hypertriglyceridemia, increased infections, and decreased alveolar oxygen diffusion capacity [40–42,51–53]. Although the evidence is far from conclusive, the possible adverse effects of lipid administration have resulted in most centers starting lipid supplementation in ill children at 0.5 gm/kg/day, and advancing over a period of days to 2–3 g/kg/day, while closely monitoring triglyceride levels. Lipid administration is usually restricted to a maximum of 30%–40% of total calories, although this practice has not been validated by clinical trials. As a result of long-term PN, cholestasis and PN-associated liver disease can develop, leading to cirrhosis and liver failure [54,55]. Patients with PN-associated liver disease may benefit from an even lower dose of soy or fish oil–based lipid formulas [47,56–59].

Electrolyte requirements

Electrolyte requirements (Na^+, K^+, Cl^-, HCO_3^-, Ca^{2+}) must be evaluated frequently in the critically injured patient. Simultaneous serum and urine electrolyte determinations often yield information regarding the renal conservation of particular salts. In addition to routine electrolyte monitoring, careful attention to phosphate and magnesium levels is needed, as hypophosphatemia may lead to thrombocytopenia and respiratory muscle dysfunction, while magnesium deficiency can cause cardiac arrhythmias. Renal failure will result in the retention of phosphate, so nutritional allotments must be reduced accordingly. Frequently, head injured patients have an iatrogenically induced respiratory alkalosis. If a metabolic alkalosis is also present due to active diuresis or gastric suction, Cl administration should be used to correct the alkalosis. Alkalemia tends to inhibit respiratory effort, drive potassium into cells, and decrease ionized calcium by increasing the affinity of albumin for calcium. Metabolic acidosis is sometimes present in traumatized children with hypotension or ischemic injuries. The provision of acetate instead of Cl in the PN solution may combat this metabolic problem. The provision of excess acetate at 1 meq/kg over 24 hours is usually a safe adjunct to other measures to limit metabolic acidosis.

Vitamin and trace mineral requirements

Vitamin and trace mineral metabolism in injured pediatric patients has not been well studied. For the neonate and child, the fat-soluble vitamins A, D, E, and K, as well as the water-soluble vitamins ascorbic acid, thiamine, riboflavin, pyridoxine, niacin, pantothenate, biotin, folate, and vitamin B_{12}, are all required and are routinely administered. Since vitamins are not stoichiometrically consumed in biochemical reactions but rather act as catalysts, the administration of large supplements of vitamins in stressed states is not logical.

The trace minerals that are required for normal development are zinc, iron, copper, selenium, manganese, iodide, molybdenum, and chromium. Trace minerals are usually used in the synthesis of the active sites of a ubiquitous and extraordinarily important class of enzymes called metalloenzymes. Like vitamins, metalloenzymes act as catalysts. Hence, unless there are excessive losses such as enhanced zinc loss with severe diarrhea, large nutritional requirements would not be anticipated in illness. The vitamin and trace mineral needs of healthy children and neonates are well defined in the literature [36]. These requirements have been used in traumatized patients, and little evidence exists that they are nutritionally inadequate. In children with severe hepatic failure, copper and manganese accumulation occurs; thus, parenteral trace mineral supplementation should be limited to once per week.

The pharmacologic use of vitamins and trace minerals in pediatric illness is controversial. Reviews of both vitamin and trace mineral toxicity clearly demonstrate that excessive dosage is a health risk [60,61].

Routes of nutrient provision

In the traumatized child, the enteral route of nutrient provision is preferable to the parenteral route whenever the gastrointestinal tract is functional. Enteral nutrition is physiologic, safer, and cheaper [62]. If there is a concern regarding aspiration, the use of postpyloric feeding tubes placed at the bedside or by interventional radiology is a very useful adjunct to the nutritional management of the injured child. Continuous feedings using standard 1 kcal/mL formulas can adequately nourish the majority of patients. Carefully controlling the enteral infusion rate and avoiding bolus feeding until tolerance is established usually obviate diarrhea. If diarrhea persists, stool cultures are sent for routine pathogens and *Clostridium difficile* toxin. At the time of extubation, feeds are held for a period of 6–12 hours. It is also our policy not to feed patients enterally who are hypotensive or have evidence of bowel obstruction in order to limit the risk of spontaneous small bowel necrosis associated with rapid enteral feeding [63].

If the gastrointestinal tract is not functional, and PN is necessary, central venous access is sought so that concentrated solutions that obviate fluid overload can be safely administered. Central access may be obtained using percutaneously placed intravenous lines that are threaded centrally (peripherally inserted central catheters) or by directly accessing major veins via Seldinger technique or cut down [64]. Groin lines are not favored for nutritional therapy because of their propensity for infection. Once gastrointestinal activity has been reestablished, the patient can usually be converted to enteral nutrition within a 2- to 3-day time period.

A protocolized approach to feeding leads to early nutrition and can reduce prevalence of acquired infections [65]. It is important to focus on the delivery of prescribed enteral nutrition. Barriers to enteral nutrition intake, such as fluid restriction, gastrointestinal intolerance, and interruptions of feeds for procedures, can lead to inadequate nutrition in critically ill children [66]. Duration of interruptions is a predicator for inadequate delivery [67]. Additionally, enteral nutrition intake is associated with lower mortality than with PN.

SUMMARY

Injured children are particularly susceptible to the loss of lean body mass and its attendant increased morbidity and mortality. Critical illness results in increased protein, carbohydrate, and lipid utilization and net negative protein balance. The judicious administration of carbohydrates, lipids, vitamins, trace minerals, and particularly protein, preferably through an enteral route, can optimize wound healing and reduce or even eliminate the consequences of this catabolic response.

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13

Pediatric vascular trauma

LUCYNA CIECIURA and JAYER CHUNG

Introduction

It is estimated that vascular injuries occur in 0.6%–1% of pediatric trauma patients [1]. The contribution of vascular trauma to death and disability is not known. In contrast to adult vascular injuries, minimal established evidence for the management of pediatric vascular injury exists. The majority of information available is based on case reports and small retrospective case series.

The overall prevalence of blunt to penetrating vascular injury is higher in children than in adults. While the reported incidence of blunt vascular injuries in children is 28%–35% [2,3], in adults only 6.8% of 5760 cardiovascular injuries were due to blunt trauma in a 30-year series [4]. Penetrating vascular injuries are more common in adults, likely due to the higher incidence of firearm injuries. In a retrospective review of the National Trauma Databank from 2001 to 2006, Barmparas et al. reported that the most common vascular injuries in adults were penetrating chest and abdominal vascular injuries, whereas upper extremity vascular injuries (both blunt and penetrating) were the most common in pediatric patients [5]. A detailed distribution of pediatric vascular trauma using data by Barmparas and Klinkner can be seen in Figure 13.1. The four most common mechanisms of injury for both children and adults who sustained vascular injuries were motor vehicle collisions, gun-related injuries, stab wounds, and falls. Children were noted to have a lower mean Injury Severity Score than adults (16.8 versus 26.3). Children spent a shorter time in the intensive-care unit and the hospital, likely related to their decreased injury burden. Barmparas et al. demonstrated no significant difference in the amputation rates between children and adults. Furthermore, the overall mortality was lower in the pediatric population than in the adult population (13.2% versus 23.2%).

Much of the available data regarding pediatric trauma are derived from wartime experiences, particularly from Iraq and Afghanistan. The U.S. military medical forces provide care to all individuals regardless of nationality or age. As a result, the U.S. military hospitals cared for over 6000 children from 2002 to 2012 [6]. In a retrospective review by Villamaria et al. [6], the incidence of vascular injury in the pediatric population during the aforementioned time span was 3.5%. Among all injury patterns in children, penetrating injury to the torso was the most lethal, with a fourfold risk of death. When there are concomitant arterial and venous injuries, Dua et al. recommended the repair of

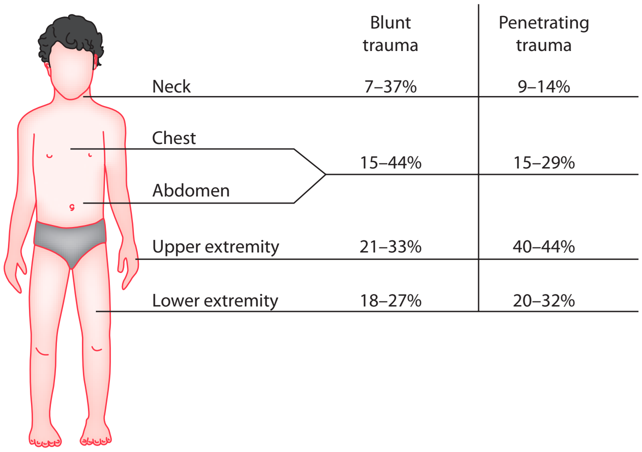

Figure 13.1 Distribution of pediatric vascular trauma as derived from civilian series stratified by mechanism of injury and anatomic region.

venous injuries if time permits, as this facilitates arterial repair patency and prevents postoperative compartment syndrome [7].

Special considerations of vascular injuries in pediatric patients

Diagnosis of vascular injury in children is technically more difficult than in adults. Pediatric vessels are significantly smaller than those of the adult population. Furthermore, injury to pediatric vessels results in a pronounced vasospasm, so it can be difficult to assess whether there is an injury that requires repair [8,9]. The incidence of vasospasm in peripheral arterial injuries has been reported to be as high as 26% in pediatric patients [10]. In theory, arterial spasm resolves within 4–6 hours after injury [11]. Nontraumatic acute limb ischemia due to vasospasm in neonates is generally treated conservatively through the use of heparin anticoagulation and/or systemic thrombolytic therapy. Unfortunately, the use of anticoagulants is often contraindicated in the setting of trauma.

Diagnostic modalities

"Soft" and "hard" signs of vascular injury aid the clinician in determining which injuries require emergent operative repair versus those that require further evaluation with imaging [12]. "Hard" signs are less frequent and include hemorrhage, rapidly expanding hematoma, loss of peripheral pulses, and a palpable thrill or audible bruit. These patients require operative exploration and repair, usually without imaging. "Soft" signs predict an occult arterial injury in up to 25% of adults and benefit from more thorough evaluation and imaging. These include a nonpulsatile hematoma, decreased pulses or pressure index, neurological deficit, unexplained anemia or hypotension, and injury in close proximity to major vascular structures.

When there are Doppler signals and no obvious signs of a vascular injury, the ankle-brachial index (ABI) can be used to assess and monitor the extent of vascular injury in the extremity [13]. The measurement of ABI can also be referred to as the injured extremity index (IEI). A systolic blood pressure is measured over the brachial, tibialis posterior, and dorsalis pedis arteries. The blood pressure cuff is placed distal to the site of injury. If the brachial artery is affected, the higher value of the radial or ulnar artery may be used. It is of paramount importance that the proper sized blood pressure cuff is utilized when performing these measurements. The cuff must be long enough to gently encircle the entire arm and wide enough to cover 75% of the length of the upper arm. The same cuff is then used above the malleoli at the ankle. The higher value between the tibialis posterior and the dorsalis pedis is taken for each ankle. This value is then divided by the higher of the two brachial pressures (Figure 13.2). Because it relies on the comparison of two extremities, only one extremity can be affected. In adults and older children, a normal ABI (>0.9) can reliably rule out a vascular injury with a 100% specificity in excluding lower extremity arterial injury [14]. Most surgeons recommend observing these patients and repeating a delayed ABI to ensure that there has not been a delayed change from an acute thrombus or a pseudoaneurysm due to injury. Alternatively patients with abnormal ABIs may undergo further evaluation with other imaging modalities.

According to Katz et al. [13], normal ABI values of newborns, infants, and toddlers are lower than those of older children and adults. Normal ABI for patients 2 years of age or younger is 0.88 ± 0.11. This is likely related to the alteration of blood flow to the lower extremity during ambulation. In addition, it can be technically challenging to obtain an accurate ABI in younger children, due to the pain of inflating the blood pressure cuff on the injured extremity. ABIs should therefore be interpreted with the understanding that a slightly lower ABI may, in fact, be falsely lower.

Should the patient continue to have diminished circulation following resuscitation, or if the ABI is unreliable and vascular injury is suspected, further localizing studies are warranted such as a computed tomography (CT) scan, CT angiography (CTA), and angiography. Radiation exposure is cumulative in the pediatric population [15]. The risks per unit effective dose associated with radiation are higher during childhood than later in life. In addition, the pediatric patient absorbs 3–10-fold more radiation than an adult patient [15,16]. While CT scans can provide vital information, selective scanning is vital when caring for the pediatric population. In order to avoid unnecessary CT scans, screening guidelines including X-ray and ultrasound are now being explored. For example, the CT scan is excellent at diagnosing aortic injury [17]. Yet a normal chest X-ray (CXR) can also rule out aortic injury, making the argument that a CT scan is unnecessary in a high-speed deceleration injury with a normal CXR.

Conventional angiography is the gold standard diagnostic modality for vascular injury, but it is invasive and has

$$\frac{\text{Highest ankle pressure (either the dosalis pedis or posterior tibial)}}{\text{Highest brachial artery pressure}} = \text{Ankle Brachial Index (ABI)}$$

Figure 13.2 Formula for the ankle-brachial index.

higher morbidity in younger children, as discussed in the next section, *Endovascular technologies in children*. Recent studies have demonstrated that CTA has the same 100% sensitivity and specificity as angiography, making it an acceptable alternative to conventional angiography [18,19]. CTA is noninvasive, fast, and reproducible. It allows for one to evaluate nearby structures in three dimensions [20]. The radiation associated with a CTA is approximately 3–6 mSv [8]. Many pediatric hospitals have imaging services utilizing dose reduction technology resulting in radiation exposure of 1–3 mSv per CTA. Unfortunately, children may have difficulty with breath-holding, which is required for optimal image acquisition. Moreover, iodinated contrast is contraindicated in the setting of renal insufficiency.

While it avoids radiation and contrast exposure, magnetic resonance imaging (MRI) necessitates longer scan time, need for sedation, and has decreased availability, making it a less acceptable option for acute trauma patients. Furthermore, magnetic resonance angiography is not recommended in children with renal failure as it can cause potentially fatal nephrogenic systemic fibrosis [21].

Endovascular technologies in children

Limited use of angiography is endorsed to prevent iatrogenic arterial injury. Angiography is recommended when injury is questionable or when it is necessary for surgical planning [22]. While the mainstay of contrast is iodine based, carbon dioxide may also be used. Low-osmolar contrast measuring 300–350 mg iodine per milliliter is used during pediatric angiography [19,21]. Neonates should receive no more than 4–5 mL/kg of contrast, whereas children should not exceed 6–8 mL/kg. Adult injection parameters may be used for children weighing more than 50 kg. The injection parameters for children less than 50 kg should be half of those for the adult. For patients weighing less than 15 kg, hand injection of contrast is highly recommended in order to prevent exceeding the maximum dose. Following successful arterial access, 75–100 U/kg of intravenous heparin is recommended for children weighing less than 15 kg in order to prevent femoral artery thrombosis. Reversal of systemic anticoagulation with intravenous protamine sulfate is rarely needed [21]. Nitroglycerin can be administered intra-arterially at 1–2 µg/kg prior to crossing an area of stenosis or before an intervention to prevent arterial spasm. Relative contraindications to contrast angiography include contrast allergy, coagulopathy, severe congestive heart failure, renal failure, homocystinuria, pheochromocytoma, and active vasculitis. In individuals allergic to iodinated contrast material, carbon dioxide can be used. The use of carbon dioxide angiography is limited to below the diaphragm. The gas undergoes a first-pass excretion in the lungs. There is no maximum dose in children. The gas will displace blood and allow the vessel to be imaged. Hand injection is recommended. Intravenous glucagon can be used during both contrast and carbon dioxide angiography to decrease subtraction artifact caused by peristalsis. The utility of carbon dioxide in trauma is unknown. Given the invasiveness of angiography, Fayiga et al. recommend operative exploration without preoperative angiography when arterial injury is suspected in children less than 5 years of age [2]. Pediatric vessels are more superficial and straight than adult vessels [21]. Their small vessel size places them at an increased risk of vessel injury during angiography [2,7].

Although conventional open surgical repair is the standard of treatment for most vascular injuries, the use of endovascular techniques has gained increasing popularity. The incidence of endovascular intervention for arterial trauma in the adult setting increased from 2.4% to 8.1% between 2000 and 2003 according to the National Trauma Databank [23]. Interestingly, an equal proportion of blunt and penetrating injury was present. Furthermore, the use of stents increased from 12 in 2000 to 30 in 2003. Reuben et al. [23] reported that patients undergoing endovascular repair were more stable on presentation and their number of associated injuries was less than patients undergoing open repair. Overall, patients undergoing endovascular repair had shorter length of stay and improved survival. Of note, patients with torso arterial injury treated endovascularly had a 50% reduction in death relative to those treated with open techniques. An endovascular approach can not only facilitate the diagnosis and treatment of a vascular injury but also temporize patients, serving as a bridge to future elective procedures in the critically ill patient. One of the earliest uses of an endograft in vascular trauma was described by Parodi et al. in 1992 [24]. An adult patient sustained a gunshot wound that ultimately resulted in a high output subclavian arteriovenous fistula. Treatment was performed under local anesthesia via right brachial access with placement of a custom-made covered Palmaz stent. Conceivably, any vessel injury could be treated endovascularly, especially if one includes balloon occlusion. Currently, the use of endovascular technologies is limited by available device sizes and local expertise.

Ultrasound-assisted arterial access lessens puncture-site complications by decreasing the number of access attempts [21]. Surgical access may be necessary particularly when larger devices are used. Of note, the umbilical artery can accommodate a larger catheter and spares peripheral access-site complications. The umbilical artery is patent and can be used as an access site up to 5 days after birth. Should the umbilical artery not be accessible, infrainguinal vascular access is recommended. Failed attempts at arterial access require pressure. Small gauge needles require 1–2 minutes of direct pressure while large gauged needles may require 5 minutes. Catheter size is determined by weight [25]. Three-French catheters are recommended for patients less than 10 kg, while 4-French catheters are recommended for children over 10 kg [21]. The formation of a thrombus following arteriography is multifactorial. Children <15 kg are at significantly higher risk of thrombosis formation. One contributing factor is vascular spasm. Vascular spasm is caused by smooth muscle contraction in the artery's media secondary to trauma or intimal damage. The predominant variable influencing vasospasm and subsequent thrombosis is catheter size. Relative catheter-to-artery size is most strongly related to vasospasm. As a result, it is of utmost importance that the smallest catheter possible should be used. If arterial thrombosis occurs, the affected limb is to be kept warm. If distal pulses do not return, systemic heparinization is recommended for at least 24 hours. Fortunately, children can form extensive collateral networks and the risk of claudication or limb discrepancy is less than 10% in patients with persistent asymptomatic common femoral artery occlusion. Contra-indications to endovascular treatment for arterial trauma include uncontrolled hemorrhage, critical limb ischemia, excessive luminal discrepancy, and inability to traverse the lesion with a wire [26]. There are limited data regarding the use of access closure devices for pediatric arteriography, with the authors avoiding closure devices. If the arteriotomy cannot be closed with pressure alone, then it is the authors' preference to perform an open exposure with direct repair of the arteriotomy.

Children are at higher risk than adults for procedure- and systemic-related complications for arteriography (7%–10% versus 1%) [21]. Puncture-site complications include hematoma formation, dissection, thrombosis, occlusion, and arteriovenous fistula formation. The risk of thrombosis formation is estimated between 8% and 16%. Low groin vascular access is a risk factor for arteriovenous fistula formation as the risk of accessing both the artery and vein is increased lower in the leg. The risk of arteriovenous fistula and pseudoaneurysm formation is approximately 0.3% in the pediatric population. Systemic complications of endovascular therapy include need for sedation or general anesthesia, hypothermia, and hypoglycemia. While endovascular therapy has many advantages, many implants, particularly endografts, require ongoing surveillance for complications. Endografts can migrate or develop endoleaks. While the most common cause of pseudoaneurysm formation is traumatic, other causes include infection and stent fracture [23,27]. Long-term durability and in-stent stenosis are unknown.

Similarly to adults, children can have different reaction to contrast material including allergic reaction and contrast-induced nephropathy. The risk of allergic reactions to contrast material in children is less common than in adults [21]. The incidence of contrast allergy in children is estimated at 0.18%. Children with asthma are five times more likely to have an allergic reaction. Reactions are dose independent, unpredictable, and include pruritus, angioedema, bronchospasm, and shock. Consequently, there is no benefit to administering a test dose. The risk of contrast-induced nephropathy in children ranges between 7% and 25%. Risk factors include decreased effective arterial volume, congestive heart failure, diabetes, nephrotic syndrome, and cirrhosis. The risk of contrast-induced nephropathy can be significantly decreased by using low-osmolar contrast medium. Preprocedural hydration is important. At the authors' institution, sodium bicarbonate infusions are performed, extrapolating weight-based infusions from adult experiences.

Vascular anastomoses

As mentioned previously, children have small vessels and are prone to vasospasm. The use of intra-arterial dilators such as papaverine and nitroglycerin may be helpful [7,22]. Papaverine can be injected into the adventitia or applied topically. At the time of injury, most children have not reached their maximal growth potential. This, therefore, adds an additional level of complexity for the surgeon. While many techniques have been described, the most recommended method of repair involves generous spatulation of anastomosis and the use of an interrupted nonabsorbable 6-0 to 8-0 monofilament suture [3,28]. Continuous repair leads to vessel narrowing over time [7]. Systemic heparinization (100 U/kg) should be used when not contraindicated by concomitant injuries [3].

Anticoagulation

Aspirin, unfractionated heparin, low-molecular-weight heparin, and warfarin remain the most common medications used for anticoagulation in the vascular patient. Aspirin or acetyl-salicylic acid irreversibly binds to and inhibits cyclooxygenase (COX), preventing the formation of prostaglandins, thromboxane, and prostacyclins from arachidonic acid [29]. Aspirin preferentially inhibits COX-1 over COX-2. Its effects last 8–10 days, the lifespan of a platelet. There is a significant interindividual variation in the dose of heparin [30]. The optimal dose of aspirin in children is not known. The clearance of aspirin in neonates is slower, putting them at higher risk of bleeding. Of note, patients with a viral syndrome treated with aspirin are at an increased risk of Reye syndrome, a lethal syndrome of encephalopathy and liver degeneration. There is a dose-dependent association between aspirin and the likelihood of developing Reye syndrome, usually >40 mg/kg. The current recommended dose for children is 1–5 mg/kg/day [30].

Unfractionated heparin and low-molecular-weight heparin are indirect thrombin inhibitors. Heparin is a mixture of sulfates mucopolysaccharides [29]. Heparin binds to antithrombin, resulting in a conformational change exposing its active site. This allows for more rapid interaction and subsequent inhibition of clotting factors, such as thrombin (IIa), IXa, and Xa. Unfractionated heparin is the first-line intervention to treat arterial and venous thrombosis in the pediatric population [31]. Age-dependent reference ranges are available for antithrombin, tissue factor pathways inhibitor, thrombin, and factor X to assist with monitoring heparin dosing. According to the Seventh American College of Chest Physicians Conference on Antithrombotic and Thrombolytic Therapy, the plasma of neonates has decreased thrombin when compared with adults. Furthermore, the proportion of thrombin in the plasma of a neonate is similar to that of an anticoagulated adult. Over time the level of thrombin increases. Children, however, have 25% less thrombin than do adults [30]. Reported rate of bleeding from heparin use in the pediatric population is 1.5%. Only three cases of heparin-induced osteoporosis are reported in the literature. Therapeutic heparinization when indicated should be titrated to a target anti-Xa activity range of 0.35–0.70 units/mL [30]. Pediatric heparin-induced thrombocytopenia is also described. The anticoagulant action of heparin can be reversed by protamine sulfate, a basic peptide that combines with heparin and leaves it inactive [29]. One milligram of protamine sulfate is necessary for every 100 U of heparin remaining in the patient. The rate of infusion of protamine sulfate should not exceed 50 mg in 10 minutes.

Low-molecularweigh the parins(LMWHs) include enoxaparin, dalteparin, and tinzaparin. Both unfractionated and low-molecular-weight heparin inhibit factor Xa [29]. Low-molecular-weight heparins have less of an affinity for thrombin. The predictability of weight-adjusted LMWH dosing on anticoagulation is reduced when compared to adults [30]. The reported incidence of LMWH-associated bleeding in neonates is 0%–10.8%. Therapeutic LMWH when given once or twice daily should be monitored for a target antifactor Xa range of 0.5–1.0 units/mL if the sample is drawn 4–6 hours from subcutaneous injection, and 0.5–0.8 units/mL in a sample taken 2–6 hours after subcutaneous injection [30].

Warfarin, or Coumadin, blocks the γ-carboxylation of glutamate residues in prothrombin, factors VII, IX, and X, and endogenous anticoagulants protein C and S by preventing the reduction of inactive vitamin K epoxide to its hydroquinone [29]. Warfarin has a very narrow therapeutic index and requires frequent monitoring via prothrombin time and international normalized ratio (INR). A variety of factors including innumerable medications can interfere with the bioavailability and pharmacokinetics of warfarin. Unlike many formulas, breast milk has no vitamin K. Depending on the breast milk to formula ratio the patient's level of anticoagulation can change. Furthermore, children often have fluctuating caloric intake and inconsistent nutritional consumption, including green vegetables and oils. In addition, children are more susceptible to illness, including the common cold. These difficulties result in children being within therapeutic range less than 50% of the time [32]. Children have poor venous access, making monitoring difficult and leading to increased anxiety to the patient. The target INR ranges between 2.0 and 3.0 [30]. According to a statement by the American Heart Association, a monthly INR check is recommended in infants and children once a stable dose has been identified. Finger-stick capillary whole-blood sampling is available. Its validity and accuracy are currently being evaluated in the pediatric population. In general, anticoagulation with warfarin is not recommended in children under the age of 1 year unless a mechanical valve is present. The long-term use of warfarin has been linked to osteoporosis.

There are no specific recommendations regarding the duration of anticoagulation therapy in pediatrics after arterial repair or for specific traumatic injuries. This results in a quandary for those caring for pediatric trauma patients, as thrombosis and arterial intimal injury often mandate anticoagulation at least for the near term. We will place patients on aspirin therapy indefinitely if there has been an arterial injury that required surgical repair or stent. Patients with a thromboembolic complication are placed on therapeutic LMWH for 3–6 months, with the duration depending upon the clinical exam and results of surveillance studies. These recommendations, however, have not been subjected to rigorous scientific examination and would benefit from further study.

Pediatric truncal vascular injury

Epidemiology of pediatric truncal vascular injury

Truncal vascular injury is rare. The majority of the literature available on this topic consists of retrospective analyses and case reports. Consequently, experiences from the adult population are extrapolated and applied to the pediatric population. Initial survival following blunt aortic injury is reported to be 7% compared with 14% in adults [33]. Other studies have reported overall mortality rates associated with pediatric truncal vascular injury between 30% and 85% [34,35]. Unfortunately, approximately 80% of children who sustain truncal vascular injuries never make it to the hospital because they die on scene. While penetrating injury was once the most common mechanism of truncal trauma, blunt injury to the thoracic and abdominal aorta is more likely to be encountered in today's pediatric population. Injury to the thoracic aorta is more common than injury to the abdominal aorta (72% versus 21%) [35]. The overall incidence of injury to the thoracic aorta is 2.1%, whereas the overall incidence to the abdominal aorta is 0.1% [36]. Thirty percent of untreated survivors die within 6 hours [35,37]. Forty percent die within 24 hours, whereas 90% do not survive past 4 months. According to a review of the National Automotive Sampling System, the overall incidence and associated in-hospital mortality of blunt thoracic aortic injury increases with age [5]. Furthermore, a recent retrospective analysis of 468 cases of pediatric traumatic aortic injuries from 1997 to 2009 by Tashiro et al. demonstrated that boys and Hispanic children had a lower associated-mortality rate than girls and Caucasian patients (OR 0.15; OR 0.17) [35]. In addition, lack of insurance or financial wealth was also associated with a higher mortality rate. Lastly, children admitted to urban nonteaching hospitals and nonchildren's hospitals had lower mortality rates than children admitted to urban teaching hospitals and children's hospitals (OR 0.15; OR 0.4), likely reflecting a referral bias.

Presentation of pediatric truncal vascular injury

The most common site of injury in the thoracic aorta is the isthmus, a location along the medial aspect of the lumen and just distal to the origin of the left subclavian artery [37,38]. High intra-aortic pressures combined with rotational forces and the tethering of ligamentum arteriosum result increased tension at the isthmus. The most common location of blunt abdominal aortic injury is at the level of the inferior mesenteric artery (30%–40%) followed by at the level of the aortic bifurcation (25%) [39]. Timely diagnosis and prompt treatment of aortic injury are critical.

The most common cause of aortic trauma is a motor vehicle accident [37,38,40]. Patients are often the unrestrained driver or front seat passenger [33]. Other causes of aortic injury include motorcycle crashes, falls, auto versus pedestrian, and gun violence. Injury is more common in boys than girls (76% versus 24%).

The diagnosis of aortic injury in children is difficult and clinical presentation is variable. Hypotension, loss of peripheral pulses, lower extremity neurological deficits, abdominal mass, and abdominal bruit are late findings [39,41]. Notably, approximately half of pediatric patients with blunt truncal injury demonstrate no signs of chest trauma [33,35]. As a result, it is imperative to have a high level of suspicion when treating a patient involved in a high-impact trauma to the thorax. In a 10-year retrospective review, Anderson et al. identified seven patients with a thoracic aortic injury. Four of these patients had associated solid organ injuries with multiple broken bones [40]. Four children with abdominal aortic injury were also identified. Unlike children with thoracic aortic injury, children with abdominal aortic injury had neither solid organ injury nor long bone fractures. On the contrary, Allison et al. reported that the most common concomitant injuries associated with abdominal vascular injuries were injuries of the small bowel (18.2%), liver (15.9%), spleen (9.1%), kidney (9.1%), and orthopedic (9.1%) [36]. Of note, the number of associated injuries was not predictive for mortality [34]. Fractures of the sternum, scapula, upper ribs, clavicle, and pelvis are markers of increased risk for thoracic aortic injury [38]. Although it is rare, the seat belt syndrome (seat belt bruising, abdominal injury, spinal fracture) can include injuries to the aorta that result from the lap belt serving as a pivot point around which the spine flexes and compresses the abdominal aorta during the rapid deceleration of a high-speed motor vehicle collision [41,42].

In a logistic regression of 468 pediatric patients with aortic injury, Tashiro et al. demonstrated that patients presenting with shock or requiring an exploratory laparotomy had the highest associated mortality (OR 47.9; OR 13.7) [35]. Hemodynamic status on presentation was the best predictor of complications and overall mortality [36]. A presenting systolic blood pressure of less than 90 mmHg was associated with poor outcome [34,40]. Hypotensive patients have a higher injury severity score [37]. In another retrospective review of 57 patients with truncal vascular injuries, all seven patients with thoracic vascular injuries who presented with hemodynamic instability died [36]. Severe head injuries were associated with a poor prognosis [36,43].

Diagnosis of pediatric truncal vascular injury

Multiple classification systems have been developed to describe aortic injury. The most commonly applied grading system for thoracic aortic was developed by The University of Washington [37]. Based on this grading system, grade I and grade II thoracic aortic injuries have no external contour abnormality. In a retrospective review by Starnes et al. [37], no patient with a normal external contour died from his or her blunt aortic injury. Grade III injuries demonstrate a change in external contour, a pseudoaneurysm. According to Starnes et al., a free rupture is classified as a grade IV injury. Unlike the original classification of Parmley in 1958, the classification proposed by Starnes et al. relies on CTA findings, the most common method of diagnosing an aortic injury. Most intimal tears were at the isthmus or at the descending aorta. Most large intimal tears were in the abdominal aorta. There was also a positive correlation between grade of injury and injury severity score. In a retrospective review of 3350 patients over a 6-year period, Aldham et al. identified 48 traumatic aortic injuries. Grade III aortic injuries were the most common, representing 69% of patients [44]. Multiple series identify grade III aortic injuries among the most common type of blunt traumatic aortic injury [45]. While the size of the pseudoaneurysm did not directly associate with mortality, the size of the periaortic hematoma did correlate with death from blunt aortic injury and is a marker for urgent repair in the adult population [37].

The abdominal aorta is classified into three zones based on possible endovascular surgical approaches [46]. According to Shalhub et al., the aforementioned grading scale can also be applied to blunt abdominal aortic injury. In this multicenter study by the Western Trauma Association consisting of 113 adult patients with blunt abdominal aortic injury, most patients presented with grade II injuries (33.6%), closely followed by grade IV injury (31.9%) primarily in zone III (66.4%) [46,47]. In a retrospective review of 112 intra-abdominal vascular injuries, the absence of vital signs and performance of cardiopulmonary resuscitation was uniformly lethal [43]. As a result, prolonged resuscitation and extraordinary measures were not recommended.

According to the EAST Practice Management Guidelines Work Group for the Diagnosis and Management of Blunt Aortic Injury, a CXR is a good screening tool to determine whether further investigation is warranted [48]. Significant findings indicative of aortic injury include a widened mediastinum, apical cap, obscured aortic knob, deviation of the left mainstem, bronchus or nasogastric tube, massive hemothorax, and opacification of the aortopulmonary window [33,38,48]. In an adult a widened mediastinum is defined as a width greater than 8 cm, a mediastinal/chest width ratio of >0.38, or a physician's opinion that the mediastinum is widened. A suspicious CXR should be followed up with a diagnostic test such as a chest CTA or angiography as seen in Figures 13.3 through 13.5.

While conventional angiography continues to be the gold standard to diagnose blunt aortic injury, spiral CT has negative predictive value and can be used alone to rule out blunt aortic injury [48]. The disadvantage of CT scan is lack of dynamic information and poor visualization of collaterals [33]. Demetriades recommended that all patients with deceleration injuries should undergo screening CT to rule out aortic injury [38]. While this is applicable to the adult population, this recommendation may not be generalizable to the pediatric population who for reasons described above are more sensitive to radiation. Nevertheless, the number of CT chest examinations has increased significantly over the years in the pediatric population [33]. In addition to conventional angiography and CT, a transesophageal echocardiogram (TEE) can also be used to diagnose blunt aortic injury [48]. This method of diagnosis is extremely valuable in patients who are unstable and cannot tolerate moving to the angiography or radiology suite. While TEE cannot visualize the ascending aorta or aortic branches well, it can identify small intimal injuries.

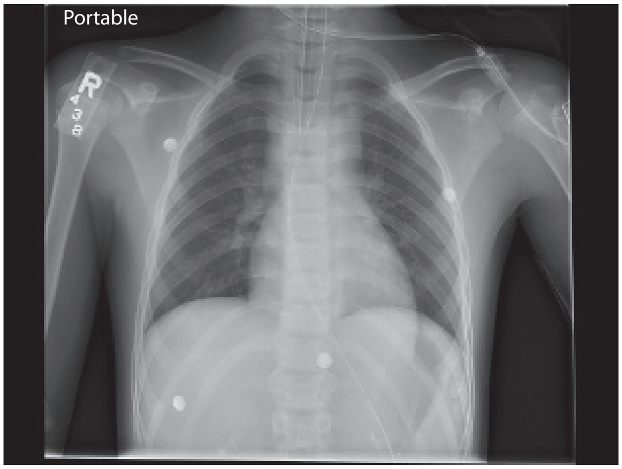

Figure 13.3 Chest x-ray revealing a widened mediastinum in an 11-year-old patient treated at Texas Children's Hospital after a motor vehicle accident.

Figure 13.4 Axial computed tomographic angiogram confirming presence in the Figure 13.3 patient of traumatic aortic injury (grade III) just distal to the subclavian artery.

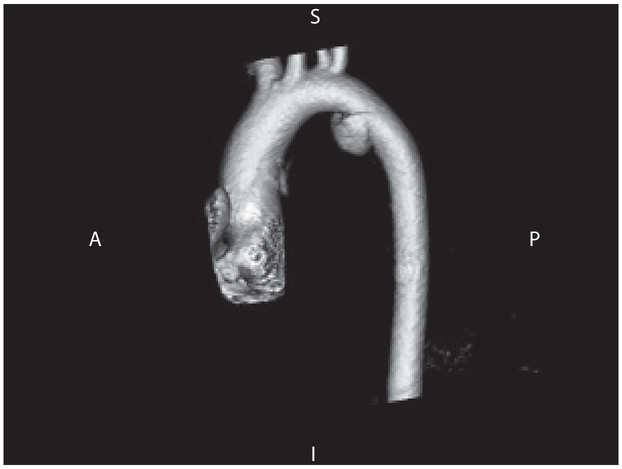

Figure 13.5 Three-dimensional reconstruction of the computed tomographic angiogram of the Figure 13.3 patient showing the grade III traumatic thoracic aortic injury just distal to the subclavian artery. Note also the anomalous aortic origin of the left vertebral artery from the aortic arch, just proximal to the left subclavian artery. A, anterior; S, superior; P, posterior; and I, inferior.

Treatment of pediatric truncal vascular injury

Much debate exists regarding the best operative approach for aortic injuries. Treatment of aortic injury is based on the mechanism of injury. Penetrating trauma is more likely to leave a clean focus of injury amenable to primary repair, while blunt mechanisms create more shear injuries often affecting a larger area of vessel [9]. Consequently, these injuries often require more extensive repairs.

While emergent operative intervention is warranted in patients with penetrating trauma and in patients with blunt injury and active extravasation, the optimal management for contained blunt aortic injuries is still in question [45]. The risk of free rupture is greatest in the first few hours after injury [38]. Nonoperative management of blunt aortic injury includes blood pressure control and the use of anticoagulation such as aspirin unless otherwise contraindicated. Blood pressure control can decrease the incidence of free rupture of a thoracic aortic injury from 12% to 1.5% [38,49]. Target blood pressures are unknown in pediatrics due to the infrequency of the injury, although in adults it is recommended to maintain a systolic blood pressure as tolerated, which is typically 90–100 mmHg.

The University of Washington clinical treatment guidelines for blunt aortic injury recommend anti-impulse therapy in all patients with radiographic evidence of blunt aortic injury [37]. Grade I and II injuries show slow progression and nonsurgical therapy can be considered [50]. Observation is warranted in patients with grade I injuries with a repeat CTA in 1 month. Grade II injuries require a CTA within 7 days following diagnosis to assess for progression of the lesion. Operative intervention is warranted if there is any evidence of progression. Patients with grade III lesions should undergo semielective repair if there is a high likelihood of survival.

Operative interventions for the treatment of aortic injury include primary repair, patch repair, autologous grafts, allografts, prosthetic grafts, shunts, ligation, extra-anatomic bypass, or endovascular repair. In general, neurologic complications correlate with ischemia time; as a result, shunt use should be considered when repairing an aortic injury [48]. Feared complications include paraplegia and renal failure. Children less than 6 years of age rarely have sufficient autologous graft options. Case reports have described the use of cryopreserved arterial allograft [51].

Given the low incidence of these injuries, a prospective or randomized control study comparing the different types of repairs is not feasible. There is no information available regarding the long-term outcomes of most repairs in children. When primary repair is not possible, a conduit must be used. As described by Corneille et al., an autologous graft such as a reversed saphenous vein is preferred [9]. Synthetic conduits such as polyester or polytetrafluoroethylene (PTFE) grafts can be used. They are prone to infection and small in diameter. Historically, prosthetic grafts have a high thrombosis rate with a poor long-term patency. As mentioned earlier in this chapter, an anastomosis should entail interrupted sutures. The "clamp and sew" technique is often mentioned in the literature. This method of repair provides rapid control of the aorta, avoids heparin, and restores flow to the distal aorta without the use of distal reperfusion techniques but in the same amount of time [35]. The area of injury is identified. Proximal and distal control is obtained and clamped. The injured area is excised and a prosthetic graft is put in its place. The graft is placed within the ends of the aorta and sutured together. The clamps are then removed [52]. Cross-clamping time is usually less than 20 minutes and there is no need for circulatory support. While the American Association for Surgery of Trauma (AAST) 1 study demonstrated a higher incidence of paraplegia in patients treated with the clamp/sew technique compared with bypass techniques, the AAST2 study published 10 years later did not replicate these findings [53]. In order to account for the future growth of a child, Kaye et al. recommended that artificial grafts be placed end to side proximally and distally with a redundant angulated C-shape, whereas cryopreserved grafts should be placed end to end [51,54]. The extent of angulation will decrease as the child grows. Future stricture plagues long-term outcomes with prosthetic grafts, making surveillance critical as the child matures. There are no pediatric surveillance guidelines, though the authors follow up at 1-, 3-, 6-, and 12-month intervals, and then annually thereafter. The frequency varies, however, depending upon the surgeon's perceived need.

A large prospective study by the AAST evaluated the outcomes of patients with blunt thoracic aortic injury according to timing of repair. They concluded that the overall crude mortality rate in the early repair group (<24 hours from injury) was ninefold higher than in the delayed repair group (>24 hours from injury) [38]. The mean time from injury to repair was 16.5 hours in the 1997 AAST1 study and 54.6 hours in the AAST2 study [53]. Delayed repair was noted by Demetriades as the only independent factor protective against mortality in patients with blunt thoracic aortic injury. The incidence of paraplegia between early and delayed repair was the same. Consequently, repair of a blunt aortic injury can be delayed if a patient has a more life-threatening injury that requires a craniotomy or an exploratory laparotomy or if a patient is a poor surgical candidate [45,48]. According to an 11-year retrospective review of blunt thoracic aortic injury in children, surgical repair was performed on all patients diagnosed with blunt thoracic aortic injury. The most common intraoperative finding was an aortic tear (53%) followed by aortic transection (35%) and pseudoaneurysm (18%) [33]. A graft interposition was the most common procedure performed (76%), followed by primary anastomosis (18%) and patch repair (6%). No deaths were reported.

The first endovascular repair of a blunt traumatic thoracic aortic injury was in 1997 [38]. Since its initial use, the popularity of endovascular repair has grown substantially. In the AAST1 study, no patient was treated with endovascular repair. Sixty-five percent of patients were managed with stent grafts in the AAST2 study 10 years later [53]. Endovascular repair can be a temporizing or permanent means of treating traumatic aortic injury. Other than the benefits mentioned in the preceding sections, endovascular surgery minimizes the risk of paraplegia and mortality as demonstrated in the AAST2 study [38]. Equally notable were the large number of device-related complications. The most common were endoleaks with a prevalence of 14%. These complications were attributed to the lack of oversizing of the stent by 10%–20%. The use of a stent that is too small or too large results in an increased risk of endoleak, infolding, collapse, migration, fistula formation, and thrombosis. The thoracic aorta becomes ectatic and tortuous with advancing age, placing stent grafts at risk of failure as a patient ages [53]. Barral et al. advocated deferring formal repair of abdominal aortic surgery until the age of 10–12 years when an 8-mm graft compatible with normal growth could be used [54]. Recent prospective nonrandomized studies such as the RESCUE trial and the GORE TAG thoracic endoprothesis trial maintain that the endovascular approach is both safe and effective in the treatment of adult traumatic aortic injuries [55,56].

There are no prospective studies available evaluating the utility of endovascular repair in children. The current aortic endografts are not ideal for use in children. Younger patients have a smaller descending thoracic aorta with a steeper aortic arch angle otherwise referred to as a "cathedral dome" shape. A current treatment algorithm proposed for adolescent patients by Malgor et al. lists an iliac diameter of >7 mm and aortic diameter of >18 mm as inclusion criteria for possible thoracic endovascular repair approach [57]. Off-label use of iliac limb endovascular stents and aortic cuffs to treat blunt thoracic aortic injury has been described [58,59]. The caliber of access vessels for endovascular repair is also problematic in children. Case reports have described performing an exploratory laparotomy to gain access to the abdominal aorta for cannulation [60]. More durable, low-profile, small-diameter, and flexible endografts are needed [33,60]. In an effort to repair a blunt thoracic aortic injury, the occlusion of the left subclavian artery by an endovascular stent is well tolerated if necessary [38,56]. In a retrospective analysis of 140 patients with blunt aortic injury, eight patients required intentional coverage of the left subclavian artery [37]. Retrograde flow through the left vertebral artery and mammarian artery can maintain perfusion to the left upper extremity. As a result, subsequent revascularization was not necessary. Case reports have demonstrated an increased rate of stroke and likelihood of spinal cord ischemia with overstenting of the left subclavian artery [50]. Hence, the ideal situation is when an adequate seal (ideally 2 cm on either end of the graft) without excessive angulation of the graft can be achieved without covering the left subclavian artery. In addition to the large caliber, currently available endovascular aortic stents are often too long for young children. The narrowest thoracic stent graft measures 18 mm, with a length of 105 mm, though endograft iliac limb components may be shorter and narrower. The longer lengths could result in a higher incidence of paraplegia, as the entire thoracic aorta, and the subsequently the vessels perfusing the spinal cord, are covered. A lumbar drain with tight lumbar pressure monitoring and blood pressure control may limit this risk (Figures 13.6 and 13.7).

Unlike blunt thoracic aortic injuries, symptomatic blunt abdominal aortic injuries are usually treated with an open operation. These lesions are more accessible than lesions in the thoracic cavity. Intraoperative ultrasound can help identify the proximal and distal extent of intimal disruption [61]. Furthermore, duplex mode can identify areas of turbulent flow. Consequently, intraoperative ultrasound can determine precise locations for clamp placement during repair. If the aortic adventitia is intact a transverse aortotomy and thrombectomy should be completed [39]. The aorta proximal and distal to the lesions should be freed to ensure a tension-free anastomosis. Isolated lumbar arteries in the vicinity may need to be sacrificed for optimal exposure [42]. If an end-to-end aortic anastomosis is not feasible, an autologous graft using the hypogastric artery, bovine graft, or synthetic graft can be used. Grade III injuries usually require excision with primary end-to-end anastomosis or interposition graft placement [47]. Among patients with aortic intimal transection in one retrospective review, 15% of patients also had associated iliac dissections which limited the utility of endovascular repair [42]. While they can be considered in zone III or in the setting of gross contamination, endovascular procedures are avoided if possible in the pediatric population. Overall, the mortality of blunt abdominal aortic injury was 32%, whereas the mortality rate of free aortic rupture was 100% [47]. Mortality also varies with zone of injury. Shalhub et al. reported the highest mortality with zone II injuries at 92.9%. The highest mortality was within the first 24 hours secondary to hemorrhagic shock.

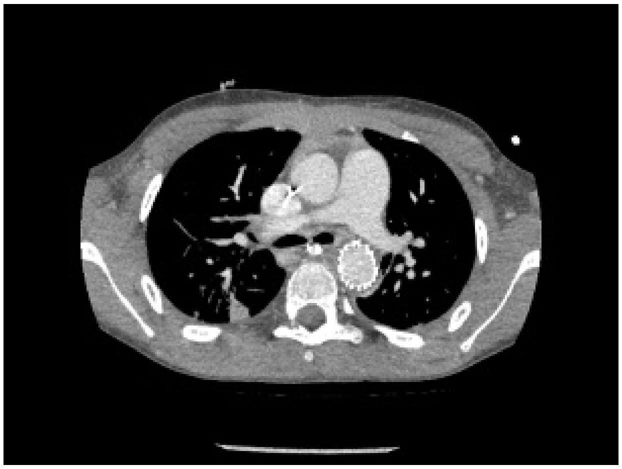

Figure 13.6 Axial computed tomographic angiogram of the Figure 13.3 patient showing the thoracic stent graft which had been placed, with repair of the injury in the thoracic aorta.

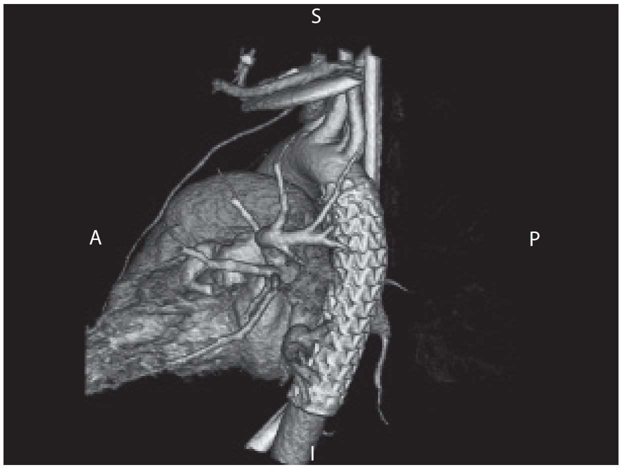

Figure 13.7 Three-dimensional reconstruction of the computed tomographic angiogram of Figure 13.3 patient showing the placement of the thoracic endograft, which was placed distal to the subclavian artery. No further evidence of injury can be seen. Given the length of the graft and concern for occlusion of spinal vasculature, a spinal drain was placed and the pressure was closely monitored. A, anterior; S, superior; P, posterior; and I, inferior.

Surveillance of pediatric truncal vascular injury

In a retrospective analysis, Barral et al. reported on eight children who underwent surgery for lesions of the abdominal aorta [54]. While none of these patients experienced trauma, this is one of the few studies that describe the long-term results of aortic reconstruction. All patients underwent a bypass procedure. Six patients were reconstructed using polyester Dacron graft. A polytetrafuoroeythylene graft and an allograft were placed in the two remaining patients. Unfortunately, the patient with an allograft aortobifemoral bypass died 2 hours after surgery as a result of extensive thrombotic disease. Three of the seven patients required further surgery. One patient experienced failure at 5 years of a 6-mm collagen-coated Dacron graft that was placed between the celiac and the infrarenal aorta. Another patient developed a noninfectious false iliac aneurysm of a graft placed between the aorta at the diaphragmatic hiatus and the iliac arteries at 20 years. All patients developed normally both in weight and in height and were asymptomatic at the time of publication. Four of the seven patients played competitive sports. Of note, arterial narrowing of less than 50% does not cause arterial insufficiency even during physical activity. Two patients, one male and one female, became parents.

Patients with nonoperative management of blunt aortic injury should be followed at 30 days, 6 months, 1 year, and then annually by repeat CTA until resolution of injury [37]. Surgery should be performed at any sign of deterioration. According to Demetriades, radiologic follow-up after endovascular treatment should be completed every 6 months [38]. Once deemed stable, the radiologic follow-up interval can be increased to annually.

Pediatric carotid artery injuries

Epidemiology of pediatric carotid artery injuries

Injury to the carotid artery can be classified as penetrating or blunt. Limited information is available regarding the incidence of carotid injury in the pediatric population. Penetrating injuries to the carotid account for 3% of arterial injuries in the civilian population [62]. Only 96 cases of blunt carotid injury were reported in the general population before 1980 [63]. The incidence of carotid injury has increased with screening. Following the implementation of screening guidelines in the adult population, the incidence of blunt carotid injury increased from 0.1% to 1.16% [64,65].

Blunt carotid injury in the pediatric population is less common overall in the pediatric population, likely secondary to the increased pliability of children's blood vessels. Within the pediatric cohort, children less than 6 years of age are at higher risk of carotid injury then their older counterparts. Although they represented 36% of the total pediatric trauma registry, children younger than 6 years embodied 73% of the patients with blunt cerebrovascular injury (BCVI) [66]. It is estimated that its overall incidence in children is 0.03%. This number may change with increased awareness and screening. While the incidence of carotid injury is rare, the associated morbidity and mortality is significant. In the adult population, retrospective multicenter reviews have estimated the morbidity and mortality secondary to blunt carotid injury as 23% and 48%, respectively [67]. In a review by Lew et al., the mortality rate secondary to blunt carotid artery injury in children was noted at 13% [66].

Presentation of pediatric carotid injury

Carotid artery injury can manifest as hemorrhage, formation of an arteriovenous fistula, pseudoaneurysm, carotid-cavernous fistula, partial or complete transection, thrombosis, and dissection. Clinical findings can include, but are not limited to, anterior soft tissue injury, bleeding, neck pain, Horner's syndrome, carotid bruit, tinnitus, aphasia, and presence of lateralizing neurologic symptoms [68–70]. Neurologic signs present in a delayed fashion from a few hours to several years after the insult. Nonfocal symptoms including irritability and lethargy may precede contralateral hemiplegia and homonymous hemianopsia. Severity of symptoms does not correlate with extent of disease.

Carotid injury can occur with both high-velocity mechanism such as motor vehicle collisions and low-velocity mechanisms such as short-distance falls. The most common mechanism of injury to the carotid artery is related to extension and contralateral rotation of the head [68]. Dissection can occur when these forces compress the carotid artery against the transverse processes, vertebral bodies of the upper cervical spine, or the styloid process [71]. The pediatric cervical spine has a greater degree of instability than that of an adult. As described by Nouh et al. this related to increased ligamentous laxity, underdeveloped spinous processes, anterior wedging of vertebral bodies, incomplete ossification of the odontoid process, weak neck muscles, and a large head. Furthermore, children have less atherosclerotic changes of their carotid arteries than do adults, further predisposing children to carotid artery injury [66]. Other mechanisms of injury include intraoral trauma, direct blow to the neck, strangulation, or association with basilar skull fracture through the foramen lacerum.

Carotid vascular injuries frequently manifest as an intimal flap which prompts the formation of thrombus and subsequent aneurysmal dissection and propagation. A unilateral carotid occlusion can remain clinically silent in the setting of a patent circle of Willis. As the thrombus extends into the middle and anterior cerebral artery, patients may become progressively symptomatic [69]. The cervical spine reaches adult proportions at approximately 10 years of age [71].

Diagnosis of pediatric carotid artery injury

Penetrating injuries

Historically, the neck is divided into three zones. These anatomic zones dictate evaluation and treatment. Demetriades et al. reported the distribution of penetrating injury in the adult neck [72]. The most common area affected was zone II (47%) followed by zone III (19%) and zone I (18%). More than one zone was affected in 16% of patients. The pediatric neck is more compact. One can conclude that the likelihood of a penetrating injury affecting more than one zone is higher in the pediatric population than in the adult population. Penetrating neck injuries are thankfully rare, occurring in 0.28% of all children in the National Trauma Databank over a 4-year period [73]. The mean age is 7.9 years, and males are affected 70.6% of the time. Stabbing (44%) and firearms (24%) were the most frequent mechanisms of penetrating injury [73].

Patients who demonstrate hard signs of vascular injury or hemodynamic instability regardless of zone affected require a secure airway and an emergent operative intervention. According to the Western Trauma Association Critical Decisions in Trauma, patients without indications for a mandatory neck exploration and without symptoms or suspicion of injury can be managed expectantly [74]. While they are easily applicable to the adult population, these recommendations may prove more difficult and even impossible when caring for the pediatric population. Nonetheless, further diagnostic imaging is recommended in patients who are hemodynamically stable and demonstrate soft signs of vascular injury. For these patients, the diagnostic algorithm is similar to those for BCVI. During the initial evaluation, removal of the penetrating object is not advised [69].

It is important to bear in mind that penetrating injury to the neck can affect all surrounding structures. Consequently, injury to the aerodigestive system must also be evaluated. Physical examination alone is insufficient to rule out esophageal injury. While CTA was initially utilized for the assessment of vascular injury, recent studies have reported high sensitivity for detecting aerodigestive injury [74]. It is recommended that patients with zone I undergo a CTA of the chest and neck. A CTA of the neck is often sufficient for zone II injuries, whereas zone III injuries require a CTA of the head and neck. Early operation is warranted in patients with evidence of aerodigestive injury on CTA. If continued concern exists regarding aerodigestive injury in zone I and II secondary to wound trajectory despite a negative CTA evaluation, esophagoscopy or esophagography is recommended. Contrast swallow studies are not recommended for zone III injuries due to decreased sensitivity in detecting hypopharyngeal injuries. Flexible or video nasoendoscopy may be required in these instances. Prompt surgical repair of aerodigestive injury is associated with improved outcome. As a result, expeditious evaluation is critical.

Blunt injuries

Screening guidelines for blunt carotid injury in adults are well established [64]. At this time, there are no standard screening guidelines in children. The current level three recommendations from the Eastern Association for the Surgery of Trauma (EAST) endorse the application of adult BCVI practice management guidelines to the pediatric population. While the available data do support the use of adult screening criteria in the pediatric population, further scientific evidence is needed.

An evaluation for BCVI should be initiated in any patient with a neurologic abnormality not explained by his or her injury pattern [64]. Asymptomatic patients with blunt head trauma should be screened for BCVI if they demonstrate any of the following risk factors: (1) Glasgow Coma Scale of ≤8, (2) petrous bone fracture, (3) diffuse axonal injury, (4) fracture of cervical spine C1–C3 with fracture extending through the foramen transversarium, (5) a cervical spine fracture with subluxation or a rotational pattern, and (6) Lefort II or III facial fractures. While patients with one risk factor had a 41% risk of BCVI, patients with four risk factors had a 93% risk of BCVI. While initially thought to be a significant predictor of injury, the presence of soft tissue swelling, referred to as the “cervical seatbelt sign,” is not associated with an increased risk of BCVI and consequently is not a sufficient criterion to screen for blunt carotid injury [64,75,76]. Other screening guidelines for BCVI include the Denver and Memphis criteria.

Diagnosis of blunt carotid injury can be difficult in the asymptomatic pediatric patient. Several constellations of injury have been associated with simultaneous injury to the carotid artery. For example, the presence of chest trauma increases the risk of BCVI fourfold, whereas a clavicle fracture increases the probability of coexisting carotid injury eightfold [63,66]. Combined head and chest trauma is associated with a sixfold increase in carotid injury. Ravindra et al. discovered that in children, petrous temporal bone fracture, Glasgow Coma Scale score <8, focal neurological deficit, and stroke on initial CT scan are independent risk factors for BCVI [77].

Doppler studies, ocular pneumoplethysmography, angiography, computed tomography imaging, and MRI can be used to evaluate patients with carotid injury. A diagnostic four-vessel cerebral angiogram (FVCA) is the gold standard for diagnosis of BCVI. Recent studies have demonstrated a similar detection rate between FVCA and multislice (eight or more) multidetector computed tomography angiography. According to Berne et al., the 16-channel CTA has an overall sensitivity of 100% and a specificity of 94% for the detection of BCVI [78,79]. This was later confirmed by Eastman et al., who demonstrated the sensitivity, specificity, and accuracy of CTA to be 97.7%, 100%, and 99.3%, respectively [19]. Upon further analysis, the positive predictive value of CTA in the diagnosis of BCVI was 100%, whereas the negative predictive value was 99.3%. According to a recent study published by Malhorta et al., the use of selective CTA was the most cost-effective imaging modality to screen patients for blunt carotid injury [8]. Duplex ultrasound is not sufficient as the sole screening modality for BCVI as its sensitivity is estimated at 38.5%–86% [64]. Furthermore, duplex ultrasound has a limited ability to evaluate proximal and distal lesions [66]. The use of magnetic resonance angiography has several advantages and disadvantages. When used with diffusion-weighted sequences, MRA has a high sensitivity for the identification of early ischemia. Unfortunately, the sensitivity of MRA for carotid artery injury, particularly of pseudoaneurysms, is 50% [64,66]. Consequently, neither duplex ultrasound nor MRA can be used as the sole screening modality for BCVI.

Treatment of pediatric carotid artery injury

The patient's hemodynamic status, location, and extent of injury determine the type of intervention pursued. Timing of treatment is important. The majority of the literature available recommends early intervention [64]. Surgery after embolic symptoms is controversial as it provides little to no benefit and may result in hemorrhagic transformation of the infarction [66,68]. Others argue that early intervention reduces secondary morbidity and mortality [69]. With only a small number of prospective studies, fixed guidelines regarding the treatment of carotid trauma in the pediatric population are not currently available. As a result, an individualized treatment approach is necessary.

Penetrating injury

The treatment of penetrating carotid vascular injury in the children is similar to that of the adult. Penetrating injuries to zone II mandate exploration, whereas penetrating injury to zone I and III require a more discerning approach secondary to difficult accessibility and exposure. If there is any concern for aerodigestive injury, direct laryngoscopy, bronchoscopy, or esophagoscopy is recommended [62,74].

An anterior sternocleidomastoid incision can address most penetrating neck injuries. Zone I injuries may require a median sternotomy and possible clavicular head resection. Although uncommon, subluxation, dislocation, or resection of the mandible may be needed to address vascular injuries in zone III. A transcervical or "collar" incision may be warranted to access both sides of the neck [74].

Surgical options include ligation, resection and primary anastomosis, and reconstruction with an autologous or prosthetic patch, resection with autologous or prosthetic graft interposition, extracranial-to-intracranial arterial bypass, and aneurysmorrhaphy. Historically, injury of the carotid artery was treated with ligation, particularly in the pediatric population. This was associated with high incidence of adverse events. Repair of the common and internal carotid is recommended. Despite interest in endovascular techniques, zone II injuries should be addressed via open techniques [74]. While ligation of the carotid artery is no longer favored, ligation may be indicated if the patient is in extremis and temporizing measures such as shunts are not available [80].

When primary repair or patch angioplasty is not possible, the use of autologous material is preferred. Native artery such as the hypogastric artery is favored [62]. However, an otherwise unnecessary laparotomy in the setting of acute trauma is not recommended. Saphenous vein is often the conduit of choice. Unfortunately, saphenous vein grafts are themselves associated with aneurysmal dilation, especially in a high-flow artery. When autologous conduits are unavailable, transposition of the external carotid artery to the internal carotid artery is an option. Although it can be used, prosthetic material is best avoided in children, given the inability to grow and the risk of infection. In a retrospective wartime review, Villamaria et al. described a primary repair, a vein patch repair, a reversed saphenous interposition graft repair, and a PTFE repair for penetrating carotid artery injury in children and promising short-term outcomes [6].

Penetrating trauma to the carotid artery can cause pseudoaneurysms. While its use in BCVI is more defined, systemic anticoagulation for pseudoaneurysms resulting from penetrating trauma remains controversial. In a case study, Galante et al. note that small pseudoaneurysms (<1.8 cm) tend to heal, whereas larger pseudoaneurysms grow [62]. Studies looking at the use of anticoagulation in patients with pseudoaneurysms of other parts of the body such as the femoral artery have demonstrated an increased tendency of these lesions to expand. As a result, patients with large or symptomatic carotid pseudoaneurysms should be treated. Options include surgery, endovascular occlusion, stent graft placement, and selective embolization [27]. Surgical options are similar to those described above.

Blunt injury

At this time, the management of blunt carotid injury in children is similar to that of the adult population. Unlike adults, children require aggressive management of intracranial hypertension. Children require smaller changes in intracranial volume to develop intracranial hypertension than do adults [81]. Consequently, children have demonstrated better outcomes than adults with aggressive management of intracranial hypertension throughout the postinjury period. Duke et al. noted that resection of infarcted brain tissue in pediatric patients with medically intractable intracranial hypertension following blunt carotid injury demonstrated improved outcomes [64,81]. While the resection of infarcted brain tissue can be viewed as extreme, there are many other modalities that can be employed to aggressively treat and manage intracranial hypertension.

The management of blunt carotid injury is dictated by grade of injury [64]. Several grading systems have been described. The most commonly used was proposed by Biffl et al. While there is no difference in mortality rates between grades I and IV, grade V carotid artery injuries are uniformly fatal [67]. Arterial disruption occurs most often at the skull base [81]. Death occurs quickly from nasopharyngeal hemorrhage.

Carotid injury can change over time. Seven percent of grade I injuries will progress to grade II injuries or higher, whereas 70% of grade II injuries will evolve into a higher grade of injury [67]. More than 50% of patients with grade I or II injury will require a change in management secondary to progression of disease based on follow-up arteriography completed 7–10 days after the initial injury [82]. The grade of injury positively correlates with incidence of stroke. Treatment of an arterial lesion significantly decreases incidence of stroke [65]. Stein et al. demonstrated that the stroke rate for those treated with any therapy was markedly smaller than for those who were untreated (3.9% versus 25.8%).

Current scientific evidence and expert opinion recommend the use of antithrombotic agents such as aspirin or heparin in the treatment of grade I and II BCVI [64]. Anticoagulation with heparin, warfarin, or aspirin has been shown to improve outcomes in patients with blunt carotid injuries resulting in intimal defects or dissections [62]. In a controlled comparison between the use of heparin and the use of antiplatelet agents such as aspirin and clopidogrel, individuals treated with heparin were found to have a lower incidence of cerebral vascular accidents [64]. Follow-up studies have failed to identify this benefit [65]. Nevertheless, complications associated with anticoagulation, such as delayed intracranial bleeding and gastrointestinal hemorrhage, can be life threatening. It is important to note that a bolus dose is not recommended if a heparin infusion is used and a conversion to warfarin is suggested when appropriate with an international normalized ratio of 2–3 for 3–6 months [64]. The presence of hemorrhagic or severe traumatic brain injury and/or severe cognitive impairment is routinely considered a contraindication to systemic anticoagulation [8]. Antiplatelet therapy may be preferred in this patient population. While anticoagulation is recommended for grade I and II BCVI, only 40% of dissections respond to anticoagulation and have little to no effect on the radiographic appearance of pseudoaneurysms [66,68]. While some argue that the use of anticoagulation may worsen grade III lesions, heparin therapy is recommended for inaccessible pseudoaneurysms in the acute postinjury period [67].

Given that grade III rarely resolve with anticoagulation, more invasive means are often necessary. Acute revascularization via surgical bypass or stent placement is recommended in patients with a neurological deficit of less than 6 hours, with no indication of cerebral infarction on CT scan, and with angiographic evidence of dissection or thrombosis [33]. Revascularization may also be considered in patients following failed medical management as seen by persistent intimal injury on imaging. Because these lesions are high risk for thromboembolism, manipulation of the internal carotid artery is not recommended within the first 72 hours of injury [67]. Biffl et al. recommend waiting 7 days before attempting to place a stent for blunt carotid injury.

The use of percutaneous thrombin injection has also gained interest in recent years for the treatment of grade III lesions. It avoids a long and invasive surgery. No foreign material is used and the flow through the carotid artery remains unaltered. Nevertheless, the complications of thrombin injection can be devastating. Thrombin escape can result in neurologic catastrophe [27]. While initially successful, subsequent recanalization can occur as well, resulting in treatment failure [83]. Limited information is available regarding the use of percutaneous thrombin injection in the pediatric population in the setting of trauma.

Twenty percent of individuals have an intact Circle of Willis. Consequently, some individuals tolerate a single-vessel occlusion, grade IV injury, in the absence of atherosclerotic disease [67]. Unfortunately, these individuals continue to be at high risk of cerebral thromboembolism. Heparin therapy is recommended for these individuals in an effort to prevent stroke.

Endovascular intervention is gaining interest as a means of treatment of carotid injury, particularly in injuries involving zones I and III. Endovascular intervention prevents children from undergoing long and invasive procedures including median sternotomy and dissection along the skull base. It also avoids precarious dissection in blood-stained and contaminated planes and potential damage to cranial nerves. Techniques such as balloon occlusion can decrease the risk of thromboembolism [69]. At this time, few data exist describing its indications, technique, and short- and long-term outcomes. Trauma patients often have other injuries and require other operative procedures such as fixation of the jaw and maxillary fractures. Cox et al. detailed two episodes of massive hemorrhage from untreated pseudoaneurysm during manipulation of surrounding structures. Consequently, the study concluded that endovascular treatment of such lesions may be prudent [84]. Endovascular stents can occlude [84]. While some studies advise full systemic anticoagulation in patients with endovascular stents, others have demonstrated no difference in outcomes between anticoagulation with heparin or with antiplatelet agents [67,85]. Furthermore, Cothren et al. recommend against the use of endovascular stent placement in general, stating that the risk of stent placement despite concurrent anticoagulation is higher than in patients who received antithrombotic agents alone for grade I–III lesions [85]. Of note, uncovered self-expanding coronary stents were used in this study. Further prospective studies are necessary. Baldawi et al. reported a pseudoaneurysm formation years following a carotid artery stent placement in an adult patient. In this case report, the distal end of the stent penetrated the wall of the artery and resulted in a pseudoaneurysm [27]. While they are recommended for the treatment of pseudoaneurysms, endovascular stents can also result in pseudoaneurysm formation in the long term.

Surveillance of pediatric carotid artery injury

Patients treated for carotid injury require close long-term follow-up. Small asymptomatic psuedoaneurysms of the carotid artery may be observed with frequent imaging.

While no formal surveillance guidelines exist, Galante et al. recommend weekly imaging until there is sufficient evidence that the lesion is stable [62].

Peripheral pediatric vascular injury

General considerations

As is the case for arterial trauma in other regions of the body, management of pediatric arterial extremity injuries is largely extrapolated from the management of adult vascular injuries. This is largely due to the infrequency of arterial injury in pediatrics, especially in the civilian pediatric trauma literature. Adult techniques generally function for children who are of sufficient size to operate upon, with excellent limb salvage, limb-length preservation, and function. Typically, children less than 2 years of age (12.5 kg) cannot be operated upon, as the extremity vessels become too small to be treated with current surgical techniques and devices [86–88]. Vasospasm complicates both the diagnosis and the performance of the revascularization. While vasospasm afflicts all pediatric age groups, the problems are most severe with the smallest caliber vessels and children less than 10 years of age. Due to the complexity of these injuries, social nuances, and limited outcome data, no single physician is an expert. Expeditious diagnosis and management within a multidisciplinary team are critical to optimizing outcomes.

Epidemiology of pediatric extremity arterial trauma

Pediatric vascular injury occurs most frequently in the extremities [1,3,5,22]. Injuries occur least frequently in infants and toddlers, with a mean age between 9.3 and 13.9 years [5,22]. The frequency varies somewhat, though the rate of extremity vascular injury has been reported to be as high as 67% of all pediatric vascular injuries in some series [1]. Males appear to be predominantly affected, ranging between two-thirds and three-fourths of the reported vascular injuries [1,3,5,22].

The most frequent location of injury appears to be the upper extremity [1,5], though one series reported a higher percentage of lower extremity arterial injuries [5]. Baramparas et al. performed a review of the American College of Surgeons National Trauma Database (ACS NTDB) between 2001 and 2006, which showed that in the United States, upper extremity injuries accounted for 37.9% of all vascular trauma in patients less than 18 years of age [5]. The brachial artery appears to be the most frequently injured, followed closely by the radial and ulnar arteries. The superficial femoral artery is the most frequently injured lower extremity artery [5], with the exception of one series, which had a high incidence of popliteal artery injuries [3].

Nationally, blunt mechanisms are most frequent, with motor vehicle accidents responsible for most of the pediatric vascular injuries; however, within the extremities, penetrating mechanisms prevailed [10]. There was significant variation in the mechanisms of injury when stratified by age, with younger children (<10 years of age) having statistically significantly more blunt extremity vascular injuries when compared to older children (11–17 years of age) [10]. Falls are the most frequent blunt mechanism. Overall, 48% of pediatric patients have an associated fracture with extremity vascular injury, driven mostly by concomitant supracondylar humerus (SCH) fracture [10].

Diagnosis of extremity vascular trauma

Without hard signs of hemorrhage and signs of acute limb ischemia, adjunctive testing is required to confirm the diagnosis of vascular injury. Since there are no pediatric guidelines regarding the diagnosis of vascular injuries, adult guidelines are often followed. However, these often rely on ABI, which is of limited value in young children. Additionally, children likely have a higher incidence of concomitant vascular injury following penetrating extremity trauma than adults do, as their structures are in closer proximity and are more likely to be affected by the injury mechanism, such as blast injury from a firearm. Therefore, at the authors' level I pediatric trauma center, guidelines developed for evaluating vascular injury in the injured extremity are in the process of being prospectively validated (Figure 13.8).

Potential consequences of untreated vascular injuries

Acutely, untreated vascular injuries usually follow a similar natural history as in their adult counterparts. Arteriovenous fistula, hemorrhage, pseudoaneurysms, gangrene, compartment syndrome, dissection, and embolization may all ensue. There are two rare complications that are more unique to pediatric vascular injuries: limb length discrepancy and Volkmann's ischemic contracture.

The revascularization of a pediatric limb must not only supply enough circulation to support the immediate viability of an extremity but also enough blood to supply future limb growth and function. Limb length discrepancies have been reported after femoral artery injuries and occlusions secondary to iatrogenic catheter-based injury, affecting mostly the tibial vessels [89]. Interestingly, these may be reversible if revascularized prior to the closure of the metaphyseal plates [89]. This is a rare occurrence, however, due to the abundance of collateral pathway development in children to accommodate occlusions of large vessels. Hence, some authors advocate waiting until the child reaches sufficient size to create a durable vascular reconstruction to revascularize the limb that the child will not outgrow. Future research is required regarding the natural history of limb-length discrepancies and the optimal timing of revascularization in children.

Volkmann's ischemic contracture is a rare, though devastating complication of extremity fractures, most commonly supracondylar humeral fractures. Following the

TCH TRAUMA PRACTICE GUIDELINES

EXTREMITY TRAUMA: PENETRATING / BLUNT WITH POTENTIAL VASCULAR INJURY

Note: Vascular exam should be performed and noted before and after fracture reduction. All fractures should be expeditiously reduced in the emergency room (unless operative reduction is indicated).
Note: Urgent Trauma service consultation is required for all patients with concern for vascular injury.

“Hard” signs of vascular injury (lack of pulse, pulsatile bleeding, bruit, thrill, expanding hematoma, signs of ischemia):

- Trauma attending to see STAT and will consult Vascular surgery or Plastic surgery as necessary
- Goal is surgical exploration within 6 hours of injury

“Soft” signs of vascular injury (history of arterial bleeding, diminished pulse, injury proximity to major artery, neurologic deficit)

- Obtain Trauma consult
- Perform Ankle-brachial index (ABI)
    - ABI (lower extremity) $= \dfrac{SBP\ (cuff\ on\ ankle\ affected\ limb)}{SBP\ (cuff\ on\ biceps)}$
    - ABI (upper extremity) $= \dfrac{SBP\ (cuff\ on\ \ wrist\ distal\ to\ injury)}{SBP\ (contralateral\ biceps)}$
- If ABI <0.9 or small child and ABI not possible or reliable → CT angio vs. formal angiogram

All patients with concern for vascular injury →

- Admit to Trauma for observation and serial vascular and compartment syndrome exams
- Follow compartment syndrome monitoring nursing protocol (q2h checks)
- Trauma team to repeat ABI in 8–12 h
- If ABI still > 0.9 and no evidence of compartments syndrome: OK to discharge
- If ABI now < 0.9: reevaluation by trauma attending

Figure 13.8 Texas Children’s Hospital Trauma Practice Guidelines for the evaluation of suspected extremity vascular injury.

initial ischemic insult, compartment syndrome may ensue, resulting ultimately in ischemia of the skeletal muscle and the median and ulnar nerves in the arm. Over time, the necrotic muscle heals by forming scarring, resulting in foreshortening of the muscle, and a classic “claw hand” with flexion of the wrist, extension of the metacarpophalangeal joint, and flexion of the interphalangeal joints [90].

Management of extremity vascular trauma

With respect to penetrating injuries, experience has been drawn mostly from military experiences. The management varies little between blunt and penetrating injuries, however. Tourniquets, temporary shunting, and fasciotomies have all been performed with high limb-salvage rates and preservation of function. Tourniquets have most frequently been applied by paramedics in the field prior to arriving to the hospital, without adversely impacting limb salvage rates [91] and are most useful for proximal injuries that cannot otherwise be controlled.

Proximal shunts are most useful as they have a higher patency rate [91], compared with distal shunts. Moreover, the proximal extremity vessels (axillary, subclavian, and brachial arteries, or the femoral and popliteal arteries) have fewer collateral pathways, making shunts more essential to reducing ischemia times. Similar to the adult experience, temporary vascular shunts do not require systemic anticoagulation up to 48 hours [92]. The authors favor the use of Javid™ (10–17 Fr) or Argyle™ (8–14 Fr) shunts with Rumel tourniquets, with the Javid™ shunts utilized for longer defects. The authors frequently utilize fasciotomy should ischemia times exceed 8 hours, ideally prior to the repair of the affected extremity [3]. Arterial ligation is no longer the treatment of choice for vascular injury, particularly in civilian series [2]. However, ligation when necessary can be life saving and is still utilized in extreme cases, without prohibitive rates of limb loss [6]. Limb loss is higher with more proximal injuries, with ligation of more distal vessels (below the elbow in the upper extremity and below the knee in the lower extremity) relatively well tolerated due to collateral circulation.

Complex arterial reconstructions are uncommon but have shown promising results in the pediatric population (Figure 13.9). In a retrospective wartime review by Dua et al., 11 pediatric patients required arterial reconstruction with saphenous graft. On follow-up, the mean graft patency rate was reported at 84% at 22 days [7]. In a civilian study, Harris et al. investigated the early and late outcomes for children undergoing peripheral bypass following trauma [22]. Nineteen patients underwent a bypass in this study. Nine were available for long-term follow-up. There was no aneurysmal degeneration identified via duplex ultrasound. While seven patients were able to return to their daily activities, two patients continued to note difficulties up to 2 years after their surgery. Unfortunately, these two individuals were also noted to have significant orthopedic, nerve, and soft tissue injuries at the time of their initial trauma.

Autologous grafts are preferred when primary repair is not feasible [9]. Synthetic conduits such as PTFE (Gortex) can also be used when no other options are available. According to Allen et al., individuals who required a synthetic graft were often older, between the ages of 14 and

Figure 13.9 Primary repair of a brachial artery transection with a short segment of reversed greater saphenous vein graft sewn in with interrupted 7-0 prolene sutures on either end. Note also the transection of the median nerve.

17 years of age [93]. A 6-mm or a tapered 6-mm to 4-mm graft was used in the repair of lower extremity vessels. A 5-mm PTFE graft was used in the repair of the axillary artery while a 4-mm graft was used in the repair of a brachial artery. Nevertheless, synthetic grafts are associated with higher rates of infection and thrombosis with lower long-term patency rates and should be avoided when possible [9]. In children who are expected to grow further, maintaining a mild amount of laxity in the graft without kinking the graft may be performed, should a synthetic bypass be absolutely necessary.

Endovascular repair of pediatric injuries in the periphery is rarely performed except as a temporizing measure toward a more definitive procedure. No stents are currently FDA approved for use in pediatrics. Off-label use of adult endovascular devices abound in select centers. Similar to adults, stents, balloons, and coils can be placed in the axillary, brachial, femoral, and popliteal arteries [94,95]. Erratic patency [96], and inability to grow limit the use of endovascular technologies in pediatrics. The caliber of the delivery systems is often too large for the pediatric population. The smallest covered stents available are the Jo Stent™ (Abbott Vascular®) family of stents, and are designed to treat vessels between 2.5 and 5.0 mm in diameter. These require a 6-Fr or 7-Fr system to pass, and have a maximum length of 26 mm. Stents, when placed, can be balloon expandable, such that they may be sequentially expanded over time as the child grows. A variety of microcoils and microcatheters are available for off-label use to embolize traumatic pathologies such as arteriovenous fistulae, pseudoaneurysms, or bleeding vessels in inaccessible sites. Care must be taken to prevent dissection, as the vessels are prone to intense vasospasm. Similar to open vascular surgery, nitroglycerin (50 μg/mL) and papaverine (5 mg/mL) can be hand-injected to limit vasospasm. Each must be injected very slowly while carefully monitoring hemodynamics to prevent overdose.

Special cases of arterial extremity trauma: The “pink pulseless hand”

SCH fractures comprise 70% of elbow fractures and are associated with a 3.2%–14.2% incidence of vascular injury [97]. Garland III fractures, which are displaced fractures resulting from an extension injury, are particularly high risk. Risk factors for vascular injuries with SCH include a history of a fall of more than 4 feet, a fall of more than four stairs, motor vehicle accidents, and athletic injuries.

The management of vascular injury in the context of SCH is relatively clear in most cases. Profound ischemia, with an absence of Doppler signals, cyanosis, and coolness that persists after reduction of the fracture require exploration and repair of the defect found. Those with a palpable pulse that is restored after reduction do not need further intervention. A small minority, however, will present with a “pink pulseless hand” which appears well perfused, and have Doppler signals in the radial and ulnar distribution, but nonpalpable pulses. The management of the “pink pulseless hand” remains unclear, resulting in variable recommendations from small case series [97–99].

Vasospasm frequently overlaps with true arterial injuries, and often clouds the diagnosis. Angiography does not help determine which patients would benefit from revascularization [98]. Valentine et al. explored 12 “pink pulseless hands” that persisted after SCH reduction, and found eight focal brachial artery thromboses. These were repaired with focal thromboectomy, short segment bypass, and angioplasty. Four of 12 brachial arteries were simply entrapped with the median nerve, with resumption of normal patency after lysis of the bands that were entrapping the brachial artery [99]. Long-term outcomes appear excellent. In a separate series of 12 “pink-pulseless” extremities after SCH, there was 100% patency of arterial reconstructions after a mean follow-up of 14 years [98]. The authors tend to favor exploration for “pink pulseless hands” after reduction of SCH, though data regarding the conservative management of this pathology remain unclear. This is due to the excellent reported durability of repairs, with minimal associated morbidity. Moreover, while complications such as limb-length discrepancy and Volkmann’s contracture are extremely rare, they are devastating and difficult to treat. Repairs include patch angioplasty, interposition grafting, primary repair, and lysis of constrictive bands. After repair, nitroglycerin is applied to alleviate vasospasm and Doppler signals are reassessed. In the authors’ experience, completion intraoperative ultrasound is a helpful adjunct to assess that the quality of the repair is excellent.

Conclusions

The rarity of pediatric vascular trauma and the paucity of outcomes data belie the catastrophic potential of these injuries if poorly managed. Care by a multidisciplinary team is critical to optimize outcomes. Pediatric trauma occurs in a bimodal distribution, with peak incidences in the toddler age group and the late teenage age group. The mechanisms of injury are more frequently blunt, with extremity injuries occurring most frequently. Much of the care for specific injuries is extrapolated from that of their adult counterparts, which applies to the late teenage group, but often not to younger children. Unique features of the management of pediatric trauma include consideration for the growth potential of children, as well as the ability of vasospasm to complicate diagnosis as well as intervention. Due to the small size and vasospasm, interventions are limited to children of sufficient size, typically greater than 12.5 kg, or greater than 2.5 years. Additionally, endovascular technologies, including development of smaller endovascular technologies, are currently limited in children as they are designed mostly for adults. Development of smaller endovascular devices represents a significant unmet need meriting future research. Due to the rarity of vascular trauma, as well as the longevity of the patients, multicenter registries with long follow-up will be required to clarify optimal management in pediatric vascular trauma.

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14

Anesthesia for pediatric trauma

YANG LIU and DAVID A. YOUNG

Introduction

Traumatic injuries to children are the most common cause of death in the United States for children above 1 year of age; this will account for approximately 20,000 deaths per year [1]. Anesthesiologists have an important role in the perioperative management of pediatric patients with traumatic injuries. The care of these patients presents unique challenges for the anesthesiologist, especially for those who do not routinely take care of pediatric patients. In addition, many injured children are treated in facilities without trauma center designation or expertise in caring for pediatric patients [2,3].

Pediatric patients with traumatic injuries can vary in complexity ranging from an adolescent with a simple, isolated elbow fracture to an infant with a life-threatening epidural hematoma requiring emergent surgery. Trauma patients may present in unstable, rapidly changing, and unpredictable circumstances. Patient information may be limited or unknown including important details such as past medical history, past surgical history, and drug allergies. Although the general principles of resuscitation for pediatric trauma patients are similar to those for adults, effective management of the pediatric trauma patient also requires understanding of the anatomical, physiological, developmental, and emotional differences that distinguish children from adults.

The management of pediatric trauma patients typically includes the participation of a multidisciplinary team. Anesthesiologists perform a fundamental role within this team in many capacities. Anesthesiologists may be summoned unexpectedly to the emergency department (ED) to assist with airway management as well as the unplanned emergent operative cases. In order to provide effective care to the pediatric trauma patient, anesthesiologists must become proficient with the immediate evaluation and resuscitation of the pediatric trauma patient and continue this process throughout the perioperative period.

This chapter provides a practical review of the anesthesia management of the pediatric trauma patient during all phases of the perioperative period including patient evaluation, emergency airway management, resuscitation, and postoperative pain management. This chapter is intended to supplement principles in the widely accepted Advanced Trauma Life Support (ATLS) program [4], which was developed by the American College of Surgeons Committee on Trauma as well as the resuscitation of the pediatric patient included in the Pediatric Advanced Life Support (PALS) course created by the American Academy of Pediatrics and the American Heart Association (AHA) [5].

Initial evaluation and considerations for the pediatric trauma patient

Anesthesiologists should be familiar with the initial evaluation and management of pediatric traumatic injuries in order to continue this care effectively into the perioperative setting. The anesthesiologist may become involved in patient care during the Primary Survey commencing right from the patient's arrival. This may be due to institutional policy requiring automatic anesthesiology response for all trauma patients or to assist with emergency airway management. During the Primary Survey, the anesthesiologist should briefly attempt to obtain a focused history, if time permits, as well as other factors including past medical history, past surgery history, drug allergies, and medications taken. Due to advances in health care, patients with comorbid conditions such as repaired congenital heart disease, syndromes associated with difficult airways, as well as common medical conditions such as asthma and diabetes mellitus may present with a significant traumatic injury. Obtaining a relevant prehospital report, including the treatment received before arrival at the ED, will also provide important information for effective perioperative care. Prompt evaluation followed by appropriate intervention(s) is the key for effective management of the pediatric trauma patient.

The prioritizing of the initial management of a pediatric trauma patient follows the common order of "ABCs," which is utilized by most anesthesiologists for the initial evaluation of any critically ill patient. In addition, recognition of the ATLS guidelines currently being performed may guide system utilization more effectively. For example, an anesthesiologist recognizes that a patient has a positive focused abdominal sonography for trauma (FAST) exam; this finding will most likely result in transfer to the operating room. This increased situational awareness can result in more efficient and effective medical care from the individual physician and the system as a whole.

Most trauma programs utilize the principles of ATLS, a multilayered assessment system which includes Primary, Secondary, and Tertiary surveys [6]. The ATLS guidelines provide an organized approach to the initial evaluation and management for all trauma patients. The Primary Survey can be easily remembered as "ABCDE" (Figure 14.1). By using these guidelines, consequences from traumatic injuries will be promptly identified and life-threatening injuries will be prioritized and treated first.

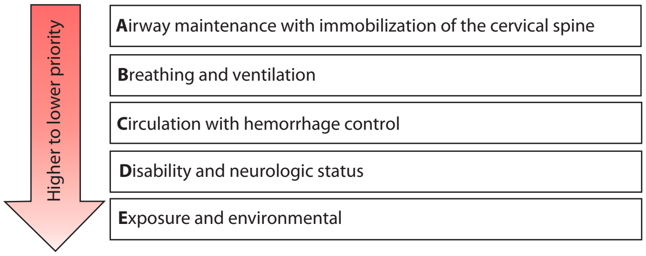

Figure 14.1 A graphic representation for the order, from top to bottom, of the Advanced Trauma Life Support management priorities during the primary survey. Airway (A), breathing (B), circulation (C), disability (D), and exposure/environmental (E).

The sequence of the Primary Survey can be remembered as "ABCDE" and includes A (airway), B (breathing), C (circulation), D (disability), and E (exposure/environment). The A (airway) should be evaluated for patency and opened using a jaw-thrust technique if obstructed. Immobilization of the cervical spine should be maintained. Suctioning of secretions from the oral and/or nasal cavities may also be required. The patient's B (breathing) and ventilation should be evaluated and immediate intervention should take place as necessary. C (circulation) is evaluated by peripheral pulses, blood pressure, sensorium, and skin turgor. Control of external hemorrhage should also take place; this can typically be accomplished by the application of direct pressure to the area that is bleeding. D (disability) is evaluated by looking for potential neurological injuries. The Glasgow Coma Scale (GCS) is perhaps the most commonly recognized scale to estimate the severity of neurological injury; a modified pediatric version has also been developed. E (exposure) of the entire patient should occur. E (environment) should consist of providing a heated treatment area to reduce hypothermia as well as evaluating for environmental threats such as chemical contamination of the patient. During the Primary Survey, the patient's status may deteriorate after the initial resuscitation. Therefore, the patient's vital signs should be regularly reassessed and the providers should be prepared to resume resuscitation.

After the patient has been stabilized, the Secondary Survey may commence. The purpose of the Secondary Survey is to perform a head-to-toe evaluation including a complete history and physical examination; frequent reassessment of all vital signs should also occur. Laboratory and imaging studies are typically performed during the Secondary Survey. If the patient decompensates during the Secondary Survey, the Primary Survey should be resumed immediately. The Tertiary Survey is usually performed after admission. It includes a complete history and physical examination followed by serial patient assessments; many children who require an urgent or emergent operation will receive their tertiary survey after surgery.

The GCS is the most commonly recognized scale to estimate the severity of neurological injury. A GCS score of 8 or less implies significant neurological injury and if present, immediate placement of an advanced airway (i.e. tracheal intubation) is strongly recommended. The GCS and modifications of the GCS for younger children are often combined with the Pediatric Trauma Score (PTS) for pediatric trauma patient evaluation [7,8]. Age-Specific Pediatric Trauma Score (ASPTS) and Revised Trauma Score (RTS) may be used to help the trauma team estimate the severity of the patient's condition and the need for transfer to a pediatric trauma center [9–11] (Figure 14.2). Using these evaluation tools, the anesthesiologist has an important role along with the surgeon in identifying surgical priorities, formulating an appropriate plan with the surgical team, and occasionally determining which procedures need to be performed first as well as which

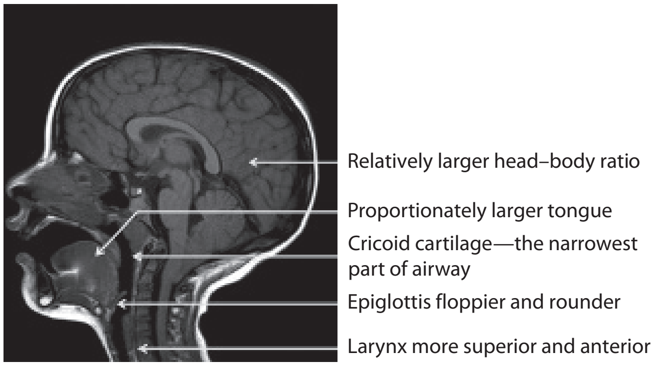

Figure 14.2 The key anatomical characteristics of the pediatric airway.

Table 14.1 List of suggested items that should be obtained during a preoperative evaluation of the pediatric trauma patient categorized by items that occurred prior to the injury (preinjury) and since the injury occurred (current)

Preinjury items	Current items
Medical history	Vital signs
Surgical history	Airway/C-spine evaluation
Drug allergies	Planned surgical procedure(s)
Current medications	List of known injuries
Fasting time	Treatment(s) since arrival
Anesthetic history	Relevant laboratory/imaging results

procedures should be postponed until the patient's condition becomes more stabilized.

Once the determination has been made that the pediatric trauma patient requires operative intervention, the anesthesiologist should perform a preoperative evaluation, if time permits based on the patient's medical stability, and should focus on the relevant items required (Table 14.1).

Anatomic and physiologic considerations in pediatric trauma patients

Many of the anatomic changes in pediatric patients directly impact anesthetic management including increased difficulty in obtaining a secure airway. Developmental changes in the anatomy of the upper airway are most dramatic in children within the first 8 years of life. Several physiologic differences in children, when compared to adults, also have significant relevance during anesthetic care.

Neonates and infants have larger head-to-body ratios when compared with adults. The large occiput naturally raises the head into the "sniffing" position, which may result in airway obstruction [12]. Compared to an adult, the pediatric airway has several characteristics relevant to anesthetic management (Figure 14.2).

From a physiological standpoint, children, on a per kilogram basis, have a basal metabolic rate that is significantly higher than adults. Their basal oxygen consumption (4–6 mL/kg of oxygen per minute) is significantly higher than adults (2–3 mL/kg of oxygen per minute) [13]. Children also have disproportionately decreased functional residual capacity when compared with adults. Both of these characteristics contribute to the development of hypoxemia more rapidly than in an adult. Infants have noncalcified ribs and poorly developed chest wall musculature. These characteristics result in predominantly diaphragmatic breathing and an overall increased work of breathing. The lack of calcification to the ribs results in decreased protection and an increased likelihood of great vessel, cardiac, and pulmonary injuries from a significant force delivered to the thorax.

The cardiac output in infants and children is more dependent on heart rate than in adults. Cardiac output can be calculated by multiplying heart rate by stroke volume. Infants and children are less effective in augmenting cardiac output by changes to stroke volume; their main mechanism is through increasing the heart rate. In addition, infants and children typically have a resting heart rate higher than adults. However, infants and children are typically at low risk for the development of myocardial ischemia due to prolonged tachycardia.

Airway management

The goals of airway management in the pediatric trauma patient include achieving adequate oxygenation and ventilation along with protection of the patient's airway reflexes. The first priority within the Primary Survey is to evaluate and maintain the integrity of the airway. If the patient's condition permits, a comprehensive airway evaluation should be performed. In the conscious child, the ability to vocalize is reassuring and may suggest a patent airway. In the unconscious child, the airway must be assessed quickly to confirm if breathing is present. If the patient has an obstructed airway, performing a jaw-thrust maneuver may reduce or eliminate the airway obstruction [14]. An oropharyngeal airway may also be considered to temporarily maintain upper airway patency until a definitive airway has been established. A nasopharyngeal airway should be used with caution particularly if midfacial injuries are suspected. Suctioning should also be considered if secretions are present. Verifying that airway obstruction is not related to inappropriate placement of the cervical collar is also indicated.

If the airway cannot be maintained despite these relatively simple maneuvers or if other indications for intubation are present such as a GCS <9, immediate tracheal intubation is usually required. The typical indications for tracheal intubation in the pediatric trauma patient include [15]:

1. Apnea
2. GCS <9
3. Unstable midface trauma
4. Airway injuries

5. Large flail chest segment(s)
6. Inability to otherwise maintain acceptable ventilation and/or oxygenation
7. Severe cardiovascular instability

The choice of tracheal intubation technique depends on many factors including the patient's condition as well as the provider's training, preference, and equipment availability. The anesthesiologist should initially assume that most pediatric trauma patients have a cervical spine injury and are at increased risk for pulmonary aspiration of gastric contents [16]. Physical examination of the head and neck should be performed, if feasible, prior to performing airway management. Although several predictors of a difficult airway in adults have been reported, none have been reliably established in children. However, physical examination of the airway in children should attempt to identify characteristics that have an increased association with a difficult airway such as decreased mouth opening, reduced neck extension, and the presence of congenital disorders (Table 14.2) [17–19].

Before airway management is performed, the anesthesiologist must ensure that the proper equipment is present and functioning, including laryngoscope blades and handles, suction, monitors, tracheal tubes of several sizes, and a tracheal tube stylet. All monitors should be properly functioning, and at a minimum, the pulse oximeter and blood pressure cuff should be applied prior to medication administration. The size of the laryngoscope blade for tracheal intubation is typically selected based on the child's age. A straight Wisconsin or Miller blade is commonly used in children up to 10 years of age; a curved Macintosh blade is commonly used in older children and adults. Additional equipment and appropriate sizes may be determined using common bedside references or with the Broselow® tape. The Broselow pediatric emergency tape is a commercially available (Armstrong Medical Industries, Lincolnshire, IL) product that has a reference color range when placed lengthwise next to the patient. Each color range corresponds to a list of equipment sizes and medication doses to perform emergency resuscitation including tracheal intubation.

Cuffed tracheal tubes are increasingly popular, replacing uncuffed tubes in most infants and children [20]. Advantages of cuffed tracheal tubes include reduced placement attempts, improved monitoring of respiratory gases, enhanced ability to ventilate patients requiring high airway pressures, and decreased risk of pulmonary aspiration. The cuffed tube that corresponds to the correctly sized uncuffed tube is 0.5 mm internal diameter (ID) smaller than the latter. Several methods are available for estimating the appropriate size for an uncuffed or a cuffed endotracheal tube in children. A 3.0 (ID in mm) tube should be used in neonates up to the age of 3 months, a 3.5-mm tube up to the age of 9 months, and a 4.0-mm tube for ages 10–18 months. Thereafter, the size of a cuffed tracheal tube can be calculated with the following formula: ID size (mm) = (age in years/4) + 3 [21].

After airway management has occurred or if a patient arrives with a tracheal tube in place, verification of the tracheal tube should occur immediately. Clinical methods of

Table 14.2 Risk factors for a potential difficult airway in pediatric patients categorized by physical examination findings, congenital disorders, and acquired traumatic conditions

Physical examination findings	Anatomic abnormality	Congenital disorders	Acquired traumatic conditions
Airway obstruction	Macroglossia	Down syndrome, mucopolysaccaridoses (Hurler's, Hunter's syndromes), Beckwith–Wiedemann syndrome	
	Airway edema		Acute burns, facial injury, smoke inhalation, laryngeal and tracheal trauma
Decreased mouth opening	Mandibular hypoplasia/micrognathia	Pierre–Robin syndrome, Treacher–Collins syndrome, Goldenhar syndrome, achondroplasia	
	Microstomia	Trisomy 18, Freeman–Sheldon syndrome	
	Limited excursion of the mandible	Temporomandibular joint dysfunction	Mandibular fracture
Decreased neck movement	Cervical spine disorder	Down syndrome, Klippel–Feil anomaly	Cervical spine injury
	Large neck circumference		Obesity

tracheal tube verification including the rise of the chest during positive-pressure ventilation, auscultation of bilateral breath sounds, and the absence of breath sounds over the epigastrium all are limited in their reliability. Measurement of end-tidal carbon dioxide concentrations is more reliable in confirming endotracheal tube position, although under selected conditions, this monitor may also be unreliable and yield false positive results [22]. If the correct placement of a tracheal tube is unclear, strong consideration should be given to verify the location of the tracheal tube by direct or indirect laryngoscopy; both techniques are equally considered very reliable.

It is important to mention that tracheal intubation in the prehospital setting may not occur due to multiple reasons. Unsuccessful prehospital airway management for pediatric patients may be due to training, experience, equipment, and environmental issues. Many prehospital providers (e.g., paramedics) have minimal initial training in pediatric airway management skills including tracheal intubation and do not typically have ongoing maintenance of these skills. Recent guidelines have suggested that avoidance of airway instrumentation in the prehospital setting may be just as effective as securing the airway for pediatric patients. For example, the AHA, PALS guidelines state that "Bag-mask ventilation can be as effective as ventilation through an endotracheal tube for short periods and may be safer" [23]. The 2010 PALS guidelines also state that "In the prehospital setting, ventilate and oxygenate infants and children with a bag-mask device, especially if transport time is short." As a result, many emergency medical services (EMS) have policies containing a "scoop and run" philosophy for pediatric trauma patients that avoids definitive airway management if the transport time is short and effective bag-mask ventilation can be performed. In addition, many EMS policies contain provisions for the placement of supraglottic airway devices in lieu of tracheal intubation if mask ventilation is difficult or tracheal intubation was unsuccessful.

Cervical spine immobilization

Cervical spine injuries should be suspected in all pediatric trauma patients until proven otherwise. About 2%–5% of all blunt trauma victims have a cervical spine injury and 7%–14% of these are unstable [16,24,25]. Patients with severe head injuries (GCS < 9) are at increased risk for cervical spine injuries [26,27]. This potential for cervical spine injuries may make airway management more challenging in the trauma patient mostly due to reduced neck extension. Neck flexion or extension for any reason including tracheal intubation may worsen preexisting cervical spine injuries. Manual in-line immobilization of the cervical spine reduces this movement by 60% and may prevent neurological deficits after direct laryngoscopy [28–30].

Special attention should be given to the mechanism of injury, level of consciousness, gross neurological deficits, and the presence of midline cervical tenderness. If neck tenderness, decreased sensorium, or a neurological deficit is present, one must assume that a cervical spine injury exists. A computed tomography (CT) scan of the cervical spine may be helpful in the identification of lesions that are not visible on plain radiographs. However, spinal cord injury without radiographic abnormality (SCIWORA) is a functional injury that has been estimated to occur in approximately 25%–50% of pediatric patients with spinal cord injuries. SCIWORA can best be diagnosed with magnetic resonance imaging (MRI).

The cervical spine cannot be cleared based solely on diagnostic imaging; cervical spine imaging must be used in conjunction with a clinical examination. MRI of the cervical spine may be indicated in the postoperative period if the cervical spine cannot be cleared by physical examination (i.e., patient remains unconscious, patient uncooperative with exam, presence of distracting injuries). It is strongly recommended to incorporate manual in-line immobilization of the cervical spine during all airway management techniques in all pediatric trauma patients unless the cervical spine has been cleared prior to airway management. No specific airway management technique has been demonstrated to be superior in the management of the pediatric trauma patient with a suspected cervical spine injury [31].

Rapid-sequence induction and intubation

Regardless of the fasting time, all pediatric trauma patients should be assumed to have an increased risk for pulmonary aspiration of gastric contents due to several factors including recent ingestion, delayed gastric emptying caused by trauma, and the previous administration of opioids [32]. Pulmonary aspiration of gastric contents is associated with a significant increase in morbidity and mortality. A rapid-sequence induction and intubation (RSI) is commonly performed for pediatric trauma patients as long as a difficult airway is not suspected [33,34].

The RSI technique consists of preoxygenation with 100% oxygen, placement of cricoid pressure, followed by the bolus administration of an induction agent such as etomidate, ketamine, or propofol, and a neuromuscular blocking agent such as succinylcholine or high-dose rocuronium, followed by laryngoscopy and tracheal intubation. An RSI airway management technique first involves preoxygenation with 100% oxygen to help reduce the rate and severity of hypoxemia development during the apnea and decreased ventilation occurring throughout airway management. Positive pressure ventilation before tracheal intubation during a rapid-sequence induction is avoided to reduce the risk of stomach insufflation followed by gastric regurgitation. Cervical spine immobilization is also performed during RSI for most trauma patients.

Despite common acceptance of RSI, there has been significant disagreement regarding many aspects of this method [35]. Evidence-based data supporting the RSI technique are lacking [36]. RSI is associated with producing rapid and significant degrees of hypoxemia. The anesthesiologist must balance the risks and benefits of an RSI with those of other airway management techniques. The decision to utilize RSI assumes that the anesthesiologist has completed an airway evaluation and predicts that the intubation will be straightforward and that mask ventilation while maintaining cricoid pressure will be adequate as a backup if tracheal intubation is unsuccessful. It is important to ensure that the correct location of the cricoid cartilage has been identified and to apply an adequate amount of pressure to it. Excessive pressure may worsen the visualization of the larynx and make tracheal intubation technically more difficult.

For the patient with a potential difficult airway, RSI is contraindicated since an unsuccessful RSI attempt will require bag-mask ventilation, which may increase the risk of pulmonary aspiration as well as the inability to adequately ventilate and oxygenate the patient. In these situations, the urgency of securing the airway takes priority over the risks associated with aspiration of gastric contents. Such cases may be managed by utilizing an “awake” intubation approach, which may include topical anesthesia and sedation medications combined with the following techniques: (1) “awake intubation” under direct laryngoscopy or rigid bronchoscopy, (2) indirect laryngoscopy using either a fiberoptic bronchoscope (FOB) or video laryngoscope, (3) supraglottic airway device used as a conduit for tracheal intubation with or without FOB, or (4) surgical techniques such as a needle cricothyrotomy or awake tracheostomy.

In a nonemergent situation, the FOB is perhaps considered the gold standard approach for difficult airway management. FOB can be very helpful especially in children with limited mouth opening, neck movement (common in the trauma patient with a cervical collar in place), or with associated congenital syndromes that make direct laryngoscopy difficult or impossible. Such approaches are potentially advantageous since the main goal of all these airway management techniques is to maintain spontaneous ventilation and perhaps allow the option of aborting the procedure if unsuccessful. However, it should be emphasized that these airway techniques can be challenging in small children or patients with copious secretions or blood in the pharynx. In addition, large amounts of sedation to achieve effective patient cooperation during airway interventions may approach levels of general anesthesia and produce significant respiratory depression and airway obstruction.

Another strategy for airway management in the patient with a suspected difficult airway is to anesthetize the child by facemask with an inhaled anesthetic agent, such as sevoflurane in 100% oxygen, combined with cricoid pressure. Once the child is thought to be anesthetized, airway management can be performed using any of the previously mentioned techniques while the child continues to breathe spontaneously. In addition to using an inhaled anesthetic agent, a total intravenous anesthetic (TIVA) could be substituted using medications such as propofol and/or dexmedetomidine while maintaining spontaneous respirations during instrumentation of the airway. Ketamine also offers potential advantages in that it provides sedation while maintaining spontaneous respirations but it can increase oral secretions making visualization more challenging.

In emergency situations, blind placement of a supraglottic airway device such as a laryngeal mask airway (LMA) is recommended as part of the American Society of Anesthesiologists Difficult Airway Algorithm. The LMA does not protect the airway from tracheal aspiration of gastric contents but it may be used as a conduit to facilitate either a blind or fiberoptic intubation of the trachea as well as providing adequate ventilation. The development of an LMA with a modified cuff and drainage tube designed specifically for emergency airway management may make this process even safer for patients who weigh more than 5 kg because evacuation of the stomach may be performed via a separate channel. Another type of LMA product has been designed to blindly place an integrated tracheal tube into the trachea from within the supraglottic airway. However, this is only of benefit in children larger than 30 kg since pediatric versions are not currently available.

The number of attempts at conventional direct laryngoscopy should be minimized to avoid bleeding and laryngeal edema. If attempts at conventional laryngoscopy fail, other nonsurgical intubation techniques for the difficult airway (i.e., LMA, FOB) should be strongly considered. If these also are ineffective, mask ventilation should continue until the child resumes spontaneous ventilation and awakens or a surgical airway can be established. Anesthesiologists caring for pediatric trauma patients should always expect and be prepared for a potential difficult tracheal intubation. They should acquire competency in other airway management techniques that may be used as rescue techniques in case of unsuccessful traditional direct laryngoscopy. A suggested algorithm for managing an unexpected difficult airway during a rapid-sequence induction is illustrated in Figure 14.3.

Common medications used in pediatric patients for rapid-sequence induction

Anesthetic medications are typically administered to pediatric trauma patients who require tracheal intubation, except for patients in severe shock or cardiorespiratory arrest [37]. The selection of medications for RSI depends on the hemodynamic stability, neurological status, and the patency of the airway as well as the preferences of the anesthesiologist. The goals of selecting a medication regimen for emergency tracheal intubation are to produce unconsciousness, create ideal intubation conditions, and maintain hemodynamic stability. A comprehensive plan should be developed to consider all relevant perioperative factors that will impact the selection of these medications. For example, an amnestic agent, such as midazolam, may be considered to alleviate substantial fear and anxiety prior to commencing the RSI. In addition, a patient with a suspected head injury requires medications, such as fentanyl, to blunt sympathetic stimulation from tracheal intubation in order to mitigate increases to intracranial pressure (ICP) during intubation. Typical

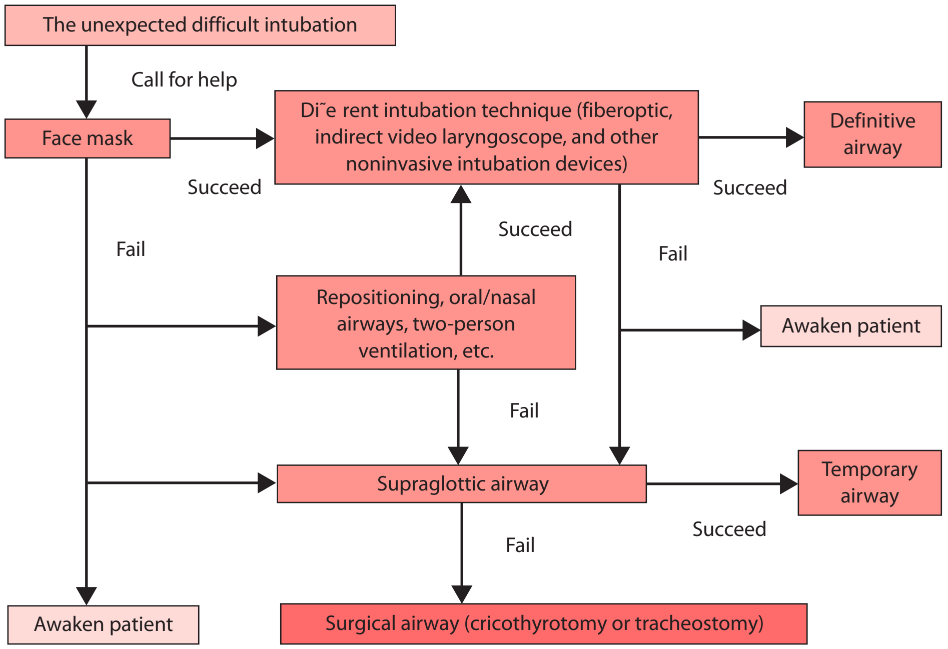

Figure 14.3 Suggested algorithm for managing an unexpected difficult airway during a rapid-sequence induction.

medications utilized for an RSI in pediatric trauma patients along with their doses, advantages, and disadvantages are listed in Table 14.3.

A typical medication regimen includes an anesthetic induction medication in combination with a neuromuscular blocking agent to provide rapid and optimal conditions for tracheal intubation [38–42]. For critically ill and hemodynamically unstable children, propofol may produce profound hypotension due to myocardial depression and vasodilation; therefore, it should be avoided or used at reduced doses. Medications such as etomidate or ketamine, which are less likely to produce hypotension, should be considered in this situation. Conversely, inadequate dosing of these medications may cause severe hypertension and tachycardia during stimulating procedures such as airway management.

Succinylcholine is a common choice for a neuromuscular blocking agent during RSI in adults due to its rapid onset of action and ultrashort duration [43]. However, in patients with several conditions including muscular dystrophy, prolonged immobilization, burns, crush injuries, upper and lower motor neuron lesions, succinylcholine may cause severe hyperkalemia and subsequent cardiac arrest [44,45]. Succinylcholine is also a triggering agent for malignant hyperthermia in susceptible patients [46]. The use of succinylcholine for tracheal intubation in children has lost popularity among pediatric anesthesiologists due to previous reports of cardiac dysrhythmias and hyperkalemic cardiac arrest, which resulted in the Federal Drug Administration issuing a black box warning regarding the routine administration of succinylcholine to children. Of note, many of the patients who developed hyperkalemic cardiac arrest after receiving succinylcholine were subsequently diagnosed with various forms of muscular dystrophy.

Rocuronium is a nondepolarizing neuromuscular blocking agent and an acceptable alternative to succinylcholine during RSI. In contrast to succinylcholine, rocuronium for RSI, when compared to routine use, requires higher doses to produce a shortened onset time with acceptable intubating conditions. However, administering a larger dose results in a prolonged duration of neuromuscular blockade [46]. Rocuronium has vagolytic properties resulting in modest tachycardia, which may improve overall hemodynamic function because in most children cardiac output is dependent on heart rate. When a pediatric trauma patient does not have a suspected difficult airway, rocuronium is the neuromuscular blocking agent selected by many, if not most, pediatric anesthesiologists.

Opioids are also occasionally utilized during RSI to minimize the sympathetic response to laryngoscopy and tracheal intubation, especially in the setting of traumatic brain injury (TBI). Fentanyl is one of the most commonly used medications due to its rapid onset and short duration of action [47]. Local anesthetics, such as lidocaine, may also be administered to minimize the sympathetic response from stimulation of airway reflexes during laryngoscopy and tracheal intubation.

Cardiopulmonary resuscitation

Trauma is one of the leading causes of cardiac arrest in children beyond 1 year of age [48]. In contrast to adults, cardiac disease is typically not a primary cause of cardiac arrest in the pediatric patient. More often, cardiac arrest in children is the terminal result of respiratory failure and/or shock, followed by bradycardia and ultimately cardiac arrest [49]. For the pediatric trauma patient presenting in cardiac arrest, hypovolemic shock

Table 14.3 Dosages, advantages, and disadvantages of commonly utilized anesthetic medications in pediatric trauma patients during RSI

Medication	Intravenous dose (mg/kg)	Advantages	Disadvantages
Amnestic			
Midazolam	0.05–0.2	Amnesia, anxiolysis, minimal respiratory depression, increases seizure threshold	Rarely may cause paradoxical agitation
Induction agents			
Ketamine	1–2	Preserves hemodynamic stability; bronchodilation	Increased oral secretions and may increase intracranial pressure (ICP); may cause hypotension if catecholamine depleted; causes nystagmus
Propofol	1–3	Sedative-hypnotic; anti-emetic properties; lowers ICP	May cause significant hypotension particularly if hypovolemic; painful on injection
Etomidate	0.2–0.3	Preserves hemodynamic stability; lowers ICP	Possible long-term adrenal suppression; painful on injection
Neuromuscular blocking agents			
Succinylcholine	1–2	Rapid onset and ultrashort duration	May cause bradycardia, hyperkalemia, malignant hyperthermia; may increase intracranial, intraocular, and intragastric pressures
Rocuronium	0.6–1.2	Rapid onset at high doses with similar onset time as succinylcholine	Intermediate to long duration; vagolytic properties increase heart rate
Opioids			
Fentanyl	0.001–0.003	Attenuates hemodynamic responses to tracheal intubation; preserves hemodynamic stability	Can cause bradycardia, respiratory depression, and chest wall rigidity; minimal sedation
Other			
Atropine	0.01–0.02	Attenuates vagal response and reduces oral secretions	Tachycardia, flushed skin, sedation
Glycopyrrolate	0.01	Attenuates vagal response and reduces oral secretions	Tachycardia
Lidocaine	1–1.5	Attenuates hemodynamic responses to tracheal intubation	Can cause central nervous system and cardiac toxicity in large doses

due to hemorrhage and direct injury to the heart, chest, and/or great vessels are the most likely causes. The AHA PALS program provides a structured approach to the effective assessment, resuscitation, and team dynamics of the critically ill pediatric patient [5]. Many of the general principles found within the PALS program are similar in concept to items within the ATLS guidelines. The PALS guidelines can be utilized during resuscitation as a supplement to ATLS to provide additional specific management strategies such as medication and defibrillation treatment guidelines.

During the Primary Survey, a prompt assessment of the patient should occur to determine if the patient is breathing and if a palpable pulse is present. If the patient is found to be pulseless, chest compressions should be started immediately. The key components of Pediatric Basic Life Support (BLS) are listed in Table 14.4. The type of electrocardiographic rhythm should then be determined. Many types of cardiac rhythms including sinus tachycardia, asystole, and bradycardia may occur in pediatric trauma patients [49] as well as ventricular fibrillation (VF) and pulseless electrical activity (PEA) [50].

The most recent 2015 PALS Pediatric Cardiac Arrest Algorithm incorporates four cardiac rhythms that are divided into shockable and not shockable categories [5]. PEA and asystole comprise the nonshockable rhythms. VF and pulseless ventricular tachycardia (VT) are shockable rhythms.

Table 14.4 The key components of pediatric basic life support

1. Determine responsiveness and pulse, if palpable.
2. Call for help and emergency equipment.
3. If pulseless, promptly begin chest compressions (15:2 ratio compressions to breaths, if multiple rescuers):
   Compression rate goal of 100–120/min;
   Breathing rate goal of 12–20/min.
4. Reevaluate patient every 2 min.
5. Analyze heart rhythm when equipment arrives.
6. Transition care to Advanced Life Support providers when available.

Defibrillation is the definitive treatment for VF with an overall survival rate of 17%–20% [51,52]. For shockable rhythms such as VF or VT, defibrillate one time at 2 J/kg and resume cardiopulmonary resuscitation (CPR) immediately. Five cycles of CPR then follow (which typically takes 2 minutes). If the rhythm is still shockable, defibrillate once at 4 J/kg and immediately resume CPR. After defibrillation, epinephrine is given every 3–5 minutes. The dose for epinephrine is 10 mcg/kg (intravenous [IV] or intraosseous [IO]) and 100 mcg/kg if given via the tracheal tube. Five cycles of CPR then occur followed by reevaluation. If the rhythm is shockable, defibrillate at 4 J/kg followed by resuming CPR. One then will administer a bolus of amiodarone 5 mg/kg IV or lidocaine 1 mg/kg. This cycle of one shock followed by five cycles of CPR is repeated until a decision is made to terminate efforts or the rhythm becomes not shockable. Pediatric paddles should be used for patients below 10 kg (<1 year of age).

For nonshockable rhythms such as asystole or PEA, an initial dose of 10 mcg/kg of epinephrine should be administered via the IV or interosseous route. If spontaneous circulation has not returned, further doses of epinephrine should be administered repeatedly every 3–5 minutes while chest compressions are continued and reversible causes treated accordingly (i.e., tension pneumothorax, cardiac tamponade, hypovolemia). Emphasis on providing high-quality chest compressions should be continued with minimal delays. Additional PALS algorithms have also been developed for the management of unstable tachycardia and bradycardia [5].

Intraoperative considerations

Vascular access

Reliable vascular access should be established as early as possible. Obtaining venous access may be very difficult in pediatric trauma patients, especially if the patient is hypovolemic. Common sites for peripheral venous access include the dorsum of the hand and foot, the saphenous vein, and the cephalic vein within the antecubital fossa [51]. Two large-bore IV lines, appropriately sized for age, are preferred; this will allow rapid infusion of medications, IV fluids, and blood products. For the critically ill patient such as one in shock or cardiopulmonary arrest, attempts at peripheral access should not be delayed. Ultrasound and other vascular access devices may be used to facilitate obtaining peripheral and central venous access. Ultrasound-guided techniques can also be used to obtain arterial line access.

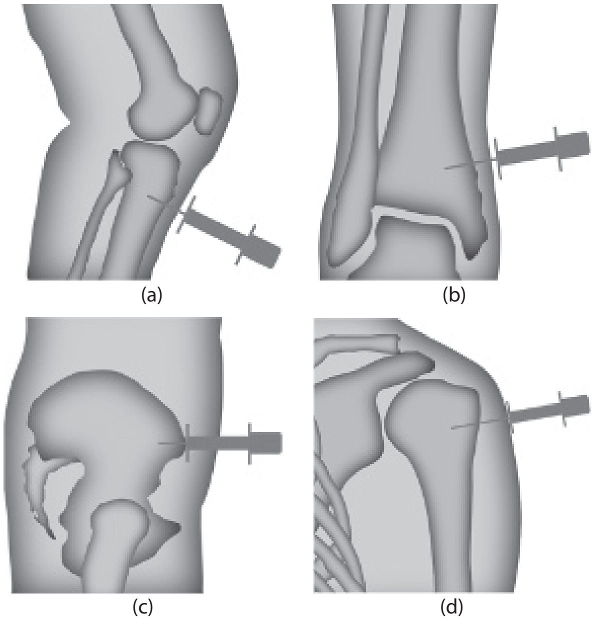

Figure 14.4 Suggested anatomical locations for placement of an intraosseous vascular access line. **(a)** One finger's breadth distal to the tibial tuberosity, **(b)** one centimeter superior to the medial malleolus, **(c)** the anterior superior iliac spine, and **(d)** the greater tubercle of the humerus.

The IO access is considered a reliable alternative for vascular access and is effective in providing fluid resuscitation. IO lines should be strongly considered if difficult venous access occurs and can accordingly reduce significant time delays when compared with other methods [52,53]. IO access gains entry to the systemic circulation and is an effective way to establish vascular access [54]. The preferred IO insertion sites are the anteromedial aspect of the proximal tibia (most common), distal tibia, proximal humerus, and iliac crest (Figure 14.4) [55]. Any medication or solution (e.g., crystalloids, colloids, and blood products) that can be given intravenously can also be administered via the IO route at the same doses. Laboratory samples may also be obtained from the IO space. The onset of action and drug concentrations by way of the IO access are comparable with those given intravenously [56,57].

Fluid management

In pediatric patients, blood pressure may not be a reliable indicator of intravascular volume loss. Hypotension is a late sign of uncompensated shock that usually does not manifest until a significant loss of intravascular volume (25%–35%)

has occurred [58]. Hypovolemia may remain unrecognized until after induction of anesthesia due to the administration of medications, which can cause rapid and severe cardiovascular collapse.

Once vascular access has been established, the type and amount of IV fluid and/or blood products administered must be individualized according to the nature of the injury and the patient's needs. Both inadequate and excessive fluid resuscitation may be detrimental to the traumatized pediatric patient. The patient's hemodynamic status (i.e., heart rate and blood pressure) should be frequently reevaluated particularly after fluid administration to determine the response to therapy. Initial fluid resuscitation typically involves administration of isotonic crystalloid solutions such as normal saline or lactated Ringer's solution. Hypotonic and glucose-containing solutions are avoided for volume resuscitation since they may lead to hyponatremia and hyperglycemia and may also worsen cerebral edema. ATLS guidelines advise giving a fluid bolus of 20 mL/kg of isotonic crystalloid. If the blood pressure is refractory after two fluid boluses of isotonic crystalloid, strong consideration should be given to the administration of blood products. The typical initial dose for administration of packed red blood cells is 10 mL/kg. A colloid solution, such as 5% albumin, has also been used for pediatric fluid resuscitation. Colloid solutions use smaller volumes of fluid to restore intravascular volume when compared to crystalloids. Hypertonic saline has also been utilized for fluid resuscitation but has not been shown to have any beneficial effect when compared to standard crystalloid resuscitation. The optimal fluid therapy for trauma resuscitation in pediatric patients has not been established.

Massive transfusion

The strategy of administering blood products earlier in the resuscitation process has now been emphasized in the updated ATLS guidelines [59]. However, no guidelines or ratios have been recommended regarding the use of specific blood products such as plasma or platelets among pediatric patients. In spite of this, if the patient's blood pressure is not improving after multiple fluid boluses including blood products, strong consideration should occur for emergent transfer to the operating room or the angiography suite for control of hemorrhage.

Massive transfusion protocols (MTPs) typically apply to situations in which 100% of the estimated blood volume is expected to be administered in less than 24 hours or 50% within 3 hours. The estimated blood volume for pediatric patients can range from 75 mL/kg for an adolescent to 100 mL/kg for a premature neonate. MTPs have been widely adopted by many hospitals [60]. Activation of the MTP commonly results in the ongoing and prompt availability of several types of blood components including packed red blood cells, fresh frozen plasma, and platelets. It is preferable to administer type-specific, cross-matched blood products. However, if adequate time is not available to acquire compatible blood products, the initial administration of uncrossmatched, type O packed red blood cells is indicated.

The administration of blood products can result in several detrimental conditions including hypothermia, transfusion reactions, and electrolyte disorders. In addition, pediatric trauma patients are at greater risk than adults for the development of hypothermia, which may result in decreased medication metabolism, delayed emergence, coagulopathies, acid–base disturbances, and cardiac dysrhythmias [61,62]. Ideally, core temperature should be continuously monitored and aggressively maintained using several methods including increased ambient operating room temperature and radiant heaters, forced-air warming devices, fluid warmers, and warmed irrigation fluids. Increased vigilance should occur during the administration of all blood products for hemodynamic instability (i.e., hypotension) and signs of a transfusion reaction (i.e., hemolysis, bronchospasm, and urticaria).

Anesthetic considerations for specific traumatic injuries

Traumatic brain injury

Head injuries are present in approximately 75% of traumatized children and account for 70% of trauma-related deaths [63]. Most head trauma in children is minor and not associated with brain injury or long-term sequelae. Falls are the most common cause of head injury, followed by motor vehicle–related incidents. Nonaccidental trauma is one of the leading causes of head trauma in children younger than 2 years of age [64,65].

Patients with TBI may experience primary brain damage at the time of initial trauma, as well as secondary brain injury. Conditions that can cause secondary brain injury include severe hypoxemia, hypotension, cerebral edema, intracranial hypertension, hyper- and hypoglycemia, and cerebral ischemia [66,67]. These injuries can produce an endogenous cascade of cellular and biochemical events resulting in cell damage or cell death [68]. The most important anesthetic goal in the acute management of the pediatric patient with TBI is to prevent the development of secondary brain injury.

Following pediatric TBI, cerebral autoregulation is likely to be impaired [69]. Therefore, prompt airway control, adequate oxygenation and ventilation, and optimizing cerebral perfusion pressure (CPP) are of the utmost importance to prevent secondary brain injury [70]. CPP is defined as the difference between the mean arterial pressure and the greater of ICP or central venous pressure (CVP). Excessive hyperventilation ($PaCO_2$<30 mmHg) will cause cerebral vasoconstriction and may result in cerebral ischemia [71] and is therefore avoided. Normal ventilation or perhaps moderate hyperventilation is recommended to selectively manage transient episodes of acute intracranial hypertension in order to prevent cerebral herniation [72,73]. Systemic hypotension is a strong predictor of morbidity and mortality after TBI [74]. Age-specific goals of CPP > 40 mmHg for 0- to 5-year-olds and >50 mmHg for 6- to 17-year-olds have been suggested [66,75].

Management strategies for increased ICP include the administration of osmotic diuretics and hypertonic saline, raising the head of bed, drainage of cerebrospinal fluid, and hyperventilation. Mannitol is a commonly used osmotic diuretic in the management of ICP; however, studies demonstrate lack of consensus on the best approach to manage increased ICP in pediatric TBI [76]. In addition, mannitol may accumulate in the injured brain, reverse the osmotic shift, and exacerbate cerebral edema [77,78].

There is limited data regarding the preferred anesthetic management for pediatric TBI. Anesthetic implications for TBI include maintenance of hemodynamic stability in order to preserve CPP. An anesthetic technique should be developed to avoid increased sympathetic stimulation while maintaining hemodynamic stability. Other considerations for intraoperative management include obtaining appropriate vascular access for volume resuscitation, maintaining an increased sense of vigilance for undiagnosed traumatic injuries, as well as avoiding hyperglycemia, hypotension, and hypothermia. Anesthetic medications such as propofol and etomidate may be selected in order to reduce the cerebral metabolic rate for oxygen ($CMRO_2$), decrease cerebral blood flow (CBF), and decrease ICP [79,80]. However, propofol may also cause significant hypotension resulting in the reduction of CPP and the development of secondary brain injury. All inhalational anesthetic agents decrease $CMRO_2$, but may cause direct cerebral vasodilatation, resulting in an increase of CBF and ICP [81].

Anesthesia for thoracic trauma

Severe thoracic trauma in children is not common and usually the result of significant blunt force [82,83]. The chest wall of a pediatric patient is relatively compliant and may receive a considerable force without producing rib fractures. Consequently, the absence of rib fractures after significant force to the chest is a poor predictor of major injury to the lungs, great vessels, and heart [84]. More than 80% of children with significant thoracic injuries also have multisystem injuries resulting in an overall mortality rate of 26% [85].

One of the most common thoracic traumatic injuries in the pediatric patient is a pneumothorax; this injury may occur with tension and hemothorax components. Pulmonary contusions with or without associated rib fractures may also be present. Depending on the severity, pulmonary contusions may cause respiratory failure and may lead to acute respiratory distress syndrome (ARDS) [86]. Many pulmonary contusions will resolve within 7–10 days [87]. Cardiac injuries may result in cardiac tamponade as well as cardiac rhythm disorders. Patients with penetrating trauma may present emergently to the operating room; some may be definitively managed with placement of a chest tube in the ED. Approximately 20% of patients will also require surgical intervention due to abdominal injuries [85,88].

The anesthesiologist needs to be prepared to manage a patient with severe underlying pulmonary compromise, massive blood loss, and/or cardiac contusion. Anesthetic management may vary greatly based on the severity of the injury. Ideally, two IV catheters should be placed, preferably one above and one below the diaphragm. When thoracic trauma is suspected, the possibility of pneumothorax should be considered. Positive pressure ventilation should be avoided if possible in children with a clinically significant pneumothorax until needle decompression or chest tube placement has been performed. A low level of positive end expiratory pressure has been advocated to reduce pulmonary atelectasis and restore resting lung volumes during general anesthesia [89].

Anesthesia for abdominal trauma

Most abdominal trauma (85%) in children is caused by blunt injury; many of these patients also have multisystem trauma. Children have proportionally larger solid organs and decreased abdominal musculature; both these characteristics predispose them to injury. The most common life-threatening abdominal traumatic injuries involve disruption of the spleen or liver [90]. Intestinal injuries in children after blunt abdominal trauma are also possible and may require emergent surgery [91].

Anesthesia management for patients with abdominal trauma should focus on the risk of pulmonary aspiration, especially for patients recently consuming oral contrast for radiographic studies. For hemodynamically unstable patients, including those with internal bleeding and those without adequate resuscitation, ketamine or etomidate should be strongly considered as the medications for RSI. Maintenance of anesthesia typically consists of a combination of inhalational anesthetic agents, neuromuscular blocking agents, and opioids. Nitrous oxide should be avoided due to the potential for expanding air-filled spaces [92]. An oral or nasogastric tube should be considered to reduce abdominal distension.

Postoperative considerations

After surgery, many children with major traumatic injuries will require critical care support in the intensive care unit (ICU) with or without planned postoperative mechanical ventilation. Successful extubation in the operating room immediately after surgery is dependent on hemodynamic stability, preexisting injuries, adequate oxygenation and ventilation, and neurological function [93]. For patients requiring ICU care, a detailed report containing the perioperative events should be given to the ICU team in order to provide effective continuity of patient care. Vigilance should continue into the postoperative period for clinical deterioration and the discovery of new injuries.

Effective postoperative pain control is an essential component of the perioperative anesthetic plan. Postoperative pain can usually be effectively managed with a combination of analgesics and regional anesthesia. Acetaminophen and nonsteroidal anti-inflammatory drugs (NSAIDS) such as ketorolac and ibuprofen, if not contraindicated, are commonly used adjuvant medications for the treatment of pain in children [94]. These medications can be administered by the oral or IV routes. If additional analgesia is needed, morphine, fentanyl, or other opioids should be carefully titrated to effect. These narcotics can also be delivered via patient controlled devices. Ultrasound-guided peripheral nerve blockade as well as central neuraxial blockade (i.e., epidural analgesia) have been utilized successfully for postoperative pain control [95,96] in patients without contraindications to regional anesthesia such as coagulopathy and high risk for compartment syndrome development. Extended release formulations for local anesthetic agents have also been utilized for prolongation of local anesthetic action [97].

Future directions

As traumatic injuries continue to be one of the largest public health hazards to children, advances in research and education must be pursued. Clinical research as well as education of parents, children, and medical providers is necessary to prevent injury as well as provide the highest quality of medical care. To accomplish this, the transition must be made from the basic science laboratory to well-designed, randomized controlled trials, which include prehospital providers as well as the medical professionals within well-organized trauma programs.

Many of the anesthetic management issues in pediatric trauma patients have not been established, are under challenge, or are significantly based on data extrapolation from adults. The most appropriate fluids, component ratios, and amounts for volume resuscitation including blood product administration are still unclear. Cricoid pressure and RSI have been challenged as effective procedures. Future studies within the pediatric trauma environment should attempt to answer these questions.

Innovative approaches for the management of the pediatric trauma patient are also in development. Laparoscopic approaches with their own set of anesthetic implications are becoming more common. The use of cognitive aids for resuscitation and crisis management are becoming increasingly utilized and part of the standard culture. The culture and priority for exhibiting high-quality team dynamics during resuscitation as well as conducting inter-professional training by using medical simulation are both expanding the development and effectiveness of the pediatric trauma perioperative team.

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PART III

Specific injuries

15

Treatment of severe pediatric head injury: Evidence-based practice

ADITYA VEDANTAM and WILLIAM E. WHITEHEAD

Introduction

Pediatric traumatic brain injury (TBI) represents an important cause of morbidity and mortality. Our understanding of the pathophysiology of TBI has considerably improved over the past few decades. Although clinical outcomes for severe TBI have improved significantly, there is still a need for high-impact interventions that can preserve neurological function and allow patients to return to a level of activity close to their pre-injury baseline. The cornerstone of treatment for severe TBI, however, continues to be astute clinical management.

Guidelines have been well established for severe adult TBI using data from well-designed randomized control trials [1]. Many of these interventions have been extrapolated to the pediatric population, given the lack of prospective clinical data in the field of pediatric TBI. The panel of experts that created the Guidelines for the Acute Medical Management of Severe TBI in Infants, Children, and Adolescents acknowledged the literature gap in pediatric TBI and the resulting low level of recommendations [2]. In 2012, these guidelines were updated and data from new pediatric TBI studies contributed to higher level of evidence and stronger recommendations compared with the first edition (Table 15.1) [3].

This chapter represents a practice-based approach to treating children with severe TBI, supported by available data and guidelines for the acute management of severe TBI.

Pathophysiology of TBI

Our understanding of TBI is based largely on the principles of primary and secondary injuries. Primary injury relates to the immediate damage to the brain created at the time of trauma. This disruption of cellular and subcellular structures contributes to neurological dysfunction that is difficult, if not impossible, to prevent and remains an important determinant of neurological outcome. Subsequently, secondary brain injury ensues, which is characterized by a cascade of intracellular and extracellular biochemical changes that can result in further neurological deterioration. These processes not only result in more extensive neurological injury but also can considerably impede neurological recovery [4].

The treatment of severe TBI is focused on limiting and preventing secondary injury. Systemic changes such as hypotension, hypoxia, hyperglycemia, and hyperthermia can accentuate secondary injury. The presence of concomitant

Table 15.1 Summary of levels of evidence and recommendations from 2012 pediatric severe TBI guidelines

Subject	Level of evidence	Recommendations
Indications for intracranial pressure (ICP) monitoring	III	Use of ICP monitoring may be considered in infants and children with severe TBI.
Threshold for treatment of intracranial hypertension	III	Treatment of ICP may be considered at a threshold of 20 mmHg.
Cerebrospinal fluid (CSF) drainage	III	CSF drainage through an external ventricular drain may be considered in the management of intracranial hypertension.
Cerebral perfusion pressure (CPP) thresholds	III	Minimum CPP threshold of 40 mmHg may be considered. Age-specific thresholds from 40 to 50 mmHg may be considered with infants at the lower end and adolescents at the upper end of the range.
Advanced neuromonitoring	III	If brain oxygenation monitoring is used, maintenance of partial pressure of brain tissue oxygen ≥10 mmHg may be considered.
Neuroimaging	III	In the absence of neurologic deterioration or increasing ICP, obtaining a routine repeat computed tomography (CT) scan ≥24 h after the admission and initial follow-up study may not be indicated for decisions about neurosurgical intervention.
Hyperosmolar therapy	II	Hypertonic saline should be considered for the treatment of severe pediatric TBI associated with intracranial hypertension. Effective doses for acute use range between 6.5 and 10 mL/kg.
Barbiturates	III	High-dose barbiturate therapy may be considered in hemodynamically stable patients with refractory intracranial hypertension despite maximal medical and surgical management.
Decompressive craniectomy for the treatment of intracranial hypertension	III	Decompressive craniectomy with duraplasty, leaving the bone flap out, may be considered for pediatric patients with TBI who are showing early signs of neurologic deterioration or herniation or are developing intracranial hypertension refractory to medical management during the early stages of their treatment.
Hyperventilation	III	Avoidance of prophylactic severe hyperventilation to a $PaCO_2$ <30 mmHg may be considered in the initial 48 h after injury.
Corticosteroids	II	The use of corticosteroids is not recommended to improve outcome or reduce ICP for children with severe TBI.
Analgesics, sedatives, and neuromuscular blockade	III	Etomidate may be considered to control severe intracranial hypertension; however, the risks resulting from adrenal suppression must be considered. Thiopental may be considered to control intracranial hypertension.
Nutrition	II	The evidence does not support the use of an immune-modulating diet for the treatment of severe TBI to improve outcome.
Antiseizure prophylaxis	III	Prophylactic treatment with phenytoin may be considered to reduce the incidence of early posttraumatic seizures in pediatric patients with severe TBI.
Temperature control	II	Moderate hypothermia (32°C–33°C) early after severe TBI up to 48 h may reduce intracranial hypertension. However, recent data indicate that it may not improve mortality or global functional outcomes after severe TBI.

Source: Kochanek PM et al., *Pediatr. Critic Care Med.*, 13 (Suppl 1), 2012, S1–82. With permission.

solid organ and long bone injuries can adversely impact the degree of neurological injury due to hypovolemia and hypotension. In addition, secondary brain injury is affected by intracranial factors such as cerebral blood flow, perfusion pressure, and metabolism. The loss of cerebral autoregulation in severe TBI can compromise cerebral perfusion and the adequate delivery of oxygen and metabolites to the brain.

The developing brain of a child presents a unique susceptibility to primary and secondary brain injuries. Children have a lower circulating blood volume, less cerebrospinal fluid volume, open fontanelles, and deformable calvaria. These factors make them dissimilar to the adult population and point to the need for treatment guidelines specific to the pediatric population.

Prehospital and emergency room management

The initial assessment and management of severe TBI patients should focus on preventing hypoxia and treating it immediately if present. Almost 25% of TBI patients can suffer from prehospital hypoxia [5], and the use of supplemental oxygen, bag-valve-mask ventilation, or endotracheal intubation should be initiated. It is recommended that endotracheal intubation for pediatric TBI patients be performed by personnel with specialized training and end-tidal CO_2 detectors should be used [6]. If this is not possible, bag-valve-mask ventilation should be continued until the patient reaches the emergency room or personnel with specialized training arrive. Current pediatric TBI guidelines do not include specific recommendations for prehospital management of pediatric patients, but refer to the adult Guidelines for Prehospital Management of Severe Traumatic Brain Injury [3].

Initial assessment

Evaluation of airway, breathing, circulation, neurological status, and disability is the goal of initial assessment. All members of the trauma team including emergency room physicians, nurses, technicians, trauma surgeons, and neurosurgeons should participate in this process. Early identification of compromised physiology is essential to prevent secondary brain injury.

Maintaining a patent airway and ensuring adequate oxygenation should be ensured while maintaining cervical spine precautions, especially avoiding hyperflexion or extension of the cervical spine. This can be performed with a cervical collar or in-line manual immobilization. Hypotension is an important contributor to secondary brain injury, and a systolic blood pressure <75th centile for age is associated with poorer neurological outcomes [7]. In children, tachycardia is an early sign of hypovolemia and needs to be evaluated early.

The Glasgow Coma Scale (GCS) is used to provide a standardized neurological assessment for severe TBI. The standard GCS can be used for children 3 years or older and the pediatric GCS is used for infants up to 2 years of age (Table 15.2) [8,9]. In addition to the GCS, pupils should be examined for size, symmetry, and reaction to light. The presence of localizing signs such as facial asymmetry, hemiparesis, hemiplegia, paraplegia, or a sensory level should be noted. These signs should be elicited prior to the administration of sedative drugs or paralytics for intubation. A rapid, systematic secondary trauma survey is also performed. This includes an evaluation of the extremities, peripheral pulses, and log-rolling the patient; examining the spine; and examination for rectal tone.

Neuroimaging

Early neuroimaging for severe TBI should be performed after the primary and secondary trauma surveys, and when the patient is hemodynamically stable. CT head without contrast is the imaging modality of choice. CT scans provide a rapid assessment for intracranial hemorrhage whether epidural, subdural, subarachnoid, or parenchymal. In addition, skull fractures and pneumocephalus are well visualized on CT scans. The incidence of intracranial injury detected on CT scans in severe pediatric TBI is 62%–75% [10]. With the quick acquisition times of CT scans, emergent neurosurgical interventions, if required, can be initiated. In cases where polytrauma

Table 15.2 Standard and pediatric Glasgow Coma Scale

Response	Score	Glasgow Coma Scale	Pediatric Glasgow Coma Scale
Eye opening	4	Spontaneous	Spontaneous
	3	To speech	To speech
	2	To pain	To pain
	1	None	None
Verbal response	5	Oriented	Coos, babbles, age-appropriate speech
	4	Confused	Irritable, cries
	3	Inappropriate words	Cries to pain
	2	Incomprehensible sounds	Moans to pain
	1	None	None
Motor response	6	Follows commands	Normal spontaneous movements
	5	Localizes to pain	Withdraws to touch
	4	Withdraws to pain	Withdraws to pain
	3	Abnormal flexion	Abnormal flexion
	2	Abnormal extension	Abnormal extension
	1	None	None

Sources: Teasdale G and Jennett B, *Lancet*, 2 (7872), 1974, 81–84. With permission; Holmes JF et al., *Acad. Emerg. Med.*, 12 (9), 2005, 814–819. With permission.

is suspected, CT head can be combined with CT scans of the chest, abdomen, or pelvis. The performance of an early CT scan also allows for timely triage and transfer to higher levels of care if needed. The use of MRI is not recommended in the acute setting of severe pediatric TBI, due to the need for sedation, the long acquisition times, and the difficulty in monitoring critically ill patients in the scanner.

The use of routine follow-up CT imaging (>24 h after admission) in severe pediatric TBI is not recommended if there is no neurological deterioration or increasing intracranial hypertension. In some instances, CT imaging is repeated in patients in whom there is a concern for a progressing intracranial lesion and the presence of sedatives or paralytics limits neurological examination. In patients who have undergone a surgical intervention for severe TBI such as evacuation of a hematoma or decompressive craniectomy, a postoperative CT scan may be performed to assess for postsurgical complications or enlargement of contralateral hematomas not addressed during surgery. Overall, a follow-up CT scan is not a trivial issue and the need for the scan should be weighed against the risks of transporting a critically ill patient and the additional radiation exposure.

Management in intensive care unit

Intracranial pressure monitoring

Children with severe TBI are at risk of intracranial hypertension, with almost a third of patients having high intracranial pressure (ICP) > 20 mmHg [11]. Intracranial hypertension has been shown to be a predictor of poor neurological outcome or death after severe TBI in children [12]. Intracranial hypertension is an important factor for decreased cerebral perfusion pressure and neural injury after severe TBI. Children with severe TBI have been shown to have improved long-term neurological outcomes if they had ICPs successfully controlled after the injury [13]. The use of ICP monitoring is a level III recommendation for infants and children with severe TBI.

A number of intracranial devices are available for monitoring and treating ICP. The commonest device is an external ventricular drain, which is inserted into the frontal horn of the lateral ventricle and connected to a pressure transducer to provide a real-time measure of ICP. In addition to being a low-cost intervention, it provides the opportunity to drain cerebrospinal fluid and treat intracranial hypertension in addition to monitoring. Intraparenchymal bolts and subdural bolts are also able to monitor ICP. These devices cannot drain cerebrospinal fluid to treat intracranial hypertension and may provide only a local estimate of ICP in the area of parenchyma adjacent to the device. At present, no studies have evaluated if the type of ICP monitor influences neurological outcome.

Thresholds for treatment of intracranial hypertension

Sustained intracranial hypertension (>20 mmHg) is associated with poor neurological outcome in children with severe TBI [14]. The normative values of blood pressure and ICP are age dependent, and it is possible that the optimal threshold for treating ICP is age dependent as well. Although there are limited data available to support these findings, it is known that the degree of autoregulation is lower in younger children as compared to older children. A comparative study on maintaining two different ICP thresholds in pediatric TBI is yet to be performed. Current level III recommendations target maintaining the ICP < 20 mmHg after severe TBI in children.

One of the important goals of intensive care management after severe TBI is to maintain adequate perfusion of the brain. The cerebral perfusion pressure, which provides a quantitative assessment of brain perfusion, is calculated as the mean arterial pressure minus the mean ICP. Decreases in cerebral perfusion pressure coupled with changes in the cerebral metabolic rate can contribute to local and global cerebral ischemia. The presence of an ICP monitoring device and an arterial line allows for accurate measurement of cerebral perfusion pressure. The optimum physiological range of cerebral perfusion pressure varies with age. This suggests an appropriate cerebral perfusion pressure threshold be targeted particularly with infants and adolescents. Actual cerebral perfusion pressure may be underestimated using current ICP monitoring practices. Theoretically, the arterial line and ICP monitor should be calibrated at the same level. However, the arterial line is often calibrated to the level of the heart, and the ICP monitor is calibrated to the level of the foramen of Monro. These limitations in current monitoring systems need to be factored into our assessment of cerebral perfusion pressure, and a standardized protocol should be followed.

Studies have shown that mortality is significantly lower in severe pediatric TBI patients with higher cerebral perfusion pressures [11,15]. However, no particular threshold for cerebral perfusion pressure has been defined. Current guidelines provide level III recommendations to maintain a minimum cerebral perfusion pressure of 40 mmHg in children with TBI. Age-specific thresholds ranging between 40 and 50 mmHg may be considered for younger and older children, respectively.

Advanced neuromonitoring is increasingly being used to treat adult TBI. In particular, brain tissue oxygen and jugular venous saturation monitoring has been shown to improve mortality after severe TBI. In children with severe TBI, a brain tissue oxygen pressure < 10 mmHg has been shown to be associated with poorer neurological outcomes [15]. At present, there is a level III recommendation to maintain partial pressure of brain tissue oxygen ≥ 10 mmHg. Methods such as microdialysis and real-time evaluation of cerebral autoregulation have not been studied in detail in pediatric TBI.

Treatment of intracranial hypertension

The critical care management of severe pediatric TBI patients should focus on maintaining euvolemia, avoiding dehydration and hypotension. Accurate measurement of fluid intake and output with or without a central venous catheter and a Foley catheter is an essential component of the acute care of these patients. Hyperosmolar therapy for intracranial hypertension is an important medical intervention. The two commonly used agents are hypertonic saline and mannitol.

Hypertonic saline

Hypertonic saline (3% saline) creates an osmolar gradient across the blood–brain barrier, which helps reduce cerebral edema and ICP. In addition, the high sodium load can improve rheology in the cerebral vasculature, as well as inhibit inflammation and enhance cardiac output. The side effects include a rebound in intracranial hypertension, high urinary water losses, and hyperchloremic acidosis [16]. In addition to treating intracranial hypertension, hypertonic saline can be used to correct hyponatremia resulting from cerebral salt wasting. This is an important cause of morbidity in pediatric severe TBI and if untreated can contribute to mortality. The presence of natriuresis combined with polyuria and hypovolemia characterizes cerebral salt wasting, which can develop 2–11 days after the injury. Studies have shown improved ICP control and maintenance of cerebral perfusion from using hypertonic saline in pediatric TBI [17]. However, the optimal timing of therapy, safety profile, and target serum osmolality have not been defined in the pediatric population. Current guidelines provide level II recommendations on the use of hypertonic saline for severe pediatric TBI with the effective doses for acute use ranging from 6.5 and 10 mL/kg. Level III recommendations include effective doses as a continuous infusion of 3% saline (0.1–1 mL/kg/h) administered on a sliding scale, while maintaining serum osmolarity below 360 mOsm/L.

Mannitol

Mannitol is a commonly used agent to treat intracranial hypertension after severe TBI. It reduces blood viscosity, creates an osmolar gradient across the blood–brain barrier, and acts as a diuretic. It acts immediately with a sustained effect lasting up to 6 h. It is excreted in urine and large boluses can produce significant diuresis and hypotension, and can cause acute tubular necrosis and renal failure. The target serum osmolarity is <320 mOsm in adults. Although mannitol has a long history of safety and reliable effect in pediatric patients, it has never been studied in the setting of a controlled clinical trial in children. Common intensive care practices and clinician preference dictates the use of mannitol to treat intracranial hypertension despite the lack of clinical evidence supporting the use of mannitol in severe pediatric TBI.

Barbiturates

Barbiturates such as thiopental and pentobarbital can be used to treat refractory intracranial hypertension seen in 21%–42% of severe pediatric TBI patients [18,19]. Children have been shown to have increased cerebral edema and hyperemia after severe TBI compared with adults, and this phenomenon is more common in younger children than older children [20]. High-dose barbiturates reduce the cerebral metabolic rate of oxygen and metabolic demands of the brain. In addition, barbiturates improve cerebral blood flow coupling, thereby reducing ischemic insults to the brain. The induction of burst suppression, as documented by electroencephalography, is associated with maximum reduction in cerebral metabolism. Barbiturates, however, should be reserved for refractory intracranial hypertension resistant to first-tier medical and surgical therapies. Barbiturates have important cardiovascular side effects such as decreased cardiac output and hypotension. Current level III recommendations state that high-dose barbiturates can be considered in hemodynamically stable patients with refractory intracranial hypertension and specify the need for continuous arterial blood pressure monitoring and cardiovascular support during therapy.

Decompressive craniectomy

Decompressive craniectomy represents an important surgical intervention in TBI. The surgery involves removal of a bone flap, usually on the side of the lesion, or sometimes bilaterally in cases of diffuse swelling. Importantly, the dura is often incised and/or repaired loosely (lax duraplasty) to release pressure on the underlying edematous brain. The removal of a bone flap as well as relaxation of dura provides space for the edematous brain to swell, thereby limiting or preventing cerebral herniation. An important component of this surgery involves decompression of the temporal lobe, which often herniates early and produces significant neurological deterioration. A mass lesion such as a subdural or epidural hematoma or cerebral contusion, if present, may be evacuated concomitantly during the surgery. Decompressive craniectomy may be performed at initial presentation in light of a poor neurological exam, clinical evidence of cerebral herniation (dilated unilateral pupil, hemiparesis), and a CT scan showing evidence of cerebral herniation. In this case, surgery is performed on the side of the mass lesion or the hemisphere that has herniated. In other cases, decompressive craniectomy may be resorted to in the presence of medically refractory diffuse cerebral edema. In this instance, a bilateral fronto-temporal decompression is performed to release bilateral hemispheres.

Decompressive craniectomy has been shown to reduce ICP in children with severe TBI [21]. Although no randomized controlled trials have been performed on the role of decompressive craniectomy in severe pediatric TBI, many retrospective studies have shown moderate clinical improvement in these critically ill patients after surgery [21,22]. In rare cases, malignant cerebral edema can cause the brain to herniate out of the craniectomy defect, making it a challenge to close the scalp. Current guidelines provide level III recommendations for decompressive craniectomy with duraplasty in pediatric TBI patients who show early signs of neurologic deterioration, cerebral herniation, or refractory intracranial hypertension.

Hyperventilation

Hyperventilation produces hypocapnia that induces cerebral vasoconstriction, reduced cerebral blood flow, and reduced volume, leading to a reduction in ICP. However, recent studies have demonstrated reduced cerebral oxygenation and brain ischemia as a consequence of hyperventilation [23,24]. Additionally, hyperventilation provides only a temporary reduction in ICP and does not have a durable effect on cerebral physiology. In spite of prior guidelines recommending against prophylactic hyperventilation, a large proportion of severe pediatric TBI patients (40%–50%) show a $PaCO_2$ <30 mmHg [25]. The impact of hyperventilation has not been studied in any randomized controlled trial, but limited evidence suggests that early hyperventilation is likely to exacerbate cerebral ischemia, while prolonged and significant hypocarbia is associated with poor neurological outcomes in severe pediatric TBI [26]. Current guidelines reiterate the avoidance of severe pediatric hyperventilation to a $PaCO_2$ <30 mmHg in the initial 48 h after injury. The delayed use of hyperventilation to treat refractory intracranial hypertension may be employed in the presence of advanced neuromonitoring to detect cerebral ischemia.

Corticosteroids

Corticosteroids are often used to treat intracranial pathology such as cerebral edema associated with brain tumors and meningitis. In severe TBI, the anti-inflammatory effects of steroids were thought to be potentially neuroprotective. However, studies using steroids in severe pediatric TBI have shown no improvement in functional outcome or reduction in mortality [27,28]. Additionally, the administration of exogenous corticosteroids suppressed the pituitary adrenal axis and showed a trend toward increased incidence of pneumonia in these patients. The current level II recommendations state that corticosteroids are *not* recommended for improved outcomes or reduced ICP in severe pediatric TBI.

Analgesics, sedatives, and neuromuscular blockade

Analgesics, sedatives, and neuromuscular blockers are important agents used in the intensive care unit for the management of severe pediatric TBI. These agents are used in the setting of emergent intubation as well as for the control of intracranial hypertension. The need for a reliable, accurate neurological exam in patients with severe TBI must be recognized when using these agents.

Analgesics and sedatives are often necessary in children with severe TBI. Intubation and various invasive procedures such as placing intravenous and arterial lines as well as intracranial monitors require adequate analgesia. Sedatives are particularly useful for patient transport, agitation, and performing imaging. For intracranial hypertension, analgesics and sedatives reduce cerebral metabolism in relation to painful stimuli and protect against physiological increases in ICP from motor activity. The caveat for the use of medications is to avoid excessive sedation that could cloud a neurological exam as well as to prevent hypotension that could exacerbate cerebral ischemia.

Neuromuscular blockade is reserved for the cases of intracranial hypertension not controlled by sedatives. These drugs reduce shivering and posturing that may exacerbate ICP, while allowing for controlled ventilation and intrathoracic pressure dynamics. These agents have considerable adverse effects and should not be used liberally. Patients receiving neuromuscular blockers who do not have a reliable neurological exam may have masking of seizures and an increased risk of nosocomial pneumonia. Additionally, up to 30% of these patients also have a risk of myopathy associated with the therapy [29].

Current guidelines provide class III recommendations for etomidate as an agent to decrease intracranial hypertension. However, up to 50% of patients in one study showed adrenal suppression with etomidate therapy [30]. Thiopental, given as a single dose, is also a potential agent for intracranial hypertension. The guidelines acknowledge the absence of adequate data to recommend a particular analgesic, sedative, or neuromuscular blocker for children with severe TBI.

Glucose and nutrition

The treatment of severe TBI in children includes addressing the nutritional needs of these patients. Children as opposed to adults have greater nutritional needs and patients with severe TBI have considerable caloric requirements for wound healing and maintaining normal organ function as well as for adequate recovery. It is advisable to meet caloric requirements for these patients as soon as possible after the injury. Either total parenteral nutrition or enteral feeds can be used in severe pediatric TBI. There are limited data available in the pediatric TBI literature to recommend one source of nutrition over another. While patients with enteral feeds via a nasogastric tube may suffer from the risk of aspiration, poor absorption, and high residuals, the placement of a nasojejunal tube has the potential to increase the delivery of calories for these patients [31]. At present, there is a level II recommendation against the use of special immune-modulating diet for the treatment of severe pediatric TBI to improve outcome [32]. There are no data to support strict glycemic control in severe pediatric TBI and the optimal glucose levels to be maintained while treating these patients are left to the discretion of the treating physician.

Antiseizure prophylaxis

Approximately 10% of children with TBI sustain posttraumatic seizures. Early posttraumatic seizures occur within 7 days of injury, while late seizures are those that occur beyond 8 days after the injury [33]. The presence of depressed skull fractures, penetrating brain injuries, and focal intracranial lesions are known to be associated with increased risk of posttraumatic seizures. Seizures after severe TBI increase the risk of aspiration, hypoxia, and increased intracranial hypertension. Infants and children have a lower seizure threshold compared with adults, and the occurrence of subclinical seizures presents an additional challenge to the management of these patients in the acute setting. Some studies suggest poorer neurological outcomes in pediatric severe TBI patients with posttraumatic seizures [34]. Current guidelines recommend the use of phenytoin as a prophylactic anticonvulsant to reduce the incidence of early posttraumatic seizures in severe pediatric TBI. The monitoring of drug levels is important when phenytoin is used due to variations in pharmacokinetics among patients. There are limited data available on the use of levetaricatem and other anticonvulsants to prevent early posttraumatic seizures. In addition, the impact of treatment on long-term seizure risk is also unknown at this time.

Temperature control

Hyperthermia is best avoided after severe TBI. Hyperthermia increases the metabolic and heart rates and can induce shivering and intracranial hypertension. Aggressive measures to prevent and treat hyperthermia should include antipyretics, cooling blankets, and cold intravenous fluids, as well as early investigation and treatment for infections.

Hypothermia has been proposed as a therapeutic intervention for severe TBI. Hypothermia reduces the cerebral metabolic rate, inflammation, and excitotoxicity, and can inhibit seizures. These physiological changes contribute to reduced intracranial hypertension and cerebral ischemia. Inducing hypothermia in severe pediatric TBI has been studied in two randomized controlled trials with a total of 300 patients studied [14,25]. Neither study showed a significant difference in mortality or clinical outcome at 6 months. However, moderate hypothermia (32°C–33°C) for up to 48 h after the injury showed a beneficial effect in terms of reducing intracranial hypertension. A more recent phase 3 study ("Cool Kids") [35], however, was terminated early for futility and failed to show an improvement in mortality with the use of therapeutic hypothermia for 48 h. Induced moderate hypothermia can increase the risk of hypotension and requirement of vasopressors. In addition, slow rewarming at a rate not greater than 0.5°C per hour is recommended. The current data appear to support hypothermia to treat intracranial hypertension in severe pediatric TBI; however, the limitations of therapy in terms of unchanged clinical outcome and the associated adverse effects need to be considered by the treating physician.

Conclusion

The treatment of children with severe TBI involves a multidisciplinary team and begins with prehospital management, emergency room care, and monitoring in a critical care unit. There are increasing amounts data available to guide treatment for pediatric TBI patients; however, many recommendations are still adapted from adult studies. Many of these patients require physical, occupational, and psychological therapy during recovery. At present, preventing secondary brain injury from hypotension and hypoxia guides the majority of our clinical efforts in the acute phase after severe TBI. We anticipate future studies will identify further specific interventions that provide neuroprotection and improve neurological outcomes from severe TBI in children.

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Pediatric facial trauma

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Introduction

Pediatric facial trauma accounts for approximately 5% of all pediatric traumas. It is distinct from adult facial trauma in a number of ways. Children tend to suffer from less severe injury; they demonstrate an accelerated ability to heal and adapt from trauma, and they often benefit from more conservative management. Children also present their own challenges, including distinct anatomy, different mechanisms of injury, and growing facial structures which can be affected by the trauma.

Anatomy and pathophysiology

An essential distinction between the facial anatomy of children and adults is the difference in proportion of cranial to facial volume. At birth, the craniofacial ratio is 8:1, and the face is protected by its relative recession beneath the skull. The face continues to grow inferiorly and anteriorly until adulthood, with a final ratio of approximately 2.5:1 [1]. These proportions help explain why children under five experience a higher incidence of cranial injuries and lower incidence of midface and mandibular fractures when compared to older children [2]. These injury patterns are further supported by the increased relative strength of the mandible in infants and toddlers due to unerupted dentition.

Developing bone is also softer and more pliable than mature bone with a thicker periosteum. The flexibility of developing bone makes "greenstick" or incomplete fractures more likely in younger children. These types of fracture do not typically require surgical intervention [3].

Finally, pneumatization of the paranasal sinuses occurs throughout childhood, with the ethmoid sinuses being the first to fully develop, followed by the maxillary, sphenoid, then the frontal sinuses [4]. As the surrounding bone is stronger before pneumatization, the risk of fracture increases as the child matures.

Epidemiology

Characteristics of pediatric facial injury vary based on age, geography, and social factors. In the Unites States, motor vehicle collision (MVC) is the most common mechanism for facial fracture in children of all ages [5–7]. Unrestrained pediatric patients experience double the risk of facial fracture from MVCs [7]. Laws mandating child safety seats have undoubtedly decreased the incidence of facial trauma from MVC. The second most common mechanism of facial fracture varies with age [7]. Among children less than 6 years of age, falls are more common, giving way to sports-related injuries around age 12 as children gain increased motor skills [2].

A unique category of facial trauma in children is dog bites. Children are disproportionately represented in dog bite injuries [8]. There is a general trend that infants and preschoolers primarily sustain these injuries to the face, while older children are bitten on the extremities [9]. This distinction likely occurs due to the fact that younger children are more likely to present their faces in close proximity to the animal.

Physical abuse should always be considered in children with poorly explained injury patterns inconsistent with the stated trauma, especially when combined with behavioral signs of abuse including poor eye contact, fear of touch, and mood changes. It has been estimated that 1% of children sustain nonaccidental injury in each year [10].

Diagnostic approach

Evaluation of pediatric facial injuries should begin with a close history and physical exam. In children who are very young or who do not communicate well with strangers, reliance on the parental account of the accident is helpful, as is their observation with regard to changes in the child's appearance. Physical exam includes a thorough orbital examination. Diminished red-color perception is the earliest sign of optic nerve damage, and can be readily assessed by placing a finger on a penlight in a darkened room and asking the patient to compare the color as seen with each eye [11]. Any perceived difference is abnormal. Extraocular muscle function should also be tested. Ophthalmologic consultation is warranted if any abnormalities are detected. The nose should be evaluated for deformity, and the septum evaluated for hematoma. Malar depression and infraorbital paresthesia may indicate a zygomatic fracture and infraorbital nerve involvement. Mandibular evaluation should begin with inspection of the teeth and mucosa, and the occlusion carefully assessed.

The gold standard for radiographic evaluation in pediatric facial trauma is computed tomography (CT) with axial and coronal views. It should routinely be used if the physical exam is abnormal or if the mechanism of injury is severe. Three-dimensional reconstruction of the CT provides enhanced views for complex injuries. Orthopantomogram (Panorex™) may offer additional information regarding mandibular injuries, and is a valuable tool for visualizing dental structures [2].

Emergency management

The initial management of the pediatric patient must account for the higher surface-area-to-body volume ratio, increased metabolic rate, and lower blood volumes, which combine to contribute to the increased risk of hypothermia, hypoxia, and hypotension seen in pediatric trauma. As with adults, control of airway, breathing, and circulation is critical in the resuscitation of children [2]. Cervical spine injuries may be associated with facial bone fractures, and diagnosis can be delayed by distracting facial injuries. In high-velocity trauma or in the presence of cervical spine tenderness, precautions should be taken and a cervical collar placed while the injuries are investigated thoroughly [12].

Treatment

Nasal fractures

Nasal fractures are the most common in children, and many are treated on an outpatient basis. Although physical exam is sufficient for diagnosis, the severity of the injury may be obscured by facial edema. CT scans can be helpful in these situations. Most nasal fractures can be treated with closed reduction. If seen immediately following injury, closed reduction should be performed. Between 1 and 5 days, swelling makes accurate correction difficult [13,14]. The primary indication for early surgery is septal hematoma, which can lead to cartilage necrosis, and saddle nose deformity if it is not addressed promptly.

Naso-orbito-ethmoid fractures

Naso-orbito-ethmoid (NOE) fractures are the least common of all pediatric facial fractures [15]. This is attributed to the absence of a fully pneumatized frontal sinus, which results in translation of the force of lower forehead impacts to the base of the skull and intracranially. Consequently, intracranial injury should always be considered in NOE fracture. The typical deformity in NOE fractures results from displacement of the medial orbital walls laterally, leading to telecanthus, shortened palpebral fissures, and often a saddle-nose deformity. CT scan is mandatory in providing the definitive diagnosis. The Markowitz classification of the injury is very useful in determining the appropriate treatment, but virtually all will require surgery (Figure 16.1).

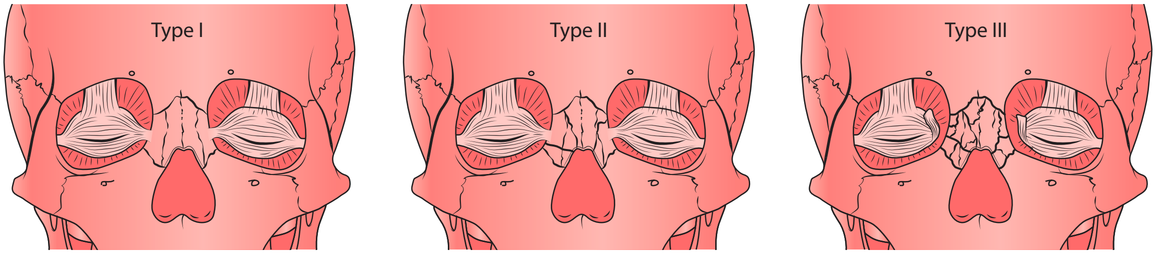


Figure 16.1 Markowitz classification. (Courtesy of Texas Children's Hospital.)

Because of ongoing growth, there is a reasonable chance that children may require additional surgery [16].

Orbital fractures

Fractures of the superior orbital rim and orbital roof are more common in children under 5 years of age due to the increased prominence of the skull and incomplete frontal sinus pneumatization. These fractures may be difficult to diagnose on exam due to periorbital swelling, although palpation along the supraorbital rim may occasionally reveal step-deformities. For this reason, CT scan is recommended in the diagnosis of all orbital fractures (Figure 16.2).

Following pneumatization of the sinuses, patterns of pediatric orbital fractures become similar to adults, with orbital floor fractures being the most common. Children are at increased risk for greenstick "trapdoor" fractures, where the inferior rectus muscle becomes entrapped in the fracture as the pliable bone opens up with the force, then closes on the displaced periorbital tissues. This defect can lead to "white eye" syndrome, which presents as inability to look upward in the affected eye. They may also present with symptoms of nausea and even syncope because of traction on parasympathetic nerve fibers that travel with the periorbita.

Orbital fracture management remains controversial, but there is a consensus on the need for early repair for muscle entrapment. In a matter of days, children may experience fibrosis and shortening of the muscle fibers, leading to prolonged diplopia. All children under 12 with prolonged dysmotility are at risk for amblyopia [17]. In cases of complete fracture, large floor defects (greater than 1 cm^2) and early enophthalmos are also indications for repair. Fracture repair is typically performed using a transconjunctival incision with the floor defect reconstructed using a variety of implants, ranging from split calvarial bone to titanium and porous polyethylene [18].

Zygomatic fractures

Zygoma fractures are rare before age five and increase steadily with advancing age. The presentation of these injuries is similar to that of adults, and often includes subconjunctival hematoma and sensory loss from damage to the infraorbital nerve. In severe injuries, facial asymmetry from inferior displacement of the zygoma may be seen. Clinical exam should include palpation of the infraorbital rim for step-deformities and a full ophthalmologic exam. CT scan remains the most accurate diagnostic modality. Minimally displaced fractures without deformity may be observed. Open reduction and internal fixation (ORIF) is indicated in comminuted or displaced fractures. Because of the exuberant healing rate of children, ORIF is preferably performed within 1 week of injury [19]. Delays may result in difficulty mobilizing the fracture.

Maxillary fractures

The small maxillary sinuses in children make fractures in this region uncommon until the teenage years. Treatment, which is only necessary when the fracture is complete, involves the pterygoid plates. Malocclusion is the hallmark presentation of these injuries. Treatment should be directed toward restoring the preinjury occlusion. In most pediatric maxillary fractures, a short period of intermaxillary fixation should be sufficient. In young children (less than 6 years of age), arch bars can be difficult to apply and circummandibular wires may have to be placed and attached to a wire passed through a drill hole near the piriform aperture. Alternatively, the fracture can also be treated using open reduction and plate fixation. This is recommended in all significantly displaced fractures. One must be careful that none of the screws are placed into a developing tooth bud. While resorbable plates and screws are advocated by some, titanium is also acceptable.

Figure 16.2 CT of right orbital trapdoor fracture in an 11-year-old female following high-speed motor vehicle collision.

Mandible fractures

Mandibular fractures are the second most common fracture in children. The condyle is the most common location (Figure 16.3). Children under five tend to sustain condylar head fractures, while adolescents sustain condylar neck fractures. Patients typically present with malocclusion and pain, particularly in the preauricular region. This is often in the setting of a chin laceration, suffered at the time of the fall. An assessment of occlusion can be difficult in children with mixed dentition, and attention to wear facets and parental input can be helpful. Most condylar head injuries should be treated by immediate mobilization to prevent ankylosis, which is very difficult to treat once established, and can lead to growth disturbance. These patients should be given pain medications and the family should be counseled to encourage jaw motion by the child. In the presence of malocclusion, consideration should be given to a short period of intermaxillary fixation. While minor occlusal discrepancies in very young children are overcome quite readily with dental compensations and growth, more significant irregularities should be treated with 10–12 days of intermaxillary fixation as mentioned in the section "Maxillary Fractures." Noncondylar fractures of the mandible with resultant malocclusion should typically be treated by open reduction and plate fixation. Typically a titanium miniplate placed along the inferior border to avoid the tooth buds is sufficient.

Soft tissue facial injuries

Principles

The vast majority of very young children presenting with soft tissue injuries of the face can be treated in the emergency room. The decision to use local anesthesia versus conscious sedation depends in large degree on the age of the child, the practice of the surgeon, and the severity of the injury. The most severe injuries should be taken to the operating room due to the better lighting, assistance, and improved instrumentation. As with any soft tissue injury, the most important aspect is thoroughly cleaning the injury prior to repair. Minimal debridement of viable tissue should be performed. Avulsed flaps should be tacked down loosely if there is any chance for survival of the tissue. Secondary revisional surgery can always be performed.

Deep dermal sutures are perhaps the most important in children. Monocryl (Ethicon; Somerville, NJ) suture is one of the most frequent choices for the deep dermal layer. A subcuticular running suture with Monocryl for the skin versus interrupted fast-absorbing plain gut sutures (Ethicon; Somerville, NJ) are typically chosen

Figure 16.3 CT of bilateral subcondylar fractures with medial displacement and dislocation of temporomandibular joints in a 5-year-old female after a fall.

for the cutaneous component. Alternatively, Dermabond (Ethicon; Somerville, NJ) has been proposed and studies show that for uncomplicated lacerations, this material has equivalent results to skin sutures [20]. If a subcuticular suture or interrupted skin sutures are used, the application of Mastisol (Eloquest Healthcare; Detroit, MI) followed by Steri-Strips (3M; St. Paul, MN) is preferable to bolster the closure and to act as a dressing for the area [21].

Scalp

Scalp injuries are problematic for several reasons. First, the thick galea tends to prevent blood vessels from retracting and slowing the bleeding process. Consequently, children can lose large volumes of blood from scalp lacerations if they are not addressed in a timely fashion. Additionally, scars in the scalp have a tendency to widen over time, leaving the area visible even in the presence of surrounding hair. Great care must be taken to place deep galeal sutures that remove tension from the skin layer. It may be helpful to score the galea using a 15-blade prior to closure to reduce the tension on the skin edges. Great care should be taken to score just through the galea and not into the subcutaneous tissue above it containing the blood vessels. A running suture for the skin of the scalp is preferred to prevent bleeding between interrupted sutures [22].

Eyelid

One must always rule out damage to the underlying globe with eyelid lacerations. When one takes into account the Bell's phenomenon, where the eye rolls up and out with closure, a laceration to the eyelid may not be coincident with the globe injury. One must also diagnose any canalicular injuries to the lacrimal system with these injuries. If present, this should be addressed by stenting at the time of laceration repair. Sutures should be placed in the tarsus if this layer is injured followed by skin sutures. The conjunctiva need not necessarily be sutured. If one does suture this area, one must be aware of irritation of the cornea from the sutures. The lid margin should also be everted to prevent notching with healing.

Lip

Full thickness lip lacerations can be problematic. One must be careful to reapproximate the orbicularis muscle to prevent subsequent scar widening. Additionally, the vermilion border must be accurately aligned. One should mark this critical anatomical landmark prior to any infiltration of local anesthesia to prevent its distortion. Even small stepoffs of this region are visible from a conversational distance. Methylene blue in a 25-gauge needle is an effective mechanism to achieve this [22–24].

Facial nerve

Injuries to the facial nerve must be diagnosed prior to infiltration of local anesthesia. Classically, the teaching is that lacerations of the facial nerve medial to the lateral canthus need not be repaired. Injuries lateral to this should be repaired within 72 hours following diagnosis of the injury. Beyond this time, the distal muscle targets typically do not stimulate, making identification of the distal nerve segment difficult. Ideally, this is addressed at the time of the repair of the laceration [22,24]. If not, any nerve ends identified should be tagged with a long Prolene (Ethicon; Somerville, NJ) suture for subsequent identification [23].

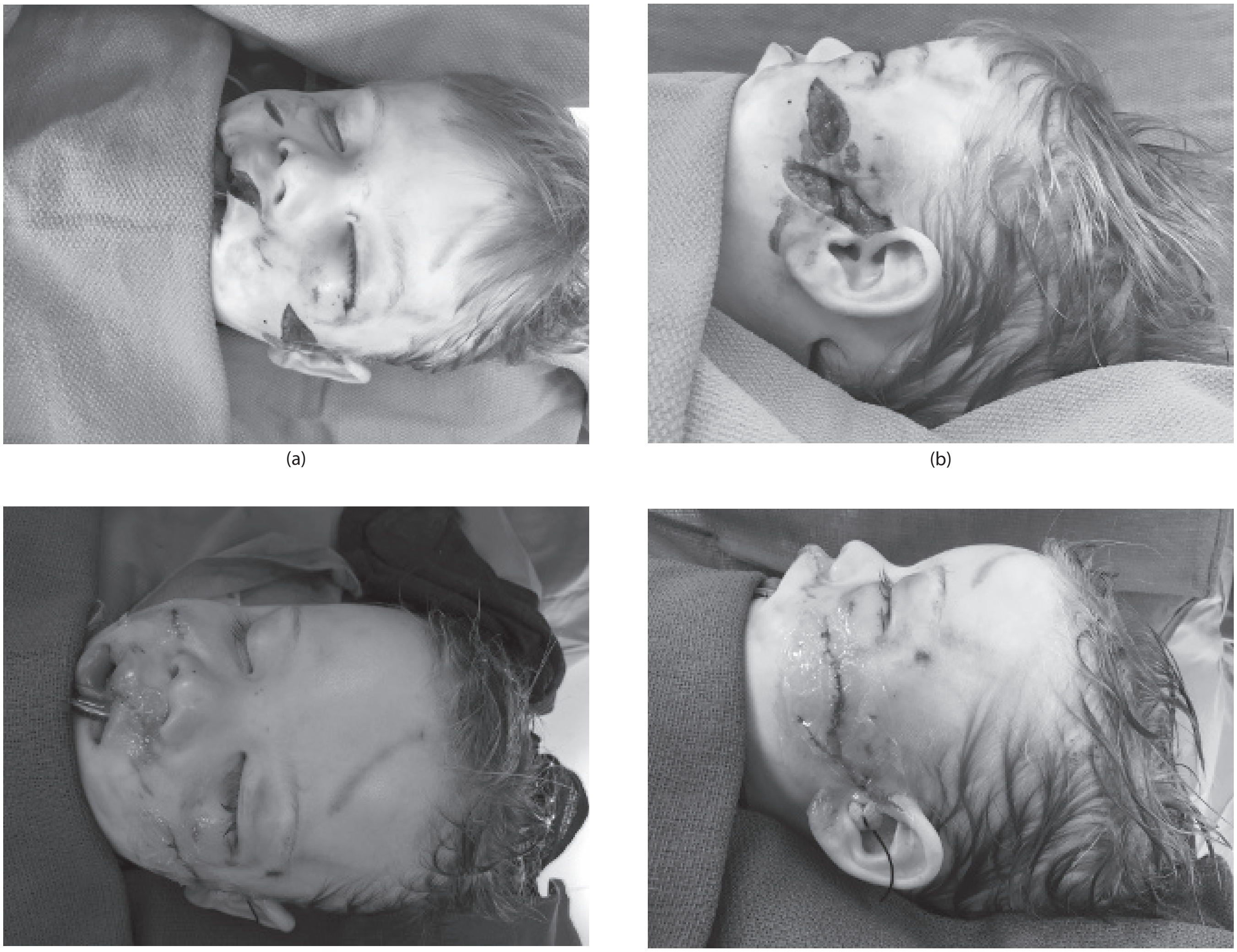
Ear

The primary concern regarding trauma to the ear is hematoma between the cartilage and the anterior skin. If allowed to accumulate here, this area becomes fibrotic and can lead to the distortion of the ear anatomy ("cauliflower ear"). Any hematoma seen here should be drained and a pressure dressing should be placed over the skin flaps to prevent reaccumulation. With respect to suturing the laceration, given the firm attachment of the anterior skin to the cartilage, skin sutures alone usually suffice. Separate sutures in the cartilage are not typically necessary. If these are used, the knot should be placed posterior to avoid visibility under the closely adherent anterior skin. One must also be vigilant for subsequent infection resulting in chondritis, which can result in loss of ear cartilage and distortion of the ear anatomy [23,25].

Animal bites

Animal bites, particularly dog bites, are some of the most common injuries seen in the emergency room (Figure 16.4). Studies have shown that amoxicillin/clavulanic acid is the best overall antibiotic for prophylaxis of infection in these cases [26].

Essentially all injuries of the face should be cleaned and sutured almost regardless of the time of presentation. One common source of problems is small puncture wounds from the canine teeth of the animals. These can create deep tracts in the skin and subcutaneous tissue that are inoculated with bacteria. While these are not typically sutured, they need to be irrigated throughout their depth, preferably with dilute hydrogen peroxide or an antibiotic-containing saline solution. Administering the irrigation with an angiocatheter is preferable to ensure that the full length of the injury has been irrigated. If not, these can be a source of subsequent infection. Of course, the vaccine status of the animal should be ascertained and the child's tetanus prophylaxis determined [8,27–32].



(a) (b) (c) (d)

Figure 16.4 Facial dog bite injuries and repair in a 4-year-old male. **(a, b)** Preoperative injury, **(c, d)** postoperative repair.

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17

Pediatric thoracic trauma

CHRISTINE M. LEEPER and BARBARA A. GAINES

Epidemiology

Thoracic trauma in pediatric patients is due largely to blunt force mechanism (80%–85%) and typically results from motor vehicle crashes, pedestrian accidents, falls, and recreational injuries. Penetrating chest trauma is more common in adolescents and is frequently the result of gunshot wounds or stabbings. The more frequently observed injuries are pulmonary contusions and rib fractures, with or without pneumothorax or hemothorax. Injuries to the tracheobronchial tree, heart, aorta, esophagus, or diaphragm are rare [1,2]. While uncommon, injuries to the thorax can be highly lethal. According to the National Trauma Data Bank (NTDB) 2015 report, only 12.8% of children sustained an injury to the thorax; however, these injuries had the highest case fatality rate of any body region at 7.74% [3]. Chest trauma has a 4%–12% mortality rate in isolation and 40% mortality rate when associated with other injuries [1,4]. Thoracic trauma is uncommonly seen in isolation in children, and serves to indicate the magnitude of force and severity of injury; most children with chest injuries have high injury severity score overall with associated head, abdominal, and extremity injuries [1].

Pediatric anatomy and physiology

The skeleton of the pediatric patient is incompletely ossified and very pliable, which places patients at risk of internal organ damage without apparent skeletal fractures. For example, children experience more pulmonary contusions in comparison with rib fractures. Therefore, when a rib fracture is seen one should assume significant force of injury and the level of suspicion for intrathoracic and intra-abdominal organ injuries should be higher; further investigation may be warranted depending on clinical presentation.

Initial evaluation—Primary survey

Initial evaluation of the patient with suspected trauma includes activation of the appropriate resources (trauma response team). The American College of Surgeons Advanced Trauma Life Support (ATLS) guidelines describe a systematic approach to the care of injured pediatric patients. Many thoracic injuries can be diagnosed and treated at the time of the primary survey, during which time airway patency, breath sounds, and neck-and-chest exam are performed expeditiously. Injuries including tension pneumothorax, hemothorax, cardiac tamponade, and sucking chest wound should all be diagnosed and treated during the primary survey. First, airway patency should be assessed (a patient who is speaking or crying vigorously typically has a patent airway) and endotracheal intubation performed for patients with inability to protect the airway (Glasgow Coma Scale [GCS] < 8, unconscious, combative, severe face/head/neck trauma), inability to oxygenate or ventilate. Breathing is assessed through auscultation, palpation/percussion, examination of trachea and chest wall, and respiratory rate/effort. Tracheal deviation, hypotension, jugular venous distention, and unequal breath sounds can indicate a tension pneumothorax, which should be managed by immediate chest decompression (needle decompression followed by tube thoracostomy). Chest radiograph is not necessary in the diagnosis of tension pneumothorax and should not delay intervention. Pneumothorax, hemothorax, or combined hemo/pneumothorax should be managed with tube thoracostomy using a tube of sufficient size to allow adequate drainage of intrathoracic blood (Figure 17.1). The chest tube insertion site is similar to the location in adults: the fifth or sixth intercostal space in the anterior axillary line. French tube size is diameter of tube in millimeters multiplied by 3 (e.g., 36 French = 12 mm diameter). Selection of tube size should be tailored to patient age, size, and indication (Table 17.1) [5,6]. Children may be large or small for their age, which should be taken into account when selecting tube size. In general, larger size should be selected to drain fluid/blood and smaller size may be sufficient to evacuate air only.

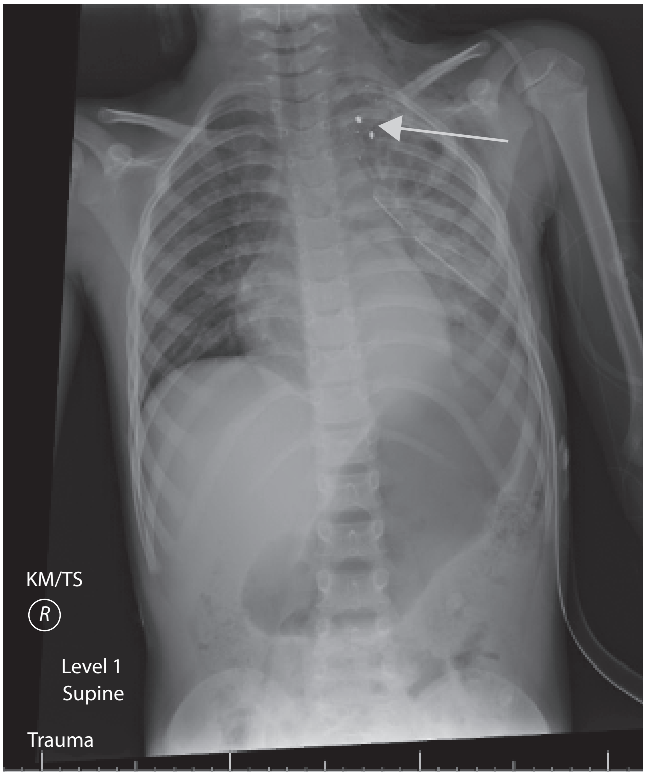

Figure 17.1 Plain radiograph of 6-year-old male with gunshot wound to the left chest (arrow to show presence of shrapnel). Patient underwent tube thoracostomy with evacuation of hemo/pneumothorax.

Table 17.1 Guide for chest tube size by patient age

Age	Approximate tube size (Fr)
Neonate (<1 month)	8–12
Infant (0–1 years)	12–16
Younger child (1–5 years)	16–20
Older child (6–11 years)	20–28
Adolescent (12–17 years)	28–36

Transfer to operating room for surgical intervention is indicated if initial chest tube drainage >15 mL/kg or subsequent output >2 mL/kg/h [7]. For an open pneumothorax or sucking chest wound, a three-sided occlusive dressing should be applied with placement of tube thoracostomy through a separate site. Signs of cardiac tamponade include hypotension, elevated jugular venous pressure, muffled heart sounds, and positive focused assessment with sonography for trauma (FAST) exam in the cardiac window. Treatment may include pericardiocentesis, pericardial window, or thoracotomy depending on the clinical condition of the patient and associated injuries.

Adjuncts to primary survey

Chest radiograph is a rapid, portable means of evaluating the thoracic cavity for suspected injuries. An anteroposterior (AP) chest film should be performed for all patients with suspected chest trauma to facilitate screening of the bony structures, airways, lung fields, diaphragmatic contours, cardiac and large vessel contours, and subcutaneous tissues. FAST exam is also utilized for patients with both penetrating and blunt thoracic trauma to evaluate the heart for traumatic pericardial effusion, which may indicate cardiac injury. In both penetrating and blunt chest trauma, "classic" signs and symptoms of injury may not be present, making FAST exam a useful adjunct in the diagnosis of uncommon pediatric injuries.

ED thoracotomy

Pediatric patients have an even lower rate of survival after emergency department thoracotomy (EDT) than do adult patients, thought to be due to the higher proportion of blunt chest trauma mechanism. A recent meta-analysis of 252 patients, most from case reports and smaller series, was performed [8]. Eighty-four percent were male, 51% sustained penetrating injuries, and median age was 15 years. Upon arrival, 17% had vital signs and 35% had signs of life. After EDT, 30% experienced return of spontaneous circulation. The survival rate was 1.6% for blunt trauma, 10.2% for penetrating injuries, and 6.0% overall. A subsequent retrospective review of 179 patients over 40 years isolated patients <15 years of age, and found that the overall survival was higher in adolescent versus pediatric patients (4.8% vs. 0%) which was attributable to the higher proportion of adolescents with penetrating injuries [9]. A study of 316 children (70 blunt, 240 penetrating) who underwent EDT-linked survival to presence of vital signs on arrival: less than 5% of patients overall survived when presenting systolic blood pressure (SBP) was ≤50 mmHg or heart rate was ≤70 bpm, and no patients with blunt injuries who had an initial pulse ≤80 bpm or SBP ≤ 60 mmHg survived [10]. In summary, EDT is indicated in pediatric patients with penetrating chest trauma only for those who lose vital signs immediately prior to arrival or in the trauma bay.

Damage control thoracotomy

If emergent operative intervention for thoracic trauma or polytrauma is required, the pediatric patient is likely hemodynamically unstable. Damage control surgery is an approach to the severely injured patient that prioritizes rapid surgical control of bleeding and contamination, appropriate resuscitation to address shock and coagulopathy while minimizing iatrogenic injury (hypothermia, hemodilution), and temporary closure to allow for second-look operations and delayed definitive repair. Damage control as a pediatric general surgery principle has been in practice for decades (e.g., use of silos in congenital abdominal wall defects) [11], and its use in pediatric trauma patients has evolved more recently [12–15] as evidence in adults suggests improved survival and outcomes [16–18].

As in adults, a rapid transfusion device and cell saver should be available in the event of massive blood loss. The patient is prepped from neck to knees to allow for entrance into either the chest or abdomen, and to permit access to the femoral vessels. Entrance to the chest can be made by either anterolateral thoracotomy or sternotomy. To achieve rapid control of pulmonary parenchymal hemorrhage, tractotomy is often employed as a definitive procedure that is less time consuming and does not carry the same morbidity or mortality as anatomic segmental resection or pneumonectomy [19]. Temporary chest closure with packing, large-bore chest drains, and vacuum-assisted devices allow for control of the pleural space without increase in airway pressures [20]. Return to the operating room is dependent on the patient's clinical condition, status of resuscitation, and restoration of normal physiology.

Diagnostic imaging considerations

Computed tomography of the chest, though more sensitive and detailed than plain radiograph, should not be performed routinely or reflexively as it does not reliably add diagnostic information that prompts a change in patient care management. In a study of 43 patients who underwent computed tomography (CT) scan based on mechanism of injury, only 4 had occult thoracic injuries (2 pulmonary contusions, 1 small pneumothorax, and 1 rib fracture) that were managed nonoperatively without a change in management [21]. Another multicenter study described 396 patients with initial chest x-ray (CXR), of whom 174 had subsequent chest CT. Of the patients with normal x-ray, nine had findings of pneumothorax or pulmonary contusion on chest CT, all of which did not require intervention [22]. In a study of 333 patients, all who required operative management of injury had abnormal CXR. There were only 30 cases in which chest CT provided new or detailed information compared with chest radiograph, most commonly small pneumothoraces (PTX) ($N = 14$), hemothoraces ($n = 11$), contusions ($n = 11$), or fractures ($n = 16$). Only one pneumothorax required tube thoracostomy [23].

The risk of malignancy from chest radiation is a real concern in pediatric patients. For patients less than 14 years of age receiving a thoracic CT, the average number of scans needed to produce one future leukemia or solid cancer is 563. The risk of solid malignancies is greater than leukemia, and the risk for females (1 cancer per 330–480) is greater than males (1 cancer per 1080–1650) across age groups for chest scans. Risk is also relative to age, with younger children at greater risk of developing both solid and hematologic malignancies after chest imaging [24]. Using this number needed to harm of 563 and a number needed to treat of 304, Ham et al. calculated a benefit to risk ratio of 1.85, meaning that for every 1.85 injuries found requiring a change in management (typically tube thoracostomy), one child would get cancer [25]. Despite increased publicity and awareness of this risk, from 1996 to 2010 the number of chest scans still increased by 50% [24].

AP chest radiograph is the mainstay of diagnosis and initial imaging modality of choice in pediatric trauma patients. For many patients with trauma to the chest, plain radiograph is sufficient as a screening tool. Additional imaging is obtained based on abnormal chest radiograph results, physical exam, and clinical judgment. For instance, chest CT is indicated if there is an abnormal chest radiograph *and* concern for major vascular injury. Adolescents who present with high-velocity mechanisms typical of adult trauma patients (e.g., motor vehicle collision [MVC] at high rate of speed or chest into steering wheel) are at risk for deceleration injuries to the thoracic aorta and should also undergo contrasted chest CT scan.

Ultrasound is a portable, readily available, low-cost imaging modality that does not carry the radiation burden of CT scan, making it as a useful adjunct in the evaluation of the pediatric trauma patient. Cardiac ultrasound is performed as part of the standard primary survey for trauma patients via the FAST exam and is routinely used in the evaluation of suspected cardiac injury. Thoracic ultrasound is performed less frequently; however, it can be valuable in the diagnosis of chest wall, pleural space, lung parenchyma, and diaphragm injuries [26].

Injuries

Pulmonary contusion

The most common injury after blunt trauma is pulmonary contusion, which can be seen in the absence of rib fracture or evidence of trauma on physical exam [1,27]. As with other thoracic injuries, chest radiograph is the diagnostic modality of choice (Figure 17.2). Parenchymal contusion may not be immediately visible on admission chest radiograph as it can take 4–6 h or more after injury for lesions to "blossom." Chest CT will occasionally demonstrate contusions not seen on chest radiograph (Figures 17.3 and 17.4); however, these CT-only lesions do not carry any increased morbidity and do not change overall management [28]. Several anatomic changes result from lung parenchymal contusion, namely hemorrhage, edema, and consolidation,

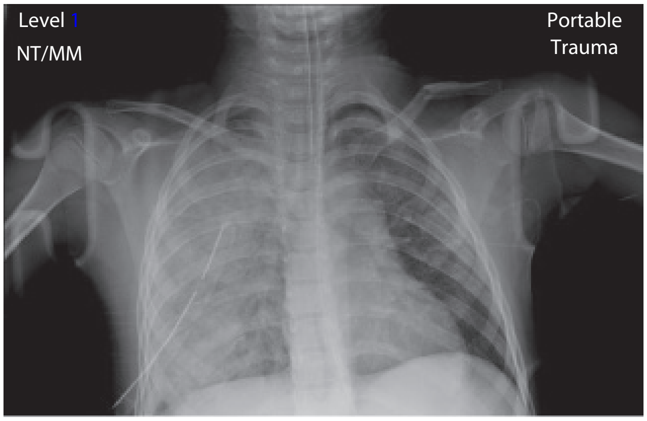

Figure 17.2 Six-year-old female pedestrian struck and pinned between two cars. Extensive pulmonary contusions are seen on plain radiograph.

Figure 17.3 Six-year-old female pedestrian struck and pinned between two cars. Extensive pulmonary contusions are seen on chest CT.

Figure 17.4 Three-year-old female MVC unrestrained and ejected from the car. CT reveals extensive bilateral pulmonary contusions.

which cause alveolar filling and interstitial thickening. This results in reduced lung compliance causing ventilation/perfusion mismatch (shunting), hypoventilation, and hypoxia [4]. In small areas these pathophysiologic changes have little effect on a patient's overall respiratory function. However, if the traumatized area is large enough, respiratory function may be compromised as evidenced by reduced Pao2/FIo2 ratio [29].

Management includes close observation, analgesia, and aggressive pulmonary toilet. With adequate treatment, the pathophysiologic changes described above resolve completely within a few days and the lung parenchyma fully recovers its gas exchange function. Complications may include the development of pneumonia [30], which occurs after bacterial colonization and superimposed infection of consolidated, inflamed lung parenchyma. Pulmonary contusion in the adult population has been associated with respiratory failure, ventilator-associated pneumonia, and acute respiratory distress syndrome; however, the risk of respiratory failure requiring intubation or mortality attributable to parenchymal contusions themselves seems to be less in children [29,31].

Rib fractures

Rib fractures are one of the more common chest injuries in pediatric patients; however, they are less frequently seen in comparison with adults due to the pliable and incompletely ossified nature of pediatric skeletal structures. Therefore their presence should signify a greater force of injury and raise the level of suspicion for intrathoracic and intra-abdominal organ injuries. In comparison with adults, children present less commonly with isolated rib fractures and more frequently have associated pulmonary contusion and hemothorax/pneumothorax as well as extrathoracic injuries, including brain injury, spleen and liver injury, and extremity fracture [1,32]. Further, children demonstrate a unique mortality risk pattern associated with rib fracture: Incidence of death doubles from 1.8% without rib fracture to 5.8% for one rib fracture and then nearly linearly increases up to 8.2% for seven fractures [33].

Rib fractures are commonly diagnosed with the initial screening AP chest radiograph in trauma patients. Chest CT scan is more sensitive and can provide additional detail regarding fracture location and characteristics (Figure 17.5); however, in most cases this is not indicated unless additional injuries are suspected. Low rib fractures may be associated with liver/spleen or diaphragmatic injury. There is some controversy regarding the association between high rib fractures and great vessel injury; some literature suggests that this association is not seen in children and no additional studies are required for first rib injury [34]; however, many pediatric centers continue to include CT angiogram in protocols for patients with evidence of significant force to the upper chest (first rib fracture proximal clavicular fractures with posterior dislocations of the sternoclavicular joint, sternal fracture from direct chest blow during a high-speed MVC, etc.). A nuanced approach to imaging based on patient injuries, mechanism, and clinical status is likely the best strategy.

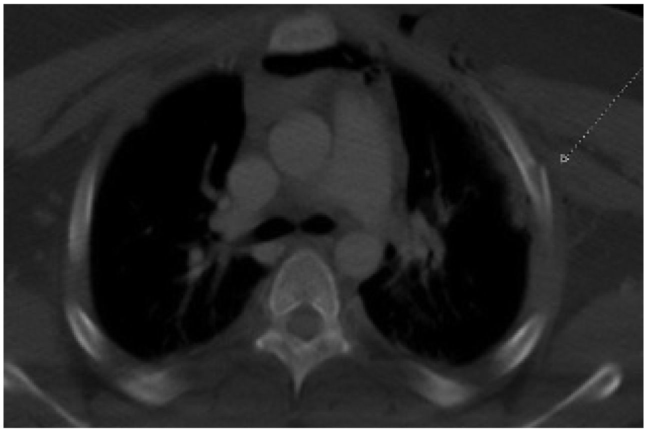

Figure 17.5 Ten-year-old male restrained passenger high-speed MVC. Fractures of left ribs 3, 4, and 5.

While rib fractures infrequently pose any functional limitation themselves, they are associated with pain and decreased respiratory effort. Treatment includes adequate analgesia (oral medications with intravenous medications for breakthrough) and aggressive chest physiotherapy to prevent atelectasis and development of pneumonia. In adults, popular analgesic strategies include paravertebral blocks or thoracic epidural analgesia. These therapies should be considered as part of the first-line analgesic plan for use in pediatric patients as well, as they can speed the time to recovery, provide superior pain control, and decrease the need for oral and intravenous narcotic medications. Unfortunately, the use of these techniques in children is less common and thought to be limited by lack of data regarding safety and efficacy, technical challenges of the procedure in children, and unfamiliarity regarding drug selection, dosing, and toxicity [35,36]. Flail chest is an incredibly uncommon entity in pediatric patients; operative stabilization with rib plating should be considered for those with ongoing pain control issues or respiratory insufficiency [37].

Rib fractures are often seen as a manifestation of child abuse (Figure 17.6). This is a "sentinel injury" in patients age <3 and should mandate additional testing to assess for nonaccidental injuries [38,39]. Fractures resulting from this mechanism tend to be anterior and posterior, and the vast majority are nondisplaced. While they may be diagnosed on skeletal survey, the characteristics of these fractures may result in missed injuries using plain film alone. Chest CT can aid in the workup of these patients in equivocal cases [40]; however, a bone scan (skeletal survey) or repeat chest radiograph several weeks after the abusive episode are more frequently used to show evidence of healing fractures without the high burden of radiation that accompanies CT scan. Abused children on average have a greater number of rib fractures than children with accidental injuries but fewer associated intrathoracic injuries; this is a reflection of the abusive mechanism and does not indicate any increased bone fragility in victims of abuse [41].

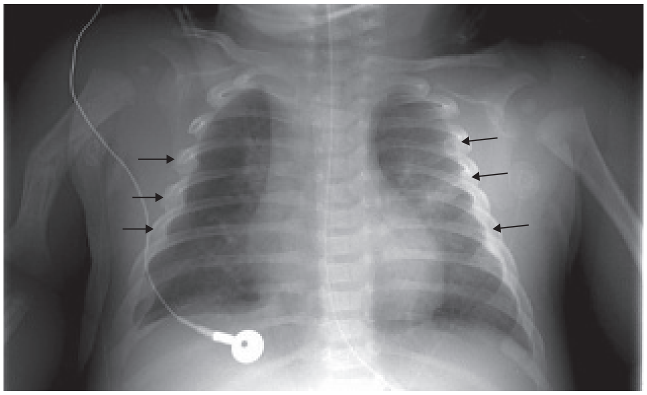

Figure 17.6 Two-month-old male victim of child abuse with right humerus fracture and healing bilateral anterolateral rib fractures (right 4th, 5th, 6th and left 3rd, 4th, 6th ribs).

Pneumothorax

The incidence of pneumothorax in children ranges from 5% to 38% [1,42] of all chest injuries. Pneumothorax may be difficult to diagnose on supine chest radiograph and is more readily apparent on upright films or lateral films with the affected side up. Findings on chest radiograph include hyperlucency of lung fields, a visible pleural line, absence of lung markings outside this pleural line, collapsed lung, and occasionally subcutaneous emphysema. A tension pneumothorax will result in midline shift of the mediastinum and tracheal deviation away from the affected side; however, this entity can often be diagnosed expeditiously on physical exam without delay or imaging. It is managed with immediate relief of the tension pathophysiology with decompression of the pleural space either by needle decompression or tube thoracostomy placement. In patients without respiratory or hemodynamic compromise, simple PTX often can be safely observed and managed with supplemental oxygen, close monitoring, and repeat imaging to document resolution/stability/improvement in PTX as well as to assess for blossoming pulmonary injury that may require intervention (e.g., hemothorax) later in the postinjury period.

With the increasing use of cervical, chest, and abdominal CT in the evaluation of pediatric trauma patients [24], thoracic injuries that may previously have gone undetected are more commonly being identified. "Occult pneumothorax" is defined as a pneumothorax identified on CT scan that was not seen on initial screening chest radiograph. In a large series from the PECARN network, occult pneumothorax accounted for 60% of all PTX diagnosed in children. Most children were observed without intervention, including those undergoing positive pressure ventilation: Tube thoracostomy was performed in 57.4% of patients with non-occult PTX and 15.6% of patients with occult PTX [43]. In another series of patients with occult PTX, the majority were managed without intervention. No patient initially observed developed a tension pneumothorax or adverse event related to observation, even in the presence of rib fractures and positive pressure ventilation [44].

Hemothorax

Hemothorax is one of the more common thoracic injuries, with a reported incidence of 7%–29% of chest injuries in analyses of pediatric trauma registries. Hemothorax appears on chest radiograph as opacification or haziness of lung fields, blunting of the costodiaphragmatic angle, or an air-fluid level (Figures 17.7 and 17.8).

Hemothoraces from penetrating trauma can be treated with tube thoracostomy drainage in the vast majority of cases. In patients with massive hemothorax or hemothorax causing hemodynamic compromise from any mechanism, immediate tube thoracostomy should be performed using a tube of sufficient size to allow adequate drainage of intrathoracic blood. Transfer to the operating room for thoracotomy is indicated if initial chest tube drainage >15 mL/kg or subsequent output >2 mL/kg/h. For an open pneumothorax or sucking chest wound, a three-sided occlusive dressing should be applied with placement of tube thoracostomy through a separate site.

Guidelines regarding the management of hemothoraces from blunt trauma in hemodynamically stable patients are less straightforward: Management options include observation, tube thoracostomy, or surgical intervention depending on the patient's clinical presentation and hemodynamic status. In a series of 23 patients after blunt trauma, patients with small volume hemothoraces, particularly those identified on CT scan but not appreciated on chest radiograph, were successfully managed without tube thoracostomy and saw no increase in retained hemothorax or empyema even in the setting of rib fractures and positive pressure ventilation. Increase in the volume of hemothorax was associated with need for tube thoracostomy [45].

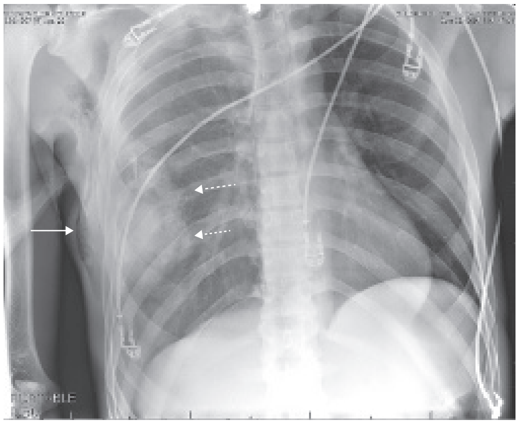

Figure 17.7 Fifteen-year-old male with penetrating trauma to the chest. Radiograph shows subcutaneous emphysema (solid arrow), 7th to 8th rib fractures (dashed arrows), and hemothorax with increased opacification of right lung fields.

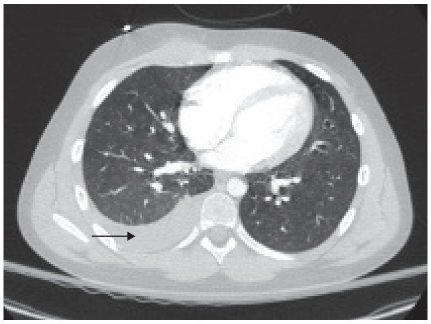

Figure 17.8 Fifteen-year-old male with penetrating trauma to the chest. Chest also demonstrates hemothorax.

Hospital admission and close observation are indicated for all patients with hemothorax. Delayed sequelae from traumatic hemothorax are of chief concern as blood in the pleural space can trigger a fibrotic reaction that results in atelectasis, inadequate lung expansion, ventilation/perfusion mismatch due to trapped lung, pneumonia, and empyema [45]. Serial imaging to document resolution of hemothorax is recommended, with intervention (tube thoracostomy placement or video-assisted thoracoscopic surgery drainage) indicated for patients with increase in volume of hemothorax or incompletely drained hemothorax on repeat radiographs.

Pneumomediastinum

Pneumomediastinum is uncommon in pediatric patients after blunt chest trauma, with some series reporting an incidence of <0.005% [46,47]. These patients typically undergo an expensive and invasive workup in order to rule out underlying esophageal, tracheobronchial, or major vascular injury. However, only a small minority of patients in these series sustained injuries to these structures (3%–4%), all of whom had other significant traumatic findings which would have been identified on CXR as well as clinical symptoms such as cardiorespiratory instability [46,47]. The finding of isolated pneumomediastinum without clinical symptoms of injury is typically self-limited and benign. The goals of management of these patients are to limit unnecessary tests while ensuring that significant aerodigestive injuries are identified; therefore, a stable, asymptomatic child who presents with isolated pneumomediastinum after blunt injury can be safely observed. In most cases, those with associated thoracic injuries may also be observed with additional testing based on the child's clinical condition.

Tracheobronchial injury

Tracheobronchial injuries in children are rare (incidence <0.05%), accounting for less than 0.05% of lesions after chest trauma in children according to retrospective database reviews over the past several decades [48]. The most common cause of tracheobronchial injuries in children is iatrogenic, typically during endotracheal intubation. Many of these injuries can be managed nonoperatively initially but may be complicated by tracheal stenosis and need for dilations and future elective procedures [49]. Accidental injuries may occur from either blunt or penetrating trauma; in contrast to adult patients, blunt trauma is responsible for 94% of pediatric tracheobronchial injuries [48]. Blunt trauma causes airway rupture due to high intraluminal pressures with a closed glottis, deceleration forces, or disruption by lung traction during compression of the thorax. Frequently reported mechanisms include MVC, chest compression, or falls.

Tracheobronchial injuries are not well visualized with conventional radiology and should instead be diagnosed via bronchoscopy. Particularly for patients with more subtle presentation (partial tears vs. complete transection), providers should maintain a high index of suspicion and pursue direct visualization of the tracheobronchial tree to rule out injury. This injury should be suspected with persistent air leak from a chest tube placed in the setting of pneumothorax, subcutaneous emphysema, or pneumomediastinum (Figures 17.9 and 17.10). The membranous trachea is the most commonly involved area in children, as it is lacking in cartilaginous support.

For patients with complete transection and uncontrollable air leak, surgical intervention is indicated. Lung resection may be required depending on the condition of the tissues and parenchyma; in other cases stump revision and primary anastomosis are possible [50]. For patients with partial tears, nonoperative management with or without endotracheal intubation distal to the site of injury often allows for healing of the trachea. Patients should receive prophylactic antibiotic coverage to reduce the risk of mediastinitis. Expedient extubation to avoid additional iatrogenic airway injury and avoidance of positive pressure ventilation to prevent existing injury exacerbation are recommended [37]. Injuries typically heal without complication, though late stricture requiring surgical intervention has been reported in patients with missed diagnosis at the time of injury [50].

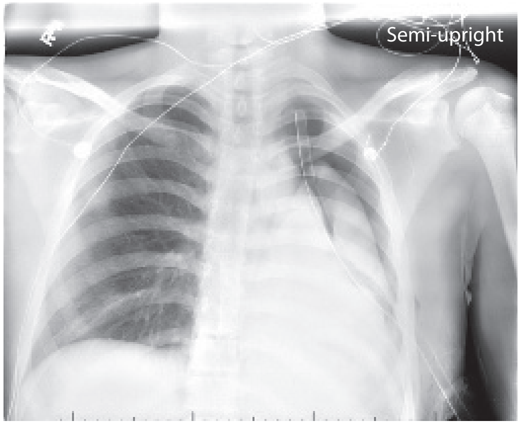

Figure 17.9 Fifteen-year-old male all-terrain vehicle (ATV) crash presented with left pneumothorax and pneumomediastinum. There was persistent pneumothorax and air leak despite two well-placed chest tubes. Bronchoscopy revealed left mainstem bronchial injury. He underwent sleeve resection of the left mainstem bronchus and a primary bronchial repair.

Major vessel injury

Thoracic aortic injuries are uncommon in children; with a prehospital mortality rate of greater than 90%, these patients represent as few as 0.1% of the cases presenting for hospital care [51–54]. Factors contributing to the low incidence are posited to be increased compliance of the chest wall and elasticity of the tissues, lack of atherosclerotic disease, and decreased body mass translating into a lower magnitude of force on impact [51]. Mechanism is predominantly blunt force due to MVC but may include penetrating trauma in adolescent age groups [53]. Injuries may include aortic tears, aortic transection, and pseudoaneurysm formation. Diagnosis is suggested by clinical history and presentation as well as widened mediastinum on screening chest radiograph. Additional imaging with contrasted chest CT will make the definitive diagnosis (Figures 17.11 and 17.12).

While many injuries in children may be successfully managed nonoperatively (e.g., blunt splenic or hepatic injury), aortic injury continues to carry a low threshold for surgical intervention in children for several reasons. First, the risk of aortic rupture carries significant lethal potential; second, the natural history of these injuries is largely unknown due to the low incidence of cases managed nonoperatively; third, many patients have concurrent traumatic brain injury and require maintenance of adequate cerebral perfusion pressures that are incompatible with blood pressure–lowering strategies for

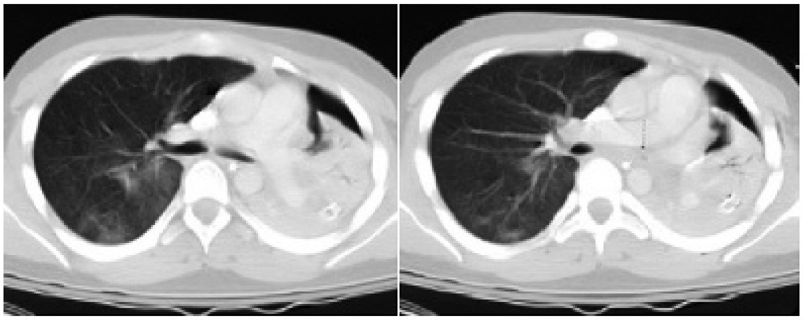

Figure 17.10 Fifteen-year-old male ATV crash presented with left pneumothorax and pneumomediastinum. There was persistent pneumothorax and air leak despite two well-placed chest tubes. CT scan showed abrupt cutoff of the left mainstem bronchus posterior to the left pulmonary artery and fluid-filled central bronchi. He underwent sleeve resection of the left mainstem bronchus and a primary bronchial repair.

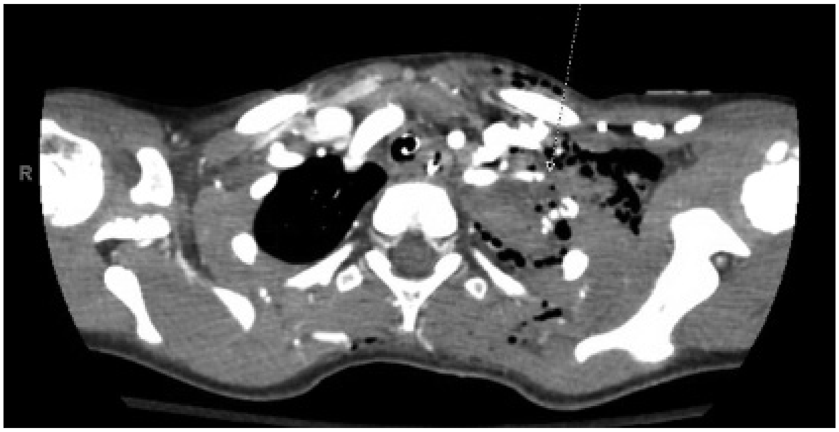

Figure 17.11 Six-year-old male gunshot wound to left shoulder, hemo/pneumothorax s/p chest tube placement. CT angiogram of the chest and neck revealed complete occlusion of the subclavian artery with distal reconstitution at axillary artery.

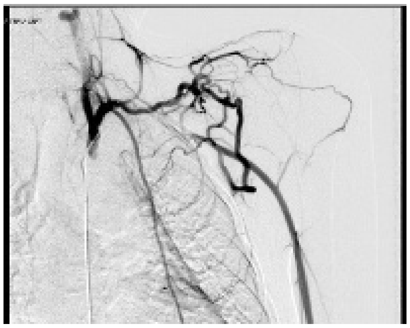

Figure 17.12 Angiogram of the left upper extremity demonstrates a cutoff of the left subclavian artery at the level of the thyrocervical trunk and reconstitution of the axillary artery through collateral arterial supply. The collateral bypass is mainly through the hypertrophied suprascapular, circumflex scapular, and subscapular arteries.

Figure 17.13 Sixteen-year-old male fell down from 30 feet. Chest radiograph showed widened mediastinum.

patients with traumatic aortic injury [54]. Operative repair is therefore indicated for the vast majority of patients with frequent procedures including graft interposition, primary anastomosis, and patch repair, depending on the extent and location of injury as well as patient anatomy. Endovascular repair may be an option for some patients (Figures 17.13 through 17.15) with similar complication and mortality compared with operative groups reported in small series [54]. However, the use of endografts in children and adolescents is not as widely utilized as in adult patients given that children will experience anatomic changes in the aorta over time due to growth. Further, CT scans are a commonly used modality for lifelong endograft surveillance, which presents a high burden of radiation for young patients.

Cardiac injury

Cardiac injuries are uncommon in injured children, with incidence reported at 0.03%, and may include myocardial contusion, life-threatening arrhythmia (commotio cordis), valvular disruption, ventricular laceration, ventricular rupture, and traumatic septal defects. Given the rarity of these injuries, evidence-based practice guidelines are lacking and frequently rely on adult literature. While cardiac enzymes, electrocardiogram, and echocardiogram may be useful adjuncts in the diagnosis of cardiac injury after chest trauma [55], a high index of suspicion and reliance on clinical presentation is vital.

The largest and most recent review to date included 626 patients over 5 years with cardiac injury from the NTDB [56]. The patient cohort and injury patterns in this study match various case reports and smaller series reported previously. The majority of subjects (73%) were adolescent and male (75%). Type of injury included contusion (59%), laceration (36%), and other (7%). Contusions were more likely

Figure 17.14 Sixteen-year-old male fell down from 30 feet. CT chest with contrast demonstrated 2.9 cm × 2.2 cm × 2.1 cm pseudoaneurysm arising from the proximal descending thoracic aorta.

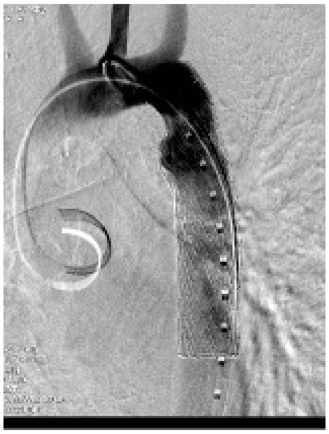

Figure 17.15 Sixteen-year-old male fell down from 30 feet. The patient underwent Thoracic Endovascular Aortic Repair (TEVAR) using stent graft device.

after blunt injury and in younger children. Lacerations were more likely after penetrating injury and in adolescent patients. A total of 77% sustained associated injuries with the most common being head injury and other thoracic injuries. A total of 9% required thoracotomy and 0.2% underwent sternotomy. Mortality rates were high and related to mechanism of injury (firearm injury 76%, MVC 31%, auto vs. pedestrian accident 27%, fall 25%).

Myocardial contusions are the most common of these rare injuries after blunt trauma. Presenting symptoms are wide ranging and may include arrhythmia, hypotension due to myocardial dysfunction, or no symptoms. Isolated myocardial contusion is not typically fatal and can be managed nonoperatively with continuous cardiac monitoring in a telemetry unit. In adult patients, the combination of normal ECG and Troponin I at admission and 8 h later rules out the diagnosis of significant blunt cardiac injury [57]; a similar strategy of serial testing during a period of observation is often utilized in pediatric patients after chest trauma. Infrequently, myocardial contusion may cause coronary artery injury and peritraumatic myocardial infarction; the underlying etiology may be related to parietal hematoma or coronary artery dissection, although in some cases it remains unknown. Cardiac MRI has been described to distinguish peritraumatic myocardial infarct from nonischemic myocardial contusion; coronary angiography may be necessary to exclude coronary injury in the presence of abnormal MR results [58].

Traumatic valvular injury and ventricular septal tears are incredibly uncommon in pediatric patients. Most are due to high-energy MVCs, may or may not be acutely symptomatic, and may be accompanied by conduction defects [55]. Injuries such as ventricular rupture tend to be rapidly fatal; however, patients who survive to hospital evaluation have increased rates of survival with rapid diagnosis and management [59]. This can be done using portable bedside ultrasound (FAST exam) or formal echocardiogram.

Patients with penetrating cardiac injury may develop tamponade over some period of time rather than abruptly; formal echocardiogram or bedside FAST exam can permit rapid identification of injury and expedite transfer to the operating room for further evaluation (pericardial window, etc.) [59].

Diaphragm injury

Diaphragm injuries are uncommon in children (incidence < 0.1%) and may result from blunt (MVC or fall) or penetrating (gunshot wound or stabbing) trauma [60–62]. They occur more often in isolation in children compared with adults; however, the majority of children sustain additional injuries as the amount of force required to injure the diaphragm commonly damages surrounding intra-abdominal and intrathoracic viscera and structures

[60,61,63]. The left side is more commonly affected, and herniation of viscera including stomach, colon, small intestine, omentum, spleen, and liver may be observed. Diagnosis can often be made using AP chest radiograph that shows a nasogastric tube coiled in the chest, elevated or absent hemidiaphragm, bowel loops in the chest, soft-tissue opacity in the chest, mediastinal shift away from the injured side, and pleural effusion. Chest CT with coronal and sagittal reconstructions may be useful to confirm in subtle or equivocal cases. However, diagnosis easily may be overlooked without a high degree of clinical suspicion. Providers should maintain a low threshold to perform diagnostic laparoscopy or thoracoscopy with thorough evaluation of bilateral diaphragms in suspected cases of diaphragm injury, and careful inspection of both diaphragms should also be undertaken routinely during trauma laparotomy. In cases diagnosed immediately after injury, approach via the abdomen is recommended given the high rate of concomitant intraperitoneal organ injuries. In the event of a delayed diagnosis, a thoracic or combined approach may be required in the presence of adhesions in the pleural cavity. Primary repair can often be accomplished, with large or chronic defects requiring a patch.

Esophageal injury

Esophageal injury is exceedingly rare in pediatric trauma. Most series in children combine multiple etiologies (iatrogenic injuries, functional disorders, and caustic ingestions) along with the few cases of esophageal injury due to penetrating and blunt trauma. The infrequency of the injury as well as the reporting prevents detailed analysis of this entity in pediatric patients. Much of the knowledge is therefore derived from adult patients, in whom esophageal injury is also relatively uncommon. Mortality and morbidity can reach 70% depending on associated injuries and time to diagnosis/intervention [64]. This highlights the importance of early diagnosis; however, this can be challenging in a multiply injured patient whose other severe injuries may take precedence or prevent the performance of diagnostic studies.

The vast majority of esophageal injuries result from penetrating trauma and should be managed surgically. Most are adequately controlled with primary repair with or without muscle flaps to buttress the repair and closed suction drainage. In some cases esophageal exclusion may be indicated [65]. The literature contains only eight case reports of esophageal perforation after blunt injury in children <16 years of age in the past 55 years [64,66]. While the intrathoracic esophagus is protected from direct injury by blunt trauma, perforations can occur due to rapid increases in intraluminal pressure, ischemic injury after devascularization from deceleration/traction mechanism, and blast injury if force is transmitted from the trachea [67].

SUMMARY

While thoracic trauma is less common than abdominal trauma or head injury, injuries to the chest can be highly lethal in children. The most common injuries include pulmonary contusions, rib fractures, and hemo/pneumothorax. Rib fractures are often seen as a manifestation of child abuse; this is a “sentinel injury” in patients age <3 and should mandate additional testing to assess for non-accidental injuries. Less common are injuries to the tracheobronchial tree, major vessels, heart, diaphragm, and esophagus. The finding of isolated pneumomediastinum without clinical symptoms of injury is typically self-limited and benign.

Providers should adhere to the American College of Surgeons’ ATLS guidelines in their approach to the care of patients who sustain trauma to the chest. Many thoracic injuries can be diagnosed and treated at the time of the primary survey, during which time airway patency, breath sounds, and neck and chest exam are performed expeditiously. Plain radiograph is readily available and carries a low burden of radiation exposure; CXR should be utilized as the primary screening modality for thoracic injuries, with additional workup (computed tomography, bronchoscopy, angiography) as indicated by the patient’s clinical presentation.

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18

Pediatric abdominal trauma

LAUREN GILLORY and BINDI NAIK-MATHURIA

Abdominal trauma remains a cause of significant morbidity in children despite advances in the care of these patients. Blunt injuries account for approximately 90% of pediatric trauma. According to a review of several trauma databases, approximately 8%–12% of children suffering blunt trauma will have an intra-abdominal injury [1]. Motor vehicle crashes, autopedestrian injuries, and falls constitute the most common mechanisms for blunt abdominal trauma. Other common causes include bicycle accidents, all-terrain vehicle injuries, and child abuse. Fortunately, most of the children suffering blunt abdominal trauma have an excellent prognosis with greater than 90% survival [2]. Nonoperative management (NOM) of the majority of blunt abdominal trauma has become a mainstay since the original advances in the 1960s and 1970s. Since the introduction of observation for blunt splenic laceration and hematoma, pediatric surgeons have continued to push the envelope with regard to minimizing unnecessary operative and diagnostic interventions.

In contrast to blunt abdominal trauma, penetrating injuries are significantly less common in the pediatric population compared to the adult population. Many similarities exist between the treatment of penetrating trauma in adults and children, therefore the major tenets of adult trauma apply in the pediatric population. The two variables that impact severity of the injury are the location of the penetrating wound and type of weapon used. Gunshot wounds and stab wounds are more likely to warrant surgical exploration due to higher probability of injury to intra-abdominal organs and subsequent hemodynamic instability.

Children are prone to solid organ injury due to proportionally larger vital organs, minimal subcutaneous tissue, and lack of sufficient protective chest wall and abdominal musculature, as well as a smaller surface area to dissipate the force associated with pediatric trauma [3]. The nonoperative approach to abdominal trauma is one of the arenas where pediatric management led the way to advances in adult trauma care. Care of children experiencing abdominal trauma has continued to evolve over the last few years. In this chapter, the current management patterns for blunt and penetrating abdominal trauma will be reviewed with attention to the most current practice and literature. We also review aspects of care that are unique to the pediatric trauma patient. In addition, we include some novel approaches to imaging and treatment that have contributed to progress in the field.

Initial evaluation of pediatric blunt abdominal trauma

Emergent care of the trauma patient follows a predictable sequential algorithm that has been validated through evidence for adults and children. Advanced Trauma Life Support (ATLS) mandates confirmation of a patent airway, adequate breathing, and appropriate circulation with assessment of neurologic disability at presentation and with each change in clinical status. If an intra-abdominal injury is suspected to be contributing to hemodynamic instability, it should be appropriately evaluated prior to proceeding to the secondary survey. The patient may require emergent surgical exploration if there is not an appropriate response to resuscitation. Once the primary survey is completed without any need for intervention, a thorough abdominal exam occurs with the secondary survey. Many children present a particular challenge in the evaluation for abdominal injuries due to inadequate or absent communication skills, minimal external signs, increased physiologic reserve leading to maintenance of normal vital signs in the face of significant blood loss, and varying injury patterns specific to age groups [4]. In the setting of a high index of suspicion for intra-abdominal injury, imaging is the most readily available adjunct and should be tailored to each individual patient depending on the mechanism of injury and findings on the secondary exam.

Abdominal CT is particularly helpful in the evaluation of trauma patients due to its high sensitivity in detecting torso injuries. However, current research supports limiting radiation when possible, particularly in the pediatric population. Clinical practice began to change after the observation in 2001 by Dr. David Brenner that radiation from CT scans increases the risk of fatal cancer in our youngest patients [5]. Subsequent researchers have shown that there is a linear increase in multiple types of cancer with the amount of radiation exposure [6,7]. Acceptance of the increased risks associated with low-dose radiation from diagnostic imaging resulted in the as low as reasonably achievable (ALARA) principle [8]. There has been a concerted effort to decrease the amount of radiation delivered with each imaging study and to limit the CT examinations to those that are absolutely indicated. In light of these recommendations, the evaluation of the trauma patient has evolved in the last two decades.

Thoughtful application of imaging in the pediatric trauma patient has resulted in the development of protocols to determine appropriateness of ordering abdominal CT scans. Prior to interventions to limit imaging, the rate of normal CT scans in the pediatric trauma population was widely variable and almost exclusively reported from trauma centers. Fenton et al. identified a group of 1422 pediatric trauma patients that underwent CT scans and 54% had normal findings [3]. When these researchers looked specifically at abdominal CT scans, 67% had no abnormal findings and only 2% of the patients were taken to the operating room for exploratory laparotomy. Since we have minimal information from transferring institutions and general hospitals, normal CT scans for pediatric trauma may be even more pervasive than reflected in the literature.

A study from Jindal et al. examined records from patients ages seven or younger who experienced mild to moderate trauma (injury severity score ≤15) admitted to a single pediatric trauma center over the course of 2 years and compared them to adult patients matched for injury severity and mechanism of injury [9]. Findings suggested that pediatric trauma patients had a higher likelihood of undergoing CT scans than their adult counterparts and that "pan-scans," which refer to CT scanning from head to pelvis, were more prevalent. This retrospective study from a single institution supports the recognized practice commonly seen in adult trauma centers where evaluation of pediatric blunt abdominal trauma is challenging to providers who have limited experience with children [10]. In addition, community hospitals are less likely to follow recommended practices to decrease radiation exposure from each individual study. According to Agarwal et al., the tube voltage and tube current were higher on average at hospitals that did not specialize in the care of children [11]. Patients are less likely to be exposed to excess radiation if promptly transferred to or initially evaluated at a pediatric trauma center [10].

At the Texas Children's Hospital, an abdominal trauma protocol has improved resource use and decreased the rate of negative CT imaging [12]. The protocol separated patients suspected of blunt abdominal trauma into four categories: (1) unconscious, (2) conscious with unreliable exam, (3) conscious with reliable exam, and (4) abdominal wall bruising. Each category had a distinct algorithm to guide the evaluation (Figure 18.1). With implementation of this clearly constructed abdominal trauma protocol, which provided consistency among many providers, rates of positive CT scan findings increased from 23% to 49% and clinically significant findings on abdominal CT went from 14% to 32%. In addition, expenditures on laboratory testing were decreased by 39% after implementation of the revised version of the protocol [12]. These improvements came at no significant increased time to CT scan when indicated, nor prolonged stay in the emergency center (prior to discharge or transfer to the inpatient ward). These findings validate multiple other studies that utilize patient history and physical exam findings to direct the evaluation of blunt abdominal trauma [13,14].

Despite the push to decrease abdominal CT imaging for children, CT remains our best noninvasive way to evaluate children with suspected abdominal injuries. Several presentations justify ordering these studies. First, abdominal tenderness or subjective complaints of pain in the setting of blunt abdominal trauma has repeatedly been confirmed as a justification for abdominal CT [12,15]. In addition, a well-defined injury that has a high association with intra-abdominal injury is the presence of abdominal wall bruising or seat belt sign. Abnormal laboratory values may be helpful to determine the need for CT in some cases, such as elevated pancreatic enzymes or anemia. The role of elevated liver transaminases or microhematuria alone as indicators of abdominal organ injury is still debatable. At our institution, we rely heavily on physical examination and less on abnormal laboratory values, unless the physical examination is unreliable such as in a child with altered mental status or a very young, agitated child.

Ultrasound is the second most commonly used imaging modality in the trauma population and focused abdominal sonography for trauma (FAST) is a widely accepted tool in the management of adults. To conduct a FAST, four views are obtained using a bedside ultrasound: the perisplenic or splenorenal space, perihepatic or hepatorenal

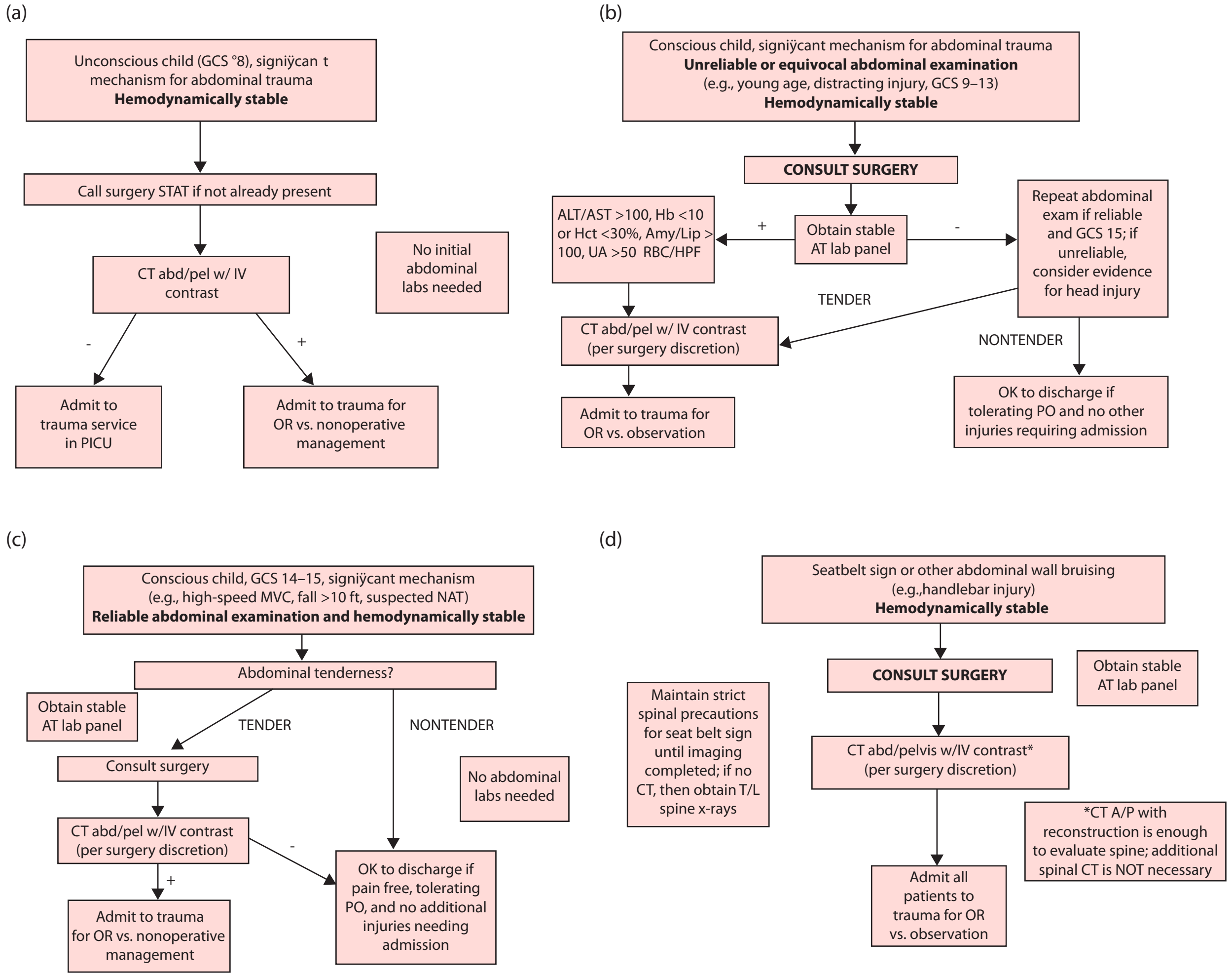
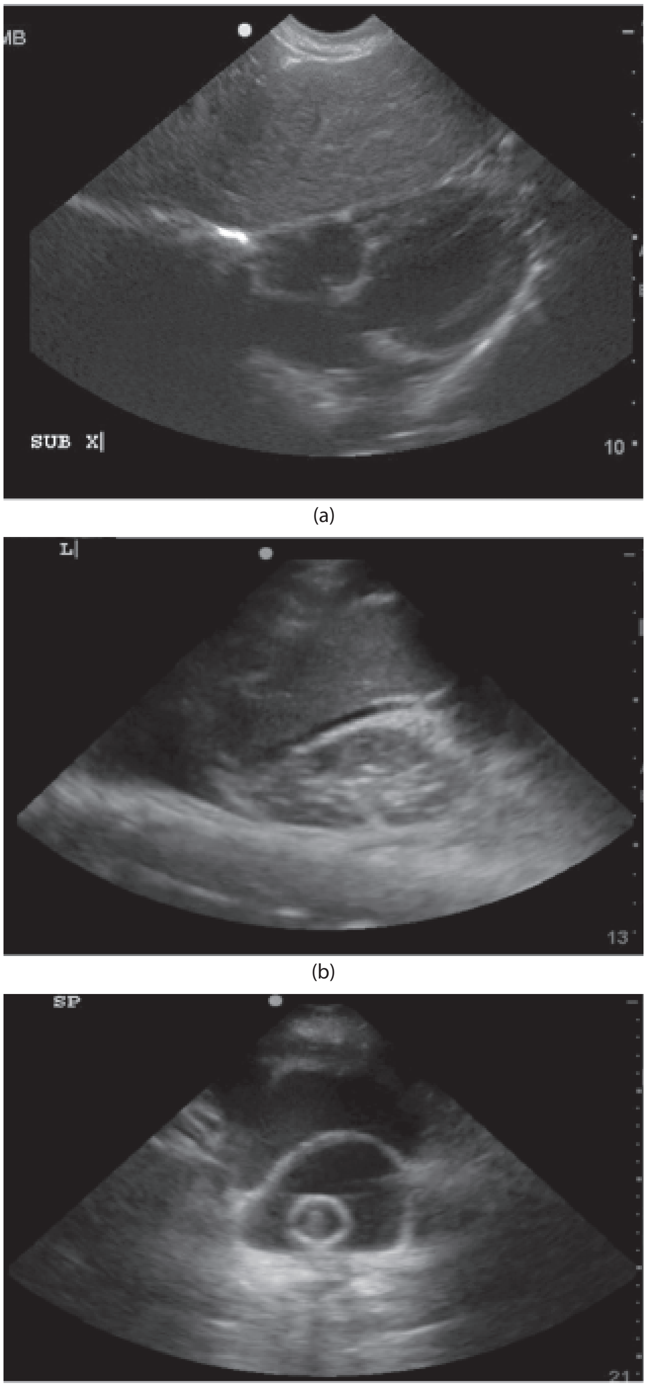


Figure 18.1 Evaluation of blunt abdominal trauma protocol utilized at Texas Children's Hospital. **(a)** Blunt trauma, unconscious. **(b)** Conscious, unreliable exam. **(c)** Conscious, reliable exam. **(d)** Abdominal wall bruising.

recess (Morrison's pouch), pelvic, and pericardial view (Figure 18.2). The strength of this examination is in the detection of free fluid in locations that can affect management or identify a source of hemodynamic instability. For pediatric patients, FAST is more controversial and not as widely utilized. Original research in the field indicated a relatively high number of missed intra-abdominal injuries in the pediatric population, especially when there was an absence of free intraperitoneal fluid [16]. A recent article from Menaker et al. indicates that appropriate ultrasound exams could restrict abdominal CT use in normotensive pediatric trauma patients. The prospective observational study conducted using data from 12 emergency departments across the United States reported that FAST exams were obtained for only 887 patients (13.7%) of 6468 who met eligibility [17]. Analysis of the results revealed that patients with low or moderate risk of intra-abdominal injury as judged by the treating physicians (1%–5% and 6–10%, respectively) were less likely to receive an abdominal CT scan if a FAST was performed. The study did not identify any missed injuries in the patient population. Although other investigators have identified a low sensitivity for FAST in the setting of pediatric trauma [18], further studies have shown that combining FAST with careful physical examination increased the sensitivity to 88% [19]. Combining FAST with laboratory values indicative of intra-abdominal injury, such as liver transaminases, also exhibits an increased sensitivity [20]. Specifically, FAST can serve as a rapid diagnostic tool in the trauma bay when a hemodynamically unstable patient may not be suitable for transfer to the CT scanner. Ultrasound has potential for improving the examination of pediatric trauma patients and limiting CT use, but more advances in its implementation are necessary.

Another promising technology to promote radiation-free assessment of pediatric trauma patients is the contrast-enhanced ultrasound (CEUS). In the last decade, there has been some investigation into evaluating solid organ injury with ultrasound examinations conducted after the administration of intravenous (IV) contrast [21]. With the addition of IV contrast, the detection of solid organ injuries after blunt trauma was increased from 50% to 91% with ultrasound. In addition to the initial survey of trauma patients, CEUS may be particularly useful for follow-up imaging of solid organ injuries and detection of pseudoaneurysms



(a)

(b)

(c)

Figure 18.2 FAST images. **(a)** Normal subxyphoid view of heart (blood within pericardium would show as a black stripe between the heart and pericardium). **(b)** Splenorenal recess with pleural and intraperitoneal fluid between kidney and spleen. **(c)** Free fluid in pelvis, with Foley catheter balloon seen in bladder. (Courtesy of Dr. Kiyetta Alade, Texas Children's Hospital.)

(a)

(b)

Figure 18.3 Contrast-enhanced ultrasound images. **(a)** CT demonstrating a grade II splenic laceration. **(b)** In the same patient, the laceration is not noted on a standard ultrasound (left), but is clearly demonstrated on contrast-enhanced ultrasound (right). (Courtesy of Dr. David Mooney, Boston Children's Hospital.)

[22,23]. According to multiple studies, sensitivity was 75% or better and specificity was 92% or better when utilizing CEUS to image delayed pseudoaneurysms when compared to contrast-enhanced CT imaging (Figure 18.3). There is not wide acceptance of CEUS in the United States and most of the literature comes from Europe. With further study and improved techniques, this technology has the potential to decrease the need for CT imaging and improve the surveillance of children after blunt abdominal trauma.

Special considerations

Seat belt sign is the presence of bruising and abrasions in the distribution of the safety belt on the abdomen of a restrained occupant involved in a motor vehicle crash. One study from the pediatric emergency care applied research network (PECARN) reported that of 3 740 traumas with appropriate documentation, a seat belt sign was appreciated in 585 (16%) patients [2]. Definitive abdominal testing (CT, laparoscopy/laparotomy, or autopsy) was obtained in 1864 patients from this subgroup and intra-abdominal injury was present in a higher proportion of the patients with a seat belt sign (19%) than without (12%). The difference is primarily due to an increased rate of hollow viscus or mesenteric injuries: 11% when seat belt sign is present versus 1% when absent. Multiple other studies with smaller numbers reported from single institutions have shown an increased rate of injuries when a seat belt sign was present [24,25]. Protocols have appropriately included the seat belt sign as a trigger to obtain abdominal CT imaging, although the patient history and physical exam remain the primary indication. Other than pain, tenderness, and seat belt sign, the PECARN group identified elements of the history or physical exam that should prompt consideration to obtain a CT scan [13]. Signs of significant injury included any abdominal or thoracic wall trauma, Glasgow Coma Scale score less than 13, decreased breath sounds, and vomiting.

Although presence of a seat belt sign indicates increased possibility of intra-abdominal injury, children without abdominal pain and tenderness are still low risk for abdominal pathology according to Sokolove et al. [26]. Therefore, the use of CT should still be considered carefully. Sometimes, there will be patients with a seat belt sign who have clear clinical signs of bleeding or hollow viscus injury, such as diffuse peritonitis and abdominal distention or discoloration, who require immediate surgical exploration. In these patients, imaging is not necessary. An additional important point in the evaluation of patients with a seat belt sign is awareness of the association of a thoracolumbar spinal Chance fracture, a flexion-distraction injury which can often involve all three spinal columns and lead to an unstable spine with a risk of paralysis. Therefore, it is prudent to maintain strict spinal precautions on patients with seat belt bruising until the spine has been cleared by imaging, which can be spinal plain films if CT is not indicated to evaluate for abdominal injury.

Another injury pattern that should raise suspicion for abdominal pathology is nonaccidental trauma. According to Larimer et al., approximately 10% of battered children will suffer an abdominal injury [27]. These authors advocate for surgeons to be involved in the care of all acutely abused children. Although abdominal injuries in these patients can sometimes be subtle, they should be considered during evaluation for other injuries. In particular, children with thoracic injuries (including acute rib fractures) and spinal fractures are at particularly high risk for having concomitant abdominal injuries [27]. In infants less than 1 year of age, the incidence of abusive abdominal injuries can be even higher than that in older children (up to 25%), and duodenal injuries are more commonly seen in this population [28]. If not already obtained based on clinical suspicion, child abuse physicians will often require abdominal imaging in this age group in order to document all injuries for legal purposes.

Once the history, physical examination, laboratory testing, and appropriate imaging are obtained for the pediatric trauma patient, the disposition becomes the next major decision branch point. Patients may require an immediate operation, floor or ICU admission, or discharge from the emergency department with observation at home and possible outpatient follow-up. The determination of whether ICU or floor admission is most appropriate remains one that is currently in question. Although head injury and altered mental status is justification for critical care admission, it is less clear which patients benefit from an ICU stay for abdominal trauma. The American Pediatric Surgical Association (APSA) guidelines in the past recommended critical care monitoring for solid organ injuries grade IV or greater [29], but recent data support the use of hemodynamic parameters and clinical condition as the criteria for a higher level of care [12,30,31]. In addition, newer abdominal trauma protocols introduce the discharge of appropriate patients who lack physical findings of abdominal tenderness or have a negative CT scan [12]. Overall, trends are moving in the direction of decreasing resource use when appropriate and encouraging trauma surgeons to triage patients based on clinical presentation as opposed to imaging findings.

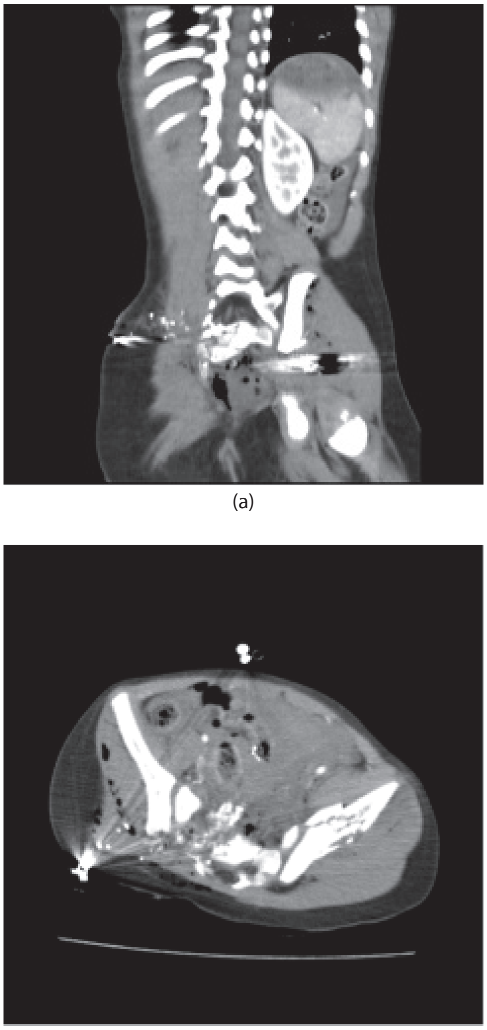
Penetrating abdominal trauma

Penetrating injuries in children primarily result from gunshot and stab wounds and constitute 10% of pediatric trauma [32]. Firearm-related injuries have a 12% case-related fatality rate and account for approximately 25% of pediatric trauma deaths according to the National Trauma Data Bank (NTDB) [33]. Younger children suffering gunshot wounds have a higher mortality risk when compared to adolescents, likely due to smaller stature and more crowded organs within the torso [34]. Unfortunately, a significant number of gunshot injuries in children are accidental. According to Oyetunji et al., a 2-year review of the NTDB revealed that 26% of firearm fatalities affected children aged 14 or younger and a significantly higher number of these injuries were unintentional [35]. Injury prevention education and other concerted efforts to decrease firearm-related injuries in children have achieved a measure of success in recent years, but penetrating pediatric trauma remains a public health concern.

Penetrating injuries should initially be managed similarly to any other trauma patient with a rapid assessment of airway, breathing, and circulation according to ATLS guidelines, but the operating room should be alerted because of the potential need for surgical intervention. Radiographic examination should occur simultaneously with the secondary survey, provided there is no hemodynamic instability. Radio-opaque markers should be placed at gunshot or stab wound sites prior to chest and abdominal radiographs in an effort to define trajectory of the missile or foreign body. For patients with peritonitis or compromised hemodynamics, emergent exploration is mandated. Neurologically impaired individuals or those without a reliable abdominal exam should prompt consideration for immediate laparotomy. For stable adult trauma patients, the selective NOM of abdominal stab and gunshot wounds has become accepted over the past two decades [36]. Demetriades et al. reported that over a 20-month period, there were 152 patients identified with 185 penetrating solid organ injuries and 61 (40%) were selected for CT scan without laparotomy. Ultimately, 41 patients did not require surgical exploration; no abdominal complications were observed. Overall, 28% of liver, 15% of renal, and 4% of penetrating splenic injuries were successfully managed nonoperatively. Abdominal CT is the routine diagnostic tool to identify the tract and involved organs when the nonoperative approach is selected for penetrating abdominal injuries [37]. Penetrating trauma is less common in pediatric practice; therefore, it is more difficult to assess the potential success of NOM for this population. Cigdem et al. described NOM in 51 out of 90 patients suffering penetrating abdominal trauma from 2003 to 2008 [38]. Of the 51 patients managed nonoperatively, only 2 required a subsequent operation and only 1 had a missed bowel injury with a 20-hour delay to surgical therapy. Both were discharged from the hospital after an uneventful postoperative course. This study suggests that a penetrating abdominal wound in a child does not always require a laparotomy. Further investigation is needed to clarify how to select children with penetrating injuries for NOM.

Even in cases when operation is mandated, CT can be useful to better evaluate for skeletal, spinal, or vascular injuries as long as the patient is stable enough to delay operation (Figure 18.4). Once in the operating room, the operation should proceed in a systematic fashion. The chest, abdomen, and groin should be prepped into the operative field. Care should be taken to ensure the room is kept at an adequate temperature to maintain homeostasis and IV fluids should be warmed. Once the incision is made, packs should be placed in the four quadrants of the abdomen to control hemorrhage. Each quadrant should be thoroughly explored to address all sources of bleeding or contamination. Many different injury patterns can be encountered in a patient with penetrating abdominal injury. The gastrointestinal tract is the most commonly injured organ at a frequency of 70% and the pancreas (6%) is generally the least affected [32]. Major vascular trauma is the most likely cause of hemodynamic instability in this patient population and a general understanding of the management of vascular injuries is vital for the pediatric trauma surgeon.

Penetrating vascular injuries can be classified based on the locations of the resulting hematoma. The central abdomen constitutes zone 1; any hematoma in this area should be formally explored. Injuries in this region are likely to involve the major abdominal vasculature and may also have associated pancreatic or duodenal injuries. Missed injuries in zone 1 can have catastrophic outcomes. Zone 2 injuries are in the lateral compartments of the abdomen containing the kidneys, renal pedicles, adrenals, and other related urinary structures. These hematomas should routinely be explored in the setting of penetrating trauma and any bleeding should be addressed. Particular attention should be dedicated to ruling out a colon injury in zone 2 injuries. If time permits and the hematoma is not rapidly expanding, it can be beneficial to establish control of the renal pedicle prior to exposing the hematoma. Zone 3 is the pelvis. These injuries are often accompanied by pelvic fractures. Penetrating trauma to this region would justify exploration of the hematoma, although this area is generally managed with angiographic interventions in the blunt trauma patient. Iliac vessel injuries can be extremely difficult to control and diagnosis with ligation or repair is important in this injury pattern. The inguinal ligament may be divided to achieve distal control of a bleeding vessel. Although vascular trauma is not a common presentation in pediatric penetrating trauma, it is a cause of significant mortality and understanding its management remains salient.


(a)

(b)

Figure 18.4 **(a)** and **(b)** CT demonstrating the tract of a bullet shot through the pelvis of a 3-year-old child. The child sustained colon and bladder injuries and multiple pelvic fractures.

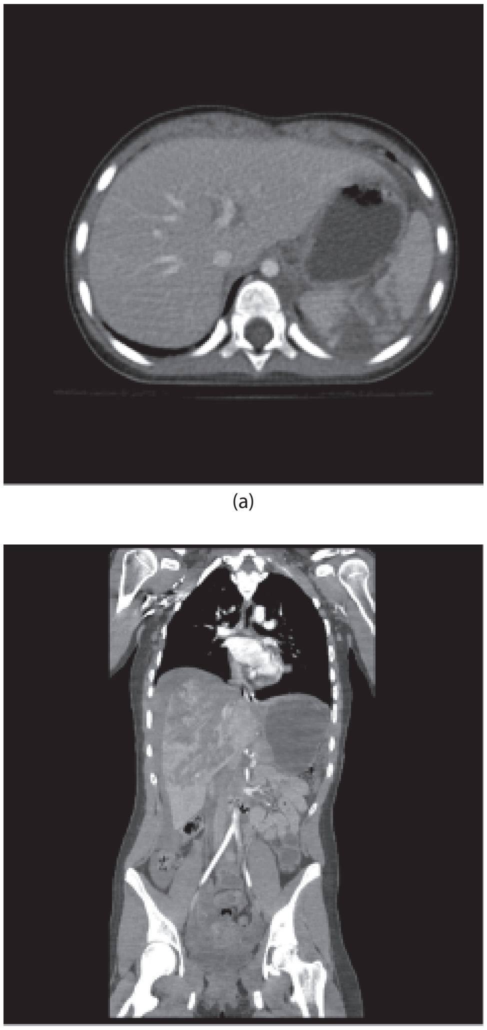
Blunt solid organ injuries

Spleen and liver

In pediatric blunt trauma, the liver and spleen are the two organs most likely to be injured. A splenic laceration is the most common isolated injury, although the liver and spleen are approximately equally involved with trauma [39]. Solid organ injury can be a significant source of mortality and morbidity if the injury is missed, so it is important to maintain a high index of suspicion. Liver and splenic trauma may result from two common mechanisms: a specific impact to the upper abdomen (e.g., bicycle handlebar, assault, football helmet contact) or multisystem trauma from a high-energy mechanism (e.g., fall from considerable height, motor vehicle collision, all-terrain vehicle accident) [40]. History and physical examination in combination with laboratory exam can result in elevated concern for solid organ injury and should progress to appropriate radiographic studies. Although there is a trend toward minimizing radiation as previously discussed in the Initial evaluation section, abdominal CT is the gold standard imaging to evaluate these injuries in a hemodynamically stable patient. The American Association for the Surgery of Trauma (AAST) grading system for splenic and hepatic injury is routinely used to classify these injuries and can help guide the management of patients (http://www.aast.org/library/traumatools/injuryscoringscales.aspx) [41]. NOM of splenic and liver injuries in stable pediatric patients gradually led the trauma community to NOM for all manner of presentations over the last few decades, including blunt and penetrating injuries. Rates of success with the nonoperative approach now approach 90%–95% in patients with traumatic injury of the liver and spleen [40]. Figure 18.5 depicts high-grade splenic and liver lacerations that were both managed nonoperatively at our institution.

The liver and spleen lie in the right and left upper quadrants of the abdomen, respectively, and are partially protected by the ribs. This protection is less effective in children due to increased compressibility of the thoracic cavity and more compliant ribs. In children, these organs often extend below the costal margin. For these reasons, the liver and spleen are more commonly injured in children compared to adults. The primary effect of liver and splenic injury is hemorrhage in these two impressively vascular structures; the blood loss can be fatal if untreated. Children who are hemodynamically unstable despite appropriate resuscitation in the setting of blunt abdominal injury should undergo emergent laparotomy. For adult trauma patients, presence of a blunt intra-abdominal injury in the setting of head trauma and inability to perform reliable abdominal exams may be used as a justification for proceeding to an operation. This approach is not usually undertaken in children since many authorities believe that NOM should be attempted in hemodynamically stable children with a combination of a head injury and spleen or liver damage [42]. Children with altered mental status are no more likely to need a laparotomy. Outcomes are improved in patients who do not require an operation for intra-abdominal injury.

The AAST organ injury scaling has been validated in adults and CT grading correlates with outcomes in children, therefore the APSA sought to develop evidence-based guidelines for the treatment of patients with isolated liver or spleen injuries [29]. There was a paucity of class I evidence to provide a basis for clinical guidelines; therefore, a survey was conducted from a multi-institutional database consisting of 832 children with isolated liver or spleen injuries managed nonoperatively at 32 centers in North America from 1995 to 1997. Utilizing these data, the guidelines were formulated and they served as a widely accepted benchmark for pediatric trauma care. The guidelines addressed indications for ICU stay, duration of hospitalization, the need for predischarge or postdischarge imaging, and activity restrictions. They did not address the indications for a laparotomy. Prospective application of the guidelines in 312 children who received care at 16 pediatric centers for isolated liver or spleen injuries resulted in significantly decreased resource utilization reflected by shorter ICU and hospital stay, diminished repeat imaging, and duration of physical activity restriction when compared to a historical control [43]. Compliance with the guidelines was 81% for ICU stay, 82% for hospital stay, 87% for follow-up imaging, and 78% for activity restriction. All pediatric patients included in


(a)

(b)

Figure 18.5 **(a)** Grade III splenic injury following a fall from a third-story window, managed nonoperatively. **(b)** Grade IV liver injury following a vehicular crush, managed nonoperatively.

the study had either isolated solid organ injury (liver and/or spleen) or an additional minor, remote injury such as nondisplaced, noncomminuted extremity fractures, or soft tissue injuries. Another important point to note is that the patients in the study were all hemodynamically stable. Six patients (2%) were readmitted, but no one progressed to an operation. These results confirmed that clinical practice guidelines (CPG) could safely reduce resource utilization and help standardize pediatric trauma care.

A pertinent clinical question in the era of NOM of blunt liver and spleen injuries (BLSI) is how the rate of blood transfusions has changed. Multiple studies actually showed a decreased need for blood transfusion in patients treated with the nonoperative approach [44,45]. In a retrospective analysis of 161 patients aged 16 years or less from the trauma registries at two urban regional trauma centers, Partrick et al. reported a significant decrease in operations from 39% to 9% for BLSI from the initial time frame cohort (1990–1993) to the second (1994–1997). For each time period examined, blood utilization was less in the nonoperative group: 46% versus 9% and 44% versus 13%, respectively. Additionally, hospital length of stay was shorter in the nonoperative group. Subsequent investigation has confirmed this trend, with 5% or less of children managed nonoperatively requiring blood transfusions [46,47].

Within the last few decades, the elements of the APSA CPG have become widely accepted and many trauma practitioners advocate further limitations in ICU admissions, hospital length of stay, and activity restrictions [48]. St. Peter et al. have published multiple studies validating the premise of abbreviated bed rest [49–51]. As opposed to the APSA CPG that recommends bed rest for a period of days equal to the grade of injury plus one day, the St. Peter protocol recommends one night of bed rest for grades I and II liver and spleen injuries and two nights of bed rest for grades III and greater. This proposal would significantly reduce hospital days and general resource utilization.

A more recent practice management guideline exists that was developed by a pediatric trauma consortium (ATOMAC) in 2012 for the management of BLSI in children [15]. This algorithm uses suspicion for ongoing or very recent bleeding as a decision point for obtaining an abdominal CT or admission to an ICU for observation (Figure 18.6). This designation

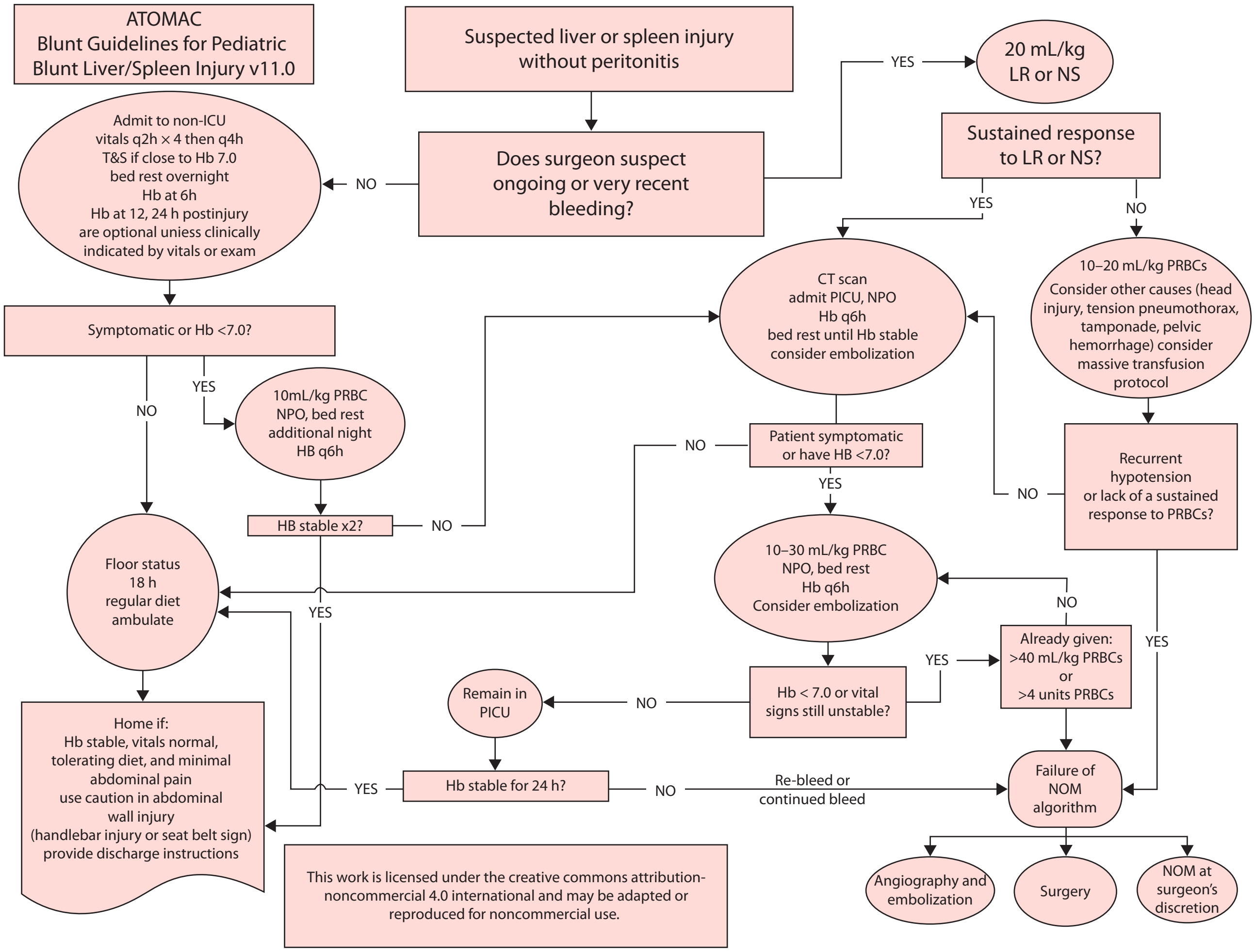


Figure 18.6 ATOMAC guideline for management of pediatric blunt liver and spleen injury. Used by permission of the ATOMAC research network. ICU, intensive care unit; T&S, type and screen; Hb, hemoglobin; PRBC, packed red blood cells; NPO, nil per os; CT, computed tomography; PICU, pediatric intensive care unit; LR, lactated ringers; NS, normal saline; NOM, non-operative management. (From Notrica DM et al., *Journal of Trauma and Acute Care Surgery*, 79, 683–93, 2015.)

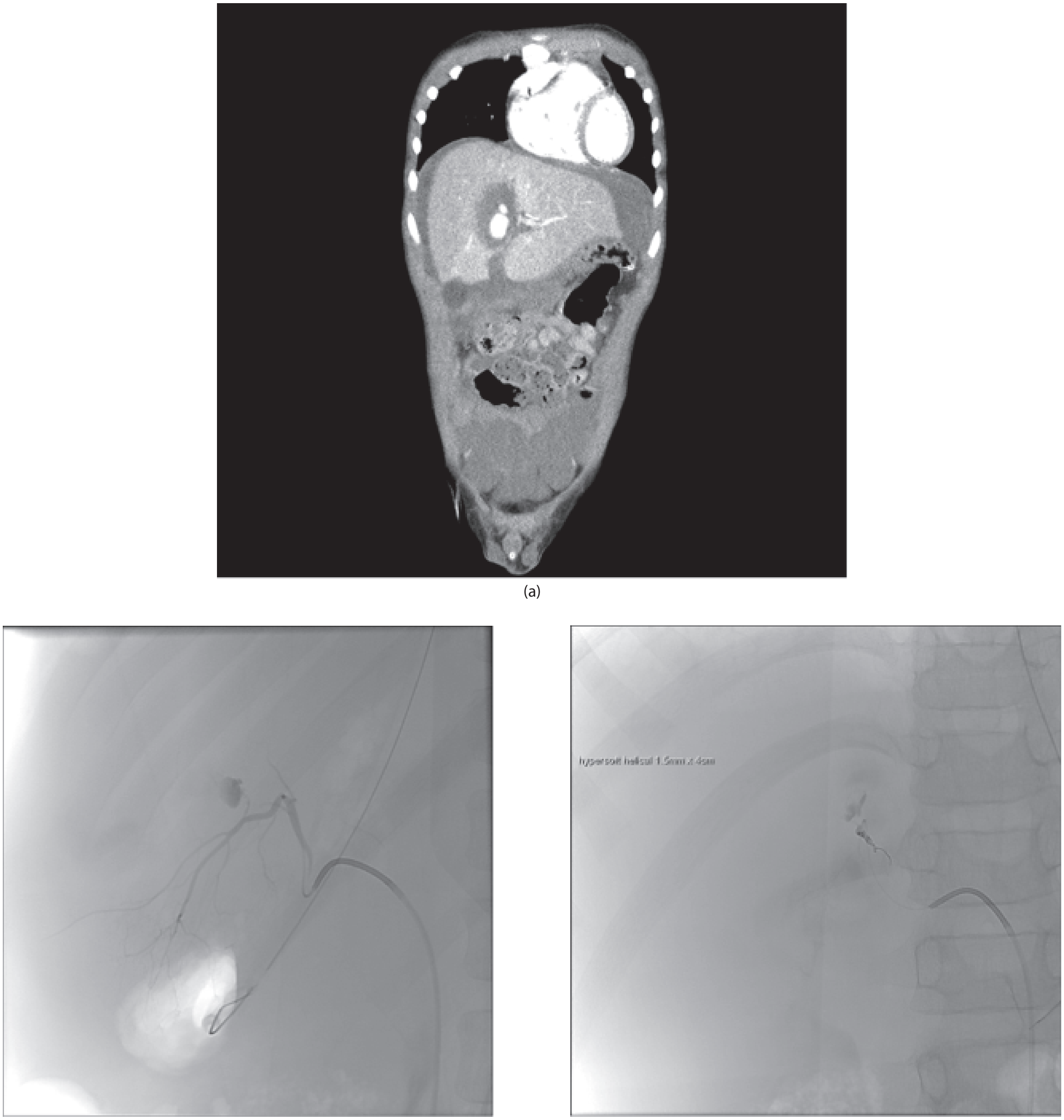
of suspicion for active hemorrhage is determined by trauma surgeons utilizing patient characteristics, such as pallor, hypoperfusion, hemodynamic signs indicating hypovolemia, anemia, inappropriate response to transfusion, and lactic acidosis. Essentially, this guideline proposes that clinical signs, hemodynamics, and trending hemoglobin values should dictate the care of BLSI in children instead of abdominal CT grade of injury. A thorough evaluation of the new recommendation reveals support by the current literature. However, a prospective study is needed to determine the safety and outcomes associated with it. The guideline has the potential to decrease CT imaging, hospital length of stay, and ICU admissions. Per the authors, management decisions should be dictated by clinical signs and symptoms to achieve the most appropriate treatment for pediatric patients with BLSI.

Adult trauma care has integrated angiographic embolization into the protocol for therapeutic interventions of spleen and liver injuries, which has led to higher rates of successful NOM [52–54]. In certain situations, prophylactic embolization has been advocated for high-grade solid organ injuries that has reduced the failure rate of NOM from 15% to 5% in the adult population [52]. Introduction of embolization into algorithms for the care of pediatric patients is more controversial and not widely accepted. Several isolated case reports and series describe the safe use of embolization in this patient population. From a retrospective review of 10 years from a trauma registry at a single level II pediatric trauma center, there were 259 patients with blunt splenic injury of which 23 underwent angiography [55]. There were 15 patients who initially underwent angiography due to active contrast extravasation on CT abdomen and another 8 patients who progressed to embolization due to continued transfusion requirements. There were no deaths in the group who were subjected to angiography. Only one of the 15 patients who initially underwent embolization required a splenectomy and none of the 8 patients embolized after attempted observation had their spleens removed. This study supports the selective use of embolization for blunt splenic injury. Multiple other studies have documented safety with arterial embolization of blunt splenic and hepatic injuries in pediatric patients [56,57]. There is evidence that transarterial embolization can assist in the NOM of children who would otherwise certainly require operative intervention. One such example is described by Fallon et al., in the case of an 8-year-old boy who presented after a bicycle handlebar injury resulting in a hepatic artery transection. On abdominal CT, there was a 4-cm liver laceration and active contrast extravasation that was confirmed on transarterial angiogram. The patient was successfully embolized and had no further bleeding issues (Figure 18.7). Of note, he did require laparoscopic drainage secondary to a bile leak complicating his liver laceration.

As demonstrated by this evidence, embolization can be pursued safely in the pediatric trauma population. This assertion is supported by the minimal rates of complications reported in the literature. One review of angiography in pediatric trauma reported a complication rate of 0%–4% with these interventions [58]. Most complications are minor such as puncture site hematoma; procedure-related mortality is virtually nonexistent. Although data confirm the safety of embolization, the primary dilemma is when to use it. Liver and spleen injuries that initially show a contrast “blush” on CT can often be managed nonoperatively. In at least some of these patients the bleeding stops [55,59,60]. Perhaps contrast extravasation should be a reason to more closely monitor patients and proceed to angioembolization more rapidly if any signs of clinical deterioration are present [61]. In a general review of the literature, it seems the best indication for angiography is persistent transfusion requirements in the setting of stable hemodynamics. Hemodynamic instability despite appropriate resuscitation is an indication for surgical exploration.

NOM for BLSI has many advantages for the pediatric trauma patient and there is evidence that delayed operation after attempted NOM does not increase transfusion rates, hospital or ICU length of stay, or mortality [62]. Unfortunately, a handful of complications from this treatment strategy have become evident in the last three decades. One of the most concerning outcomes is late hemorrhage. This is problematic because there are no well-defined risk factors for this entity. From a report published in 2009, delayed splenic bleeding occurred in 1 out of 293 children managed nonoperatively at a single level I pediatric trauma center from 1992 to 2006 [63]. This patient was a 15-year-old boy who presented with bleeding that proved fatal 23 days after his initial grade IV splenic injury due to a fall from his bicycle. Judging from the review of prior literature by Davies et al. and other reports of delayed splenic bleeding, this is an exceedingly rare entity [64–66]. Although mechanism of injury, grading on imaging, and presence of a pseudoaneurysm have no correlation with delayed bleeding from the spleen, this appears to be a trend in adolescents. Delayed bleeding after blunt injury can also be seen in hepatic injury. Shilyansky et al. reported on two children who returned with delayed bleeding after traumatic hepatic laceration [67]. Both presented with hypotension and pain 10 days after the initial injury with evidence of delayed bleeding. These case reports emphasize the importance of counseling parents and patients on signs and symptoms that should prompt return to the hospital after blunt solid organ injury.

Delayed hemorrhage is the primary dreaded complication of NOM, but other rare occurrences include traumatic pseudoaneurysms, splenic pseudocysts, and biliary injuries. The low rate of 5% or less for pseudoaneurysm after blunt spleen and liver injury is generally accepted [68], but there are some studies that feel this phenomenon is underreported [22,23]. Groups from the United Kingdom and Italy advocate surveillance imaging with CEUS to identify patients with a pseudoaneurysm, to avoid any possible morbidity. Further studies are needed to determine if this is necessary. The therapeutic approach to pseudoaneurysm ranges from surgical therapy or angioembolization to continued expectant management. Another extremely rare complication is splenic pseudocyst formation after trauma



(a)

(b)

(c)

Figure 18.7 **(a)** CT of a grade V liver injury caused by a handlebar showing active extravasation from a hepatic artery branch. **(b)** and **(c)** Angioembolization with coiling controlled the actively bleeding vessel.

[69,70]. These patients generally present years later with pain or abnormal imaging and there are reports of successful treatment with alcohol sclerotherapy or splenectomy. Finally, biliary system morbidity after blunt abdominal trauma is quite rare and includes bile peritonitis, biloma, bile duct leak, and hemobilia. One report from seven urban adult level I trauma centers reported that 6% of grade III–V liver injuries managed nonoperatively will have a resulting biliary complication [71]. Liver injury grade and transfusion requirements within 24 h of injury were predictive of subsequent hepatic complications. Bile leaks are often diagnosed after complaints of abdominal pain prompt a hepatobiliary iminodiacetic acid (HIDA) scan. Endoscopic and interventional radiology (IR) techniques provide less invasive options for the treatment of these complications (Figure 18.8). In one series, 11 patients with traumatic bile

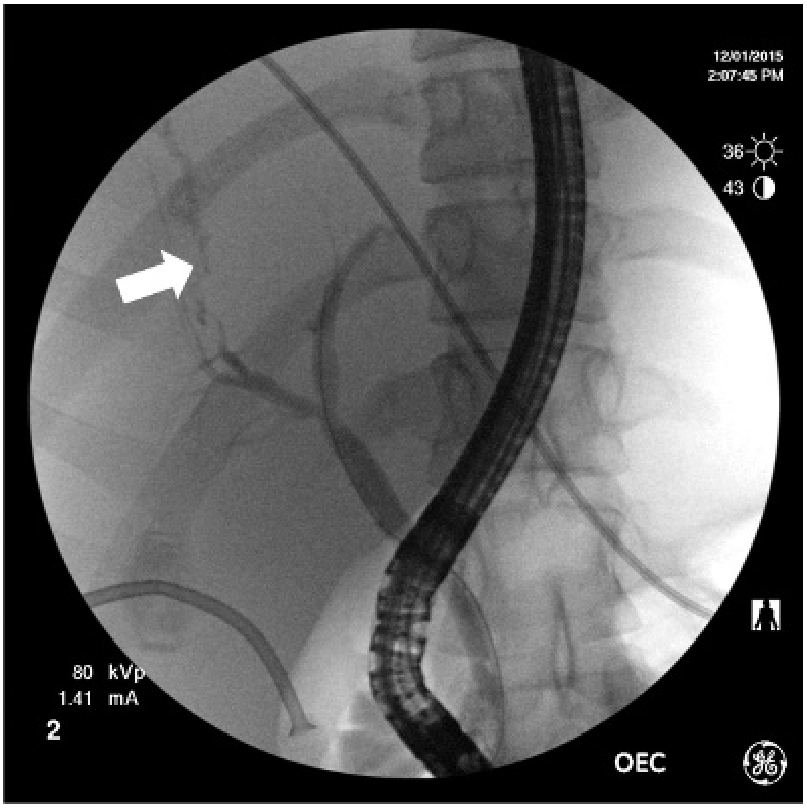


Figure 18.8 Cholangiogram demonstrating bile leak (white arrow) following a grade V liver laceration. Sphincterotomy was performed, which hastened resolution of the leak.

leak after NOM of blunt liver injury were managed with endoscopic retrograde cholangiopancreatography (ERCP) and stenting, with the occasional adjunct of IR drainage. None of the patients progressed to operative therapy [72].

Although there is general agreement that persistent hypotension after transfusion of >40 mL/kg or four units packed red blood cells qualifies as failure of NOM for BLSI in children, the next step in management is not universally accepted. Laparotomy would be the traditional progression, but changes in pediatric trauma have resulted in new options. Surgical intervention or continued NOM should be determined by a trained trauma practitioner. Under certain circumstances, angiographic embolization or continued nonoperative maneuvers may be appropriate. Once the care of these children progresses to an operation, most of those with a high-grade splenic injury will require splenectomy. At times, it may be possible to preserve the spleen through attempts at direct repair or partial splenectomy that maintain at least 1/3 of the organ with adequate perfusion. There are some interesting reports of successful laparoscopic splenorrhaphy for splenic trauma in adults and these techniques could possibly be applied to pediatric patients. Lin et al. described a sandwich repair technique that incorporates "figure of eight" sutures to fixate hemostatic plugs consisting of Gelfoam® and Surgicel® to the splenic laceration covered by an omental patch [73]. This technique achieved hemostasis in a median time of 30 min. Only 1 patient out of 15 who underwent the procedure required conversion to laparotomy and splenectomy. Although multiple approaches may be utilized to optimize splenic salvage even in patients requiring operation, there are situations where splenectomy is justified and indicated.

Splenectomy can be achieved through an open or laparoscopic approach, even in the setting of trauma [74]. In most pediatric trauma patients the goal of a laparotomy is to achieve rapid hemostasis and to recognize concomitant injuries. For children undergoing splenectomy, overwhelming postsplenectomy infection (OPSI) is a significant concern. Encapsulated organisms are the most virulent pathogens in an asplenic child. Those who require splenectomy for trauma should receive vaccinations for *Streptococcus pneumoniae*, *Haemophilus influenza*, and *Neisseria meningitidis*. In addition, all practitioners should have a high index of suspicion for this entity when a postsplenectomy patient arrives for evaluation [75]. These individuals may initially appear relatively well, but they can rapidly decline to florid sepsis and death. Current recommendations are to administer broad-spectrum antibiotics with IV vancomycin and ceftriaxone for all patients suspected of having OPSI. Unfortunately, OPSI has mortality rates of 38%–70% despite appropriate therapy. Splenectomy has also been linked to other pathologic consequences, such as increased risk for venous thromboembolism and susceptibility to severe infections with malaria and babesiosis [76].

These risks are heightened for children, who have immune function that is not fully matured and a lifetime of exposure to these complications. This constellation of clinical consequences is part of the justification for avoiding splenectomy in pediatric trauma patients whenever possible.

Although NOM of high-grade liver injuries has gained widespread acceptance [77,78], the fact remains that some blunt hepatic trauma will require operative intervention. Initial attempts at controlling bleeding from the liver may include direct manual pressure, packing, and the Pringle maneuver (occlusion of the portal triad). If there is an obvious source of bleeding that can be easily addressed, this may be accomplished using cautery, argon beam coagulation, or application of a topical hemostatic agent. Hepatorrhaphy is another option using an absorbable suture on a large, blunt-tipped needle to approximate the edges of a significant laceration. If none of these interventions is successful, liver hemorrhage may require advanced maneuvers to achieve control. In young children, the sternum can be rapidly divided to achieve control of the suprahepatic inferior vena cava and achieve complete hepatic vascular isolation. Once the hemorrhage subsides, the injury can be more effectively evaluated and addressed. At times, it may be needed to pack the liver and proceed to transarterial embolization for deep arterial injuries. In contrast to the spleen, which can be removed when hemostasis cannot be achieved, liver resection should be reserved for the most extreme circumstances and adequate liver must be preserved to maintain function.

In this era of wide acceptance of NOM for pediatric blunt abdominal trauma, the number of patients progressing to surgical interventions is minimal. Because of this, surgeons should review how to address massive hemorrhage after trauma. It is important to frequently review current management strategies and the tried-and-true approaches to bleeding. Damage control laparotomy has improved survival after massive hemorrhage in the trauma setting, specifically with liver injuries [79,80]. If the "lethal triad" of hypothermia, acidosis, and coagulopathy is present, it is potentially too late to benefit from damage control. The decision should be made early when the patient is beginning to deteriorate and the operative plan becomes rapid tamponade of bleeding with temporary abdominal packing and control of contamination. Once a temporary abdominal closure is placed, the patient should be resuscitated in the ICU until stability is ensured. At the appropriate time, the child can be brought back to the operating room for removal of packs, definitive repair of injuries, and abdominal closure. In a series of 22 children treated with temporary packing for intra-abdominal hemorrhage, 21 (95%) had successful control of hemorrhage and 18 patients survived [81]. From these data and experience in the adult population, temporary abdominal packing is useful in the care of pediatric abdominal trauma and it is imperative that surgeons are aware of the physiology of each patient during the operation to make the decision promptly to proceed to damage control strategies.

In summary, spleen and liver injuries are the most common intra-abdominal injuries in pediatric trauma. The introduction of NOM and other adjuncts such as embolization have improved the care of these patients. Although some discrepancies persist in the rates of surgical intervention for children, major strides have been made over the last few decades. In addition, there are new guidelines and imaging options on the horizon that hold promise for continuing to advance the practice of trauma surgery in the pediatric population. Although the treatment for these patients has become largely expectant, a surgeon is still the most appropriate primary physician to manage these children. The decision not to operate remains a surgical decision.

Duodenum and pancreas

Duodenum and pancreas injuries are much less common than those of the spleen and liver and only occur in 3%–5% of patients with intra-abdominal trauma [82,83]. This lower incidence is likely owing to their protected location in the retroperitoneum. Because of the central location and close proximity to other vital structures, concomitant trauma to other organs is common. In addition, the relationship of the duodenum and pancreas to the spinal column put them at particular risk in seat belt injuries or directed blows to the mid-abdomen. Early diagnosis of these injuries is important, but can be challenging due to the retroperitoneal location, which may delay peritonitis and other clinical findings on physical exam. Indications for operative therapy are similar to other injury patterns with persistent hemodynamic instability or obvious bowel perforation necessitating exploration, although other associated trauma may also require a trip to the operating room.

Duodenum

Most literature discussing duodenal injuries deals with the adult or a combined adult and pediatric population with few studies specifically addressing this trauma in children. The AAST Duodenal Organ Injury Scale provides a classification system and can help guide therapy (http://www.aast.org/library/traumatools/injuryscoringscales.aspx). A retrospective review from Ballard et al. compiled all the blunt duodenal injuries in the state of Pennsylvania over a 10-year period [84]. From the population of 103,864 adult and children treated at 28 trauma centers, only 206 (0.2%) duodenal injuries were encountered and only 30 patients suffered from full thickness rupture. Physical findings and CT results were extremely variable and not reliable for diagnosis. The researchers examined the various types of repairs performed. This investigation highlights the challenge of analyzing duodenal trauma due to the low rate of this injury and the limited exposure for each institution and surgeon.

Despite the inherent difficulty in diagnosing duodenal trauma, there are a handful of signs and symptoms that should heighten suspicion and prompt further evaluation. Most children will present with abdominal pain if a duodenal hematoma or perforation is present with complaints ranging from mild abdominal tenderness to involuntary guarding consistent with peritonitis. Abdominal wall bruising from a seat belt or blow to the abdomen (e.g., handlebar injury) should also increase concern for damage to the duodenum. In several series, child abuse was a common mechanism for duodenal injury, especially in children aged five or less [85]. Unless the patient meets criteria for immediate exploration, a CT of the abdomen is indicated to better characterize the extent of injuries.

Duodenal injuries can be divided into two general categories: hematoma and perforation. While duodenal hematomas can generally be managed nonoperatively, duodenal perforations are customarily addressed with laparotomy. Shilyansky et al. reported on a series of 27 children who presented with duodenal injury over a 10-year period [86]. This cohort included 13 duodenal perforations (mean age 9 years) and 14 duodenal hematomas (mean age 5 years). Associated injuries were appreciated in 19 children and affected the pancreas (10 patients), spine (5), liver (4), central nervous system (1), long bones (2), kidneys (1), jejunum (1), and stomach (1). This report provides insight into the multitude of concomitant injuries that can be present and imaging characteristics to help differentiate hematoma and perforation preoperatively [86]. Of the 27 patients, 19 underwent abdominal CT scans. There were nine patients who underwent a CT scan who had suffered from a duodenal perforation and every one had retroperitoneal air or extravasation of contrast on imaging. Duodenal hematomas also had a characteristic presentation on abdominal imaging. There were no deaths in this series, but 6 of 13 patients with duodenal perforation had complications, including 3 duodenal fistulae, 2 abscesses, and 1 urinary tract infection.

Similar outcomes were reported by Clendenon et al. in a retrospective chart review conducted over a 10-year period of all children 18 years or less treated for duodenal injuries at two pediatric trauma centers [82]. From a cohort of 42 patients that met inclusion criteria, 25 had duodenal perforations and 17 had duodenal hematomas. All of the perforations underwent an operation and only one patient with a hematoma required operative drainage due to persistent bowel obstruction. There were no mortalities but multiple complications were described: pancreatitis ($n = 5$), pleural effusions (2), sepsis (2), failure of duodenal repair (2), subphrenic abscess (1), wound dehiscence (1), superior mesenteric artery occlusion (1), bowel obstruction requiring lysis of adhesions (1), abdominal abscess (1), pancreatic fistula (1), and duodenal necrosis (1). The operations performed for duodenal perforation were primary repair ($n = 18$), duodenal resection and reconstruction (3), pyloric exclusion (2), and complete resection with gastrojejunostomy (2). Delays in diagnosis or operative intervention greater than 24 h were associated with increased complication rates, length of hospital stay, and ICU length of stay.

Duodenal hematomas can usually be managed nonoperatively, but can result in prolonged hospitalizations and high medical costs. In one retrospective case series by Peterson et al., all duodenal hematomas from a single large volume level I trauma center were identified and demographics, clinical and radiographic characteristics, and hospital course were documented [87]. Grade I duodenal hematomas were compared to grade II. There were 19 patients in the analysis and every patient underwent abdominal CT. There were 10 grade I and 9 grade II injuries. Mechanisms included direct blow to the midabdomen (handlebar, sports-related, assault, and stepped on by a horse), non-accidental trauma, falls, and motor vehicle accident. Child abuse was a relatively common mechanism occurring in five patients, which confirms previous assertions that duodenal trauma should raise a high index of suspicion for this mechanism. Exploratory laparotomy was performed for five patients who had concern for additional hollow viscus injury, but none of the hematomas required operative drainage and only one was drained percutaneously. Twelve of the patients required parenteral nutrition with a median duration of 9 days. The only significant difference between the two groups was the time period of parenteral nutrition with 6.5 days in the grade I group and 12 days in the grade II group. Although there was a trend toward longer hospital stay and time to oral intake in the grade II duodenal hematomas, these were not statistically significant in the small patient sample. This observational study supports the assertion that duodenal hematomas can be successfully managed nonoperatively and provides expectations for duration of hospital stay and parenteral nutrition requirements.

In contrast to duodenal hematomas, which can be managed nonoperatively in most circumstances, duodenal perforation mandates surgical exploration. There are many approaches described for the repair of these injuries. Primary closure of duodenal injuries is recommended whenever possible and can usually be performed [82]. Repairs should follow the general rule in all of the small bowel injuries, with a transverse closure preferable to avoid narrowing the lumen. When anything more than a straightforward repair is needed, it is recommended to perform a pyloric exclusion and diversion of flow away from the duodenum. Pyloric exclusion can be accomplished with closing the pylorus with an absorbable suture or thoracoabdominal stapler and creating a gastrojejunostomy (Figure 18.9) or with a draining gastrostomy and feeding jejunostomy [88]. A “triple-tube technique” has been advocated for more complex duodenal injuries, which includes a duodenal closure and duodenostomy tube for drainage, a gastric tube placement, and feeding jejunostomy. All of these options can be paired with external drainage with a closed suction drain depending on the concern for leakage and concomitant injuries. Although it has been described as an option, a pancreatoduodenectomy should be avoided if at all possible. The anastomoses are a setup for failure in the trauma setting where expeditious management of injuries is vital. Of primary importance in complicated repairs is the protection of the duodenal repair and distal feeding access, as these interventions have been shown to decrease complications and shorten the time to enteral nutrition.

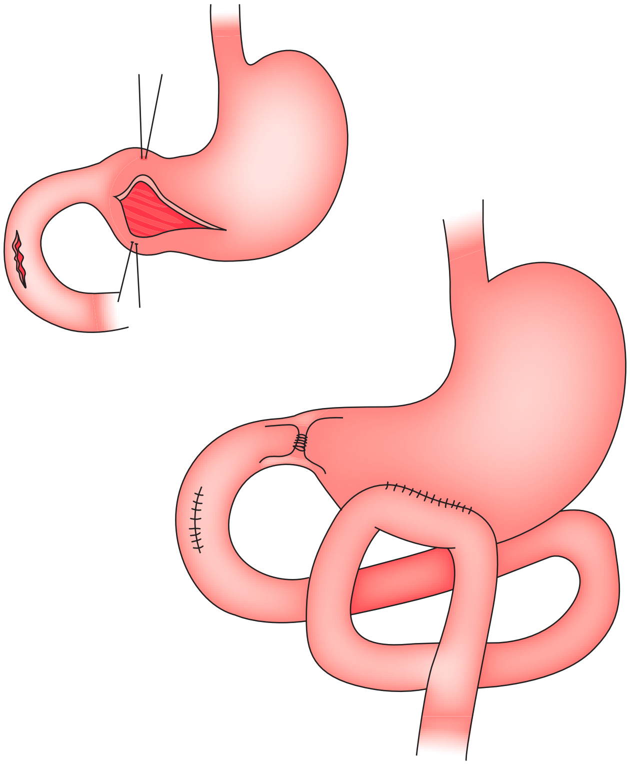


Figure 18.9 Technique for pyloric exclusion to manage a duodenal injury. (Courtesy of artist, Dr. Mark Mazziotti, Houston, Texas.)

Figure 18.10 CT demonstrating a pancreatic laceration (arrow) following a handlebar injury. When this CT was reviewed by two experienced pediatric radiologists at our center, one gave it a grade II and the other gave it a grade III.

Pancreas

Blunt pancreatic injury occurs when high-energy force is applied to the upper abdomen, crushing the retroperitoneal structures against the vertebral bodies and causing a spectrum of injury from minor contusion to complete transection. CT is the most common modality to identify a pancreatic injury, although grading per the AAST scale can be challenging (especially in young children) as duct disruption is often unclear, and the scale demands differentiation of duct disruption between a grade II and III injury (Figure 18.10) [89]. Other methods of evaluating ductal integrity are magnetic resonance cholangiopancreatography or ERCP [90,91]. Ductal integrity is so important because leakage of pancreatic enzymes can increase complications such as pancreatic ascites, persistent fluid collections called pseudocysts, and fistula formation [92]. Traditional teaching has always been to control duct leakage when possible.

The management of AAST grade III pancreatic injuries, which involve transection of the pancreatic duct at the body of the pancreas (to the left of the mesenteric vessels), remains one of the few controversial areas within pediatric abdominal trauma. There is general agreement in both adult and pediatric trauma patients that AAST grade I and II injuries that do not involve injury to the main pancreatic duct, can be safely managed with observation alone or simple external closed-suction drainage, as long as there is no evidence of bleeding mandating operative control [93]. At the other end of the spectrum, grade IV and V injuries, which involve injury to the pancreas to the right of the mesenteric vessels or the pancreatic head, are complex injuries that may also involve the duodenum, and are managed on a case-by-case basis. Extensive pancreatic head injury, especially involving the ampulla of Vater, may have to be managed with a pancreatoduodenectomy, but this should be the last option as it is likely to lead to complications and increased morbidity and mortality [90]. Other damage control options such as drainage, omental pancreatography, endoscopic pancreatic duct stenting, and concomitant duodenal damage control procedures should be considered (Figure 18.11) [90]. While these injuries are very rare and variable in children, grade III injuries, which involve the main pancreatic duct, often occur from direct epigastric force such as from a handlebar or hockey stick [92] causing pancreatic transection overlying the spine, are far more common.

Management of grade III injuries differs in adult and pediatric practice and even among pediatric surgeons. The Eastern Association for the Surgery of Trauma (EAST) guidelines suggest that these injuries should always be managed with distal pancreatectomy with proximal pancreatic duct control [93]. These guidelines are based mostly on adult data, and the practice of operative management (OM) for these injuries is widely accepted in adult patients. In children, however, following successful reports of NOM, many pediatric surgeons have switched to this approach. The literature to date consists mostly of case reports and case series. There are several multicenter studies comparing operative to NOM, all of which are retrospective, that report variable outcomes. The majority of these studies did not differentiate

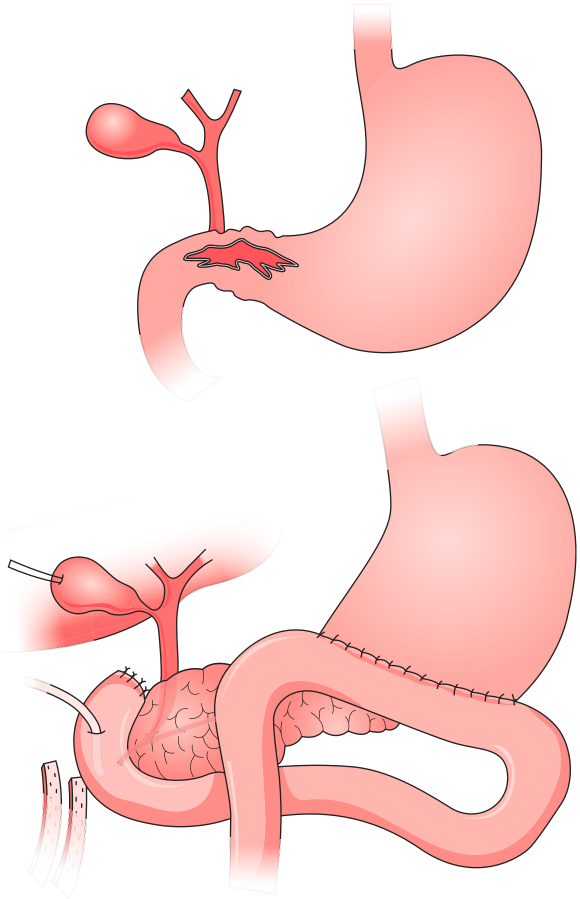


Figure 18.11 Duodenal diverticulization technique for severe duodenal/pancreatic injury. The operation consists of gastric antrectomy with end-to-side gastrojejunostomy, tube duodenostomy, duodenal closure, and drainage. (Courtesy of artist, Dr. Mark Mazziotti, Houston, Texas.)

outcomes based on the severity (CT grade) of the injuries or on the location of the injury; thus minor and major and head and body pancreatic injuries were all grouped together, which makes it difficult to accurately judge outcomes. In the largest multicenter study, pancreatic injuries grades II and above were separately analyzed. Iqbal et al. reported that children with these injuries who were managed by NOM had significantly higher rates of pseudocyst formation, longer time to oral feeds, less morbidity, and longer cumulative hospital stay than those managed with early operation [94]. In contrast, a recent 10-year review of the NTDB of blunt pancreatic injuries with Abbreviated Injury Scale (AIS) scores ≥3 reported that children managed with NOM had equivalent or better outcomes than those managed with OM and delayed OM, with lowest length of stay and infection rates actually reported in the NOM group [95]. A Cochrane review concluded that given the lack of randomized trials, there is no firm evidence to support either treatment strategy [96]. A systematic review of 25 studies including 1 014 injuries demonstrated that the majority (72%) were managed with NOM, and outcomes were very difficult to compare given the heterogeneity of data [97]. Meta-analysis could only be performed for the outcomes of pseudocyst and fistula formation, and showed that the odds ratio of pseudocyst formation was two times higher for NOM than OM, but fistula development was similar among the groups [97].

When operative therapy is chosen for grade III injuries, a laparoscopic or open approach can be employed. The lesser sac is opened and the pancreas exposed. Often, the pancreas is completely or near-completely transected. Splenic preservation is always recommended. The splenic vessels can be retracted cephalad and multiple small branches between the splenic vessels and pancreatic parenchyma are ligated. The pancreas can be divided with a stapler proximal to the transection if there is some distance from the mesenteric vessels. If the transection is complete, then the proximal stump needs to be controlled with sutures. Overly tight suturing of the pancreatic stump should be avoided as it may lead to early necrosis and increase the risk of fistula or pseudocyst. An omental flap can be placed over the stump 92]. The role of ERCP for pancreatic injury is still in evolution. It can be used as a diagnostic tool to definitely determine the presence or absence of ductal transection when imaging is unclear. Some have also demonstrated success with stenting across the injury or stenting the ampulla of Vater to allow passive duodenal drainage [98,99].

Stomach, small and large intestine

Hollow viscus injury after blunt abdominal trauma is relatively infrequent with rates of 1%–5% reported in most series [100–102]. Although injury to the gastrointestinal tract is rare, it is one of the most common indications for surgical intervention in abdominal trauma. It is important to understand the presentation and management for damage to these structures to avoid a delay in diagnosis and appropriate management. Penetrating abdominal trauma commonly results in gastrointestinal compromise. Patients with penetrating abdominal injuries require surgical exploration. Blunt injuries may also result in hollow viscus injury, although less frequently. There are several mechanisms. First is a crush injury when the organ is compressed violently against the spine. Second is by burst when rapid forces are applied to a distended and tense hollow viscus. Third, shear injury with rapid acceleration or deceleration occurring at a point of fixation, e.g., ligament of Treitz, ileocecal valve, and so on. Avulsion of the mesentery of the small bowel can cause ischemia, which can in turn lead to perforation or stricture formation. The presentation of these injuries may be delayed. Motor vehicle collision is the prevalent cause of gastrointestinal injury with falls, bicycle handlebar injuries, and child abuse as other common mechanisms. In the majority of pediatric trauma patients, contamination resulting from hollow viscus injury will result in peritoneal irritation and subsequent clinical signs to guide diagnosis.

As a general rule, gastrointestinal injuries will result in symptoms (pain, nausea, vomiting) or physical findings (tenderness, guarding, distention). Although it is optimal to diagnose and treat these injuries early to minimize the duration of contamination, selective patients suspected of having a hollow viscus injury can be appropriately managed with careful repeated physical exams and close observation of vital signs. Gastric injury is rare, but perforation is the most common injury and is most likely to occur after a meal when the stomach is distended. These injuries tend to present with generalized peritonitis and free air, making detection more straightforward [103]. Injuries to the jejunum and ileum can result from direct force causing rupture or compromised blood flow due to destruction of the mesentery. Spillage from the small bowel is less caustic than gastric contents, so these patients may have a slightly more indolent course. Colon and rectal injuries can similarly be the result of blowout near a point of fixation or with compression against the spine. Mesenteric damage can occur in the colon where avulsion is possible, but is not a risk in the rectum. Colorectal trauma is also prone to delayed diagnosis, although contamination with feces is more likely to cause infectious complications and ultimately frank symptoms.

As previously discussed in the section *Special considerations*, the presence of a seat belt sign (abdominal wall ecchymosis) should raise clinical suspicion for a hollow viscus injury. Per Borgialli et al., the rate of this injury increases from 1% in patients without a seat belt sign to 11% when present [2]. The seat belt sign may also indicate an underlying chance fracture, duodenal or pancreatic contusions, and isolated jejunal or ileal perforation. CT can be useful in cases when the diagnosis of an abdominal injury is not clear but suspected (Figure 18.12). Admission should be considered for all patients with a seat belt sign, as bowel injury may not be apparent on initial exam or imaging but will become clinically apparent with the passage of time.

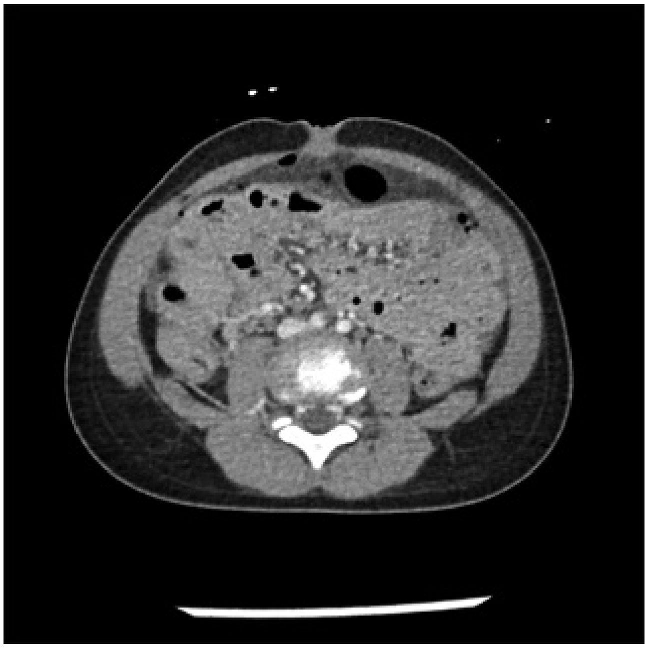


Figure 18.12 CT demonstrating free intraperitoneal air, free fluid, and thickened bowel loops. This child had a small bowel perforation associated with a seat belt sign.

Similar to solid organ injury, abdominal computed tomography is the best imaging resource to evaluate for hollow viscus injuries. Unfortunately, CT is not as sensitive for gastrointestinal rupture or mesenteric injuries that may ultimately cause ischemia and perforation. Albanese et al. in Pittsburgh published a retrospective review of 30 patients with gastrointestinal injury from abdominal trauma and documented the findings on abdominal CT [104]. Eleven of the patients with gastrointestinal injury were immediately taken to the operating room for generalized peritonitis, shock or free air on plain film. The CT scans of the other 19 patients who were found to have hollow viscus injuries were reviewed. Findings included localized free air (7), free fluid without associated solid organ injury (11), isolated thick-walled and fluid-filled bowel loops (9), and mesenteric infiltration (4). Additionally, five studies were interpreted as normal, indicating false negative results. Due to the variability in indicators of hollow viscus injury and presence of false negative CT scans, these authors concluded that serial physical examinations remains the gold standard for diagnosis.

Additional research from the EAST Multi-Institutional Hollow Viscus Injury Research Group confirms the inaccuracy of imaging in the diagnosis of small bowel injury [105]. The registries of 95 trauma centers were interrogated to examine small bowel injury in all admissions. When comparing matched controls without small bowel perforation, the CT scans of patients with small bowel injury were not significantly different. From those with documented small bowel perforations, 13% were not identified on CT scan. The high false negative rate means that it is unwise to rely on abdominal CT to rule out intestinal injuries.

Although missed injuries can be disastrous in the care of trauma patients, controversy persists as to whether a delay in diagnosis of gastrointestinal injuries increases morbidity and mortality. Letton et al. published a multi-institutional retrospective chart review including all children who suffered from blunt intestinal injury at 18 pediatric trauma centers from January 2002 to December 2007 [106]. According to this examination of 214 patients, there was no correlation between time to operation and complication rates, including death, wound infection, intra-abdominal abscess, or postoperative bowel obstruction. In addition, time to surgery did not have a significant effect on length of hospital stay. Another study utilized charts from one pediatric trauma facility to identify all the small bowel injuries over an 11-year time period. There was no significant difference in complication rates between those operated on immediately or later in the hospital course [107]. Obviously it is best to address bowel injuries in a prompt fashion, but these studies and others support observation as a reasonable approach when the diagnosis is in question.

Blunt intestinal injury that causes perforation requires operative intervention. Laparoscopy is now a reasonable first step in the management of these patients and may be the only operation needed in certain situations. Current use of laparoscopy will be discussed in the section "The Role of Laparoscopy" in this chapter. Once a gastrointestinal injury is identified, the best operation must be determined. A distended stomach will generally rupture along the greater curvature and the damage is amenable to debridement and primary repair. Due to the robust blood supply of the stomach, most repairs will heal nicely. Small bowel injuries can range from lacerations to transections to large segments of mesenteric avulsion (often referred to as a "bucket handle injury"). Regardless of the pattern, almost all damage to the small intestine from the ligament of Treitz to the ileocecal valve can be addressed with debridement and repair, or simple resection and primary anastomosis. Large bowel perforation may also be repaired by resection and primary anastomosis if there has been minimal contamination and the repair occurs soon after the traumatic event. If there is a significant delay in diagnosis, massive contamination or multiple concomitant complex injuries, fecal diversion with a colostomy is advisable. A mucous fistula or Hartman's pouch can be created for the distal segment. Intraperitoneal rectal injury is managed as other colon injuries. In the setting of rectal injury that is not accessible from an abdominal incision, thorough irrigation and proximal diversion is often the best approach to allow the injury to heal. Subsequently, a contrast study can be obtained to confirm no leak is present and the ostomy can be reversed. All patients with contamination after gastrointestinal injuries should be treated with appropriate perioperative antibiotics and careful consideration of leaving the abdominal wound open with healing by secondary intention is advised.

Diaphragm injury

Diaphragm rupture or injury in pediatric trauma is uncommon and easily missed on initial evaluation. According to a retrospective series extracted from the National Pediatric Trauma Registry, 4% of patients with proven thoracic or abdominal trauma had a diaphragm injury [1]. Diaphragmatic injury is often associated with penetrating mechanism [108]. There is a high incidence of accompanying injuries, most commonly of the musculoskeletal system and abdomen [108–110]. Complaints that may indicate this injury include chest pain radiating to the shoulder, shortness of breath, and abdominal pain. Children have a higher propensity for swallowing air and causing gastric distention, which may lead to respiratory distress with a left-sided diaphragmatic rupture [108]. Other physical findings to suggest the injury are bowel sounds in the chest, absence of breath sounds, and scaphoid abdomen. The most classic radiographic finding is loops of bowel in the chest on plain film, but CT scan of the abdomen may be useful to confirm the diagnosis and evaluate for accompanying injuries. Early diagnosis of traumatic diaphragmatic injury requires a high index of suspicion, as it may not be obvious on clinical exam or imaging.

Diaphragm injuries are infrequent enough that there are no single institutions with a robust experience caring for these patients, but several small series exist. Ramos et al. in Toronto published a retrospective review of their Trauma Center Registry from January 1977 to August 1998 [109]. A total of 15 patients were identified, 13 blunt trauma and 2 penetrating. Although classically left-sided injuries are more common [111], there were equal numbers of left- and right-sided injuries in this series (seven each) and one patient with bilateral. Associated injuries included liver lacerations (47%), pelvic fractures (47%), major vessels tear (40%), bowel perforations (33%), long bone fractures (20%), renal lacerations (20%), splenic lacerations (13%), and closed head injuries (13%). Five patients died due to multisystem trauma. The high mortality rate supports the association with increased severity of trauma.

Management of children with diaphragmatic trauma is operative, but in hemodynamically stable patients initial resuscitation and appropriate intervention for accompanying injuries should precede the surgical exploration. Nasogastric tube placement can allow for gastric decompression and maintain adequate lung expansion until the operation. Chest tube placement should be avoided if at all possible. There is a risk of injury to abdominal organs with tube thoracostomy. Diaphragmatic repair can be approached laparoscopically or via an open laparotomy depending on the operator's comfort level. A thorough examination of the abdomen should be undertaken at the time of repair. For most injuries, direct suture repair is appropriate after debridement of devitalized tissue. In the setting of extensive destruction when a direct repair would result in tension on the suture line, a muscle flap or prosthetic mesh can be utilized. Obstruction, intestinal necrosis, sepsis, and death may all be sequelae of diaphragmatic hernia if it is missed.

Injuries to the perineum, anus, and genitalia

Generally, there are two mechanisms responsible for injury to the perineum, anus, and external genitalia: accidental straddle injuries and sexual abuse. Straddle injuries are more common and sustained by falls onto blunt or sharp objects, such as bicycles, playground equipment, fence posts, sticks, or other similar objects [112]. Blunt injuries typically are unilateral and present as a superficial abrasion, bruising, or laceration to the anterior portion of the external genitalia in both boys and girls. Impalement will more commonly require surgical repair [113,114]. Accidental injuries usually involve the external genitalia, urethra, perineal body, and anus. Any vaginal or rectal perforation should raise suspicion for sexual abuse. These injuries are uncommon in patients with accidental trauma. The extent of perineal and genital trauma often cannot be adequately assessed at the bedside. These patients often require examination under anesthesia for complete evaluation and may benefit from proctoscopy, sigmoidoscopy, or formal urethral investigation with cystoscopy or urethrogram [115]. Most injuries can be addressed with anatomical reconstruction of the perineum, anus, and external genitalia. Occasionally, urinary or fecal diversion may be necessary with more extensive injuries.

The role of laparoscopy

Pediatric abdominal trauma has become a largely nonoperative endeavor, but there are certainly situations where surgical intervention is warranted. Indications for operation include intra-abdominal injury with persistent hemodynamic instability despite aggressive resuscitation, pneumoperitoneum, or clinical evidence of hollow organ perforation, and a penetrating mechanism with peritoneal violation. Laparotomy is the gold standard for evaluation, but it carries a high morbidity and occasional mortality, as well as a life-long risk for adhesive intestinal obstruction [116]. Laparoscopy is a diagnostic and therapeutic alternative to laparotomy in hemodynamically stable pediatric abdominal trauma cases [117,118]. Laparoscopy can provide vital information that may prevent unnecessary laparotomy. In addition, some injuries may be addressed with laparoscopy with a resultant reduction in morbidity.

Laparoscopy has become standard of care for many pediatric surgery procedures, but its use in trauma is more controversial. A retrospective review from Pittsburgh published by Feliz et al. confirms that laparoscopy is safe for the evaluation and treatment of selected patients [116]. Information was extracted over a 5-year period from January 2000 to December 2004 examining patients who had operations for abdominal trauma at a pediatric level I trauma center. There were 7127 total trauma admissions. Abdominal operations were performed in 113 patients who experienced 88% blunt and 12% penetrating injuries. Eighty-one patients had emergent laparotomy and 32 patients had initial laparoscopy. Average age for those undergoing laparoscopy was 8 years (range 2–15). Laparoscopy was positive in 23 (72%) patients. Negative laparoscopy occurred in nine (28%) patients, five with blunt and four with penetrating trauma. Laparoscopic therapeutic interventions were successfully performed in 6 patients, while 14 patients required a laparotomy to repair identified injuries. Three patients had diagnostic laparoscopy with diagnosis of nonexpanding hematomas requiring no further therapy. Overall, laparotomy was avoided in 17 (56%) patients. There were no missed injuries or technical complications associated with laparoscopy and none of the patients died. From this review, the authors proposed an algorithm to guide the use of laparoscopy in trauma. Any stable pediatric trauma patient with suspected blunt intra-abdominal injury should undergo CT of the abdomen and pelvis and, if there is evidence of hollow viscus injury or free peritoneal fluid in the absence of solid organ injury, diagnostic laparoscopy is justified. In the setting of penetrating abdominal injury and stable hemodynamics, a diagnostic laparoscopy may be indicated with confirmed or questionable penetration of the peritoneal cavity to rule out a visceral injury. While there should be no hesitation to perform an exploratory laparotomy if it is indicated, this study and a few other smaller series [103,104] provide evidence that laparoscopy is a diagnostic and therapeutic alternative. Although the various procedures performed through the laparoscopic approach depend on the comfort level of the operating surgeon, the experience with minimally invasive surgery is expanding rapidly. The injuries commonly addressed with laparoscopy include simple bowel perforation, diaphragm injury, mesenteric tear, abdominal wall hernia, and simple pancreatic lacerations. As more evidence accumulates that supports the use of laparoscopy in trauma, its role will likely expand.

SUMMARY

Through recent advances in trauma and critical care management strategies, improvements have been made in outcomes for children suffering from abdominal trauma. Despite these strides, abdominal injury remains a source of significant mortality and morbidity in the pediatric population. Ongoing research is vital and there is continued promise for improved care in the future.

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19

Pediatric genitourinary trauma

JASON AU and NICOLETTE JANZEN

Introduction

Trauma is the greatest cause of death and acquired disability in children [1]. When the genitourinary (GU) system is involved, the kidney is the most frequently injured organ. While GU injuries may not necessarily present with life-threatening injuries, missed injuries may contribute to significant patient morbidity. Thus, a high index of suspicion should be maintained for GU injury for any blunt or penetrating injury to the abdomen, flank, or groin.

Renal trauma

The kidney is the most commonly injured organ in the GU system. Greater than 90% of GU trauma in the United States involves the kidney and it is more frequently injured than the spleen, liver, pancreas, bowel, lung, heart, or great vessels [2–4]. Renal trauma has been estimated to occur in 10%–20% of pediatric blunt abdominal trauma cases [5,6]. According to the National Trauma Data Bank, there were more than 18,000 pediatric renal lacerations from 2002 to 2007 [5]. Compared with the adult kidney, the pediatric kidney is more susceptible to trauma due to several anatomic factors: less cushioning from perirenal fat, weaker abdominal musculature, and a less well-ossified thoracic cage. The child's kidney also occupies a larger space in the retroperitoneum than that of an adult kidney [7]. Retained fetal lobulations may also predispose to parenchymal disruption [2]. Congenital renal anomalies may predispose the kidney to injury. Additionally, a pelvic kidney may be predisposed to traumatic injury as it is less protected by the lower ribs and abdominal muscles compared with an orthotopic kidney.

Broadly speaking, renal trauma is divided into blunt and penetrating trauma. Blunt renal injuries are typically associated with rapid deceleration, motor vehicle collisions, auto-pedestrian collisions, falls >15 feet, contact sports, and non-accidental trauma. A recent pediatric renal trauma review of the National Trauma Database showed that penetrating renal injuries accounted for 9.7% of all renal injuries, whereas 90% were blunt renal injuries [8]. Penetrating renal injuries typically result from gunshot wounds or stab wounds from knives or other sharp objects. High-velocity and -energy gunshot wounds produce a radiating wave of injury and cavitation known as "blast effect," which damages tissue beyond the tract of the projectile [9]. Penetrating injuries to the chest, abdomen, and flank areas should be assumed to have renal injuries until proven otherwise [10].

Evaluation

After the patient has been appropriately resuscitated and life-threatening injuries addressed, the GU system can be assessed. Unlike adults, children may not manifest hypotension, and early hematocrit measurements and degree of hematuria are not related to the degree of renal injury. These differences are due to increased vasculogenic responsiveness to catecholamines in children who have sustained traumatic injury. The increased vascular tone allows the child to better maintain blood pressure, hemoglobin and hematocrit levels, and reduce blood flow to the kidney compared with an adult with a similar degree of renal injury [11,12].

Studies have shown that similar criteria can be used in both adults and children regarding the evaluation of renal trauma provided that physical exam findings and mechanism of injury also be taken into consideration [13]. Thus standard indications for imaging a children for suspected renal injury after blunt abdominal trauma include: (1) gross hematuria, (2) microhematuria (≥50 red blood cells per high-power field) and shock (systolic BP < 90 mmHg), (3) mechanism of injury (high-speed deceleration injury, fall >10 feet, direct blow to the flank), and (4) physical exam findings (abdominal or flank ecchymosis, lower rib fractures). However, any penetrating wound to the lower thorax, abdomen, or flank should prompt radiologic evaluation for a renal injury [6,14].

Because of the need to rule out concurrent intra-abdominal organ injury in patients with suspected renal injury, the baseline lab evaluations include complete blood count, electrolytes, creatinine, blood urea nitrogen, liver function tests, amylase, lipase, and urinalysis.

Radiographic evaluation

Although the gold standard for evaluation of a suspected traumatic renal injury remains a triphasic computed tomography (CT) scan, there have been various protocols used to minimize radiation exposure. The "split bolus protocol" involves two boluses of intravenous (IV) contrast followed by a single CT series of images taken 5–10 min later [15]. After review of these images, if there is concern for ureteropelvic junction (UPJ) disruption or distal ureteral avulsion injury, a delayed KUB or limited CT cuts 15 min postinjection may be useful.

Recently, there has been significant concern regarding radiation exposure in children potentially leading to increased incidence of future malignancy. One study noted that in a 1-year-old an abdominal CT conferred a 0.18% lifetime risk of cancer mortality, which is an order of magnitude higher than adults, over the natural background rate [16]. The authors have suggested lower milliampere-second settings for children without significant loss of information. Other institutions have adopted an "as low as reasonably achievable" concept in the management of pediatric blunt renal trauma, by using CT as the initial mode of imaging but preferentially using renal ultrasound (RUS) for follow-up imaging and found this protocol to be feasible and safe [17].

Although CT imaging is the most reliable method used to exclude significant urinary tract injuries after trauma, radiation exposure is a significant concern. Focused assessment with sonography in trauma (FAST) examination is generally used in two settings. In a major trauma in which the patient is unstable, FAST may be used to image the kidneys to confirm a normal contralateral kidney in case an emergent nephrectomy is necessary. In the setting of minor trauma, a FAST exam may be used and if the ultrasound is normal and physical exam findings are normal for 6 hours, the combination of these two findings essentially rules out major renal injury [18]. However, the accuracy of the FAST exam is highly dependent upon the experience of the examiner, with the sensitivity ranging from 60% to 90%, whereas the specificity is close to 100% [19].

An intraoperative one-shot IV pyelogram (2 mL/kg IV bolus of contrast with a single image obtained 10–15 min later) may be used to confirm a contralateral functioning kidney is present in rare cases when the patient is taken to the operating room without a CT if the surgeon is considering renal exploration or nephrectomy [20].

Renal trauma grading system

The original renal organ injury scale, described by Moore in 1989 [21], for the American Association for the Surgery of Trauma (AAST), categorizes renal injuries from grades I through V (Table 19.1).

In 2011, Buckley and McAninch proposed a revision of the original 1989 renal organ injury scale (Table 19.1), with the main differences including segmental vascular injury and UPJ disruption or renal pelvic lacerations as grade IV injuries and removal of the term "shattered kidney" [12]. Thus, all collecting system injuries in the new classification system are grade IV injuries and hilar injuries to the main renal artery and vein are grade V. The reclassified grade V injuries are more likely to characterize patients with severe life-threatening injuries. With this reclassification, the overall nephrectomy rate for a grade V injury is about 75% and functional salvage rate (>25% residual function of the involved kidney on renal scan) is 4% [12]. Despite this revised classification system, the majority of recent pediatric renal trauma literature still uses the original 1989 classification scheme.

Preexisting renal anomalies (i.e., UPJ obstruction, hydronephrosis, horseshoe kidney) are three- to fivefold more common in pediatric patients undergoing a screening CT for trauma than in the adult population [22]. Overall, these congenital renal anomalies are seen in 12%–35% of the children who undergo CT imaging for suspected renal trauma [14,23]. When urinary extravasation is seen in patients with preexisting hydronephrosis or UPJ obstruction, rupture of the renal pelvis or major laceration extending through a thinned renal cortex into the collecting system is the most common finding, not a UPJ disruption [22,24].

Table 19.1 AAST renal injury classifications

Grade	Moore et al. (1989)	Buckley and McAninch (2011)
I	Subcapsular hematoma and/or contusion	Subcapsular hematoma and/or contusion
II	Laceration <1 cm in depth and into cortex, small hematoma confined within Gerota's fascia	Laceration <1 cm in depth and into cortex, small hematoma confined within Gerota's fascia
III	Laceration >1 cm in depth and into medulla, hematoma confined within Gerota's fascia	Laceration >1 cm in depth and into medulla, hematoma confined within Gerota's fascia
IV	Parenchymal laceration extending through renal cortex, medulla, and collecting system	Laceration through the parenchyma into the collecting system; vascular segmental vein or artery injury; laceration into one or more collecting system with urinary extravasation; renal pelvis laceration and/or complete ureteropelvic junction disruption
V	Completely shattered kidney; avulsion of renal hilum which devascularizes the kidney	Main renal artery or vein laceration or avulsion of main renal artery or vein thrombosis
Additional notes	Advance one grade for bilateral injuries up to grade III	A renal unit can sustain more than one grade of injury and should be classified by the higher grade of renal injury

Sources: Modified from Moore EE et al., *J. Trauma*, 29, 1664–1666, 1989, American Association for the Surgery of Trauma (AAST) renal trauma classification comparing original 1989 classification; Buckley JC and McAninch JW, *J. Trauma Inj. Infect. Crit. Care*, 70, 35–7, 2011, the proposed 2011 revision.

Management

The vast majority of hemodynamically stable patients with grades I through III injuries will require no operative intervention and may be put on a nonoperative management protocol. Certain patients with grades IV and V injuries may be put on the protocol initially as well, with the understanding that changes in clinical status may warrant additional imaging and possible operative intervention. Most nonoperative management protocols call for frequent vital signs, hemoglobin/hematocrit monitoring, serial abdominal exams, intravenous (IV) fluid resuscitation, and bed rest until the resolution of hematuria [14,25–27]. Notably, Graziano's study challenged this paradigm by proposing an abbreviated best rest protocol calling for early mobilization, no urinary catheter, antibiotics, or routine imaging, and discharge when tolerating diet regardless of hematuria, which resulted in reduction in mean length of stay from 6.6 to 2.9 days [28]. Admission to an intensive care unit (ICU) and the length of ICU stay varied from 24 hours to 1 week [27,29,30]. Empiric antibiotic therapy was used in several studies but the majority do not report the rate of urinary tract infection or infected hematoma [29,31,32]. Thus the necessity of empiric antibiotic use in the trauma setting is unknown. Traditionally, the recommendation for repeat CT imaging is usually within the first 24–72 hours [27,31,33]. However, it is reasonable to consider RUS as a primary form of follow-up imaging, reserving CT for situations with ambiguous findings, in an effort to reduce radiation to the child [17].

While nonoperative management for hemodynamically stable children who have sustained all grades of renal trauma has become the norm, there are still certain indications for surgical intervention. An absolute indication for surgical therapy, either open exploration or angioembolization, is a hemodynamically unstable patient with no or transient response to resuscitation [34]. Other absolute indications for surgery are an expanding or pulsatile retroperitoneal hematoma found at the time of surgical exploration, and inability to stop persistent bleeding by angioembolization. In patients who were initially managed nonoperatively, but demonstrate persistent fever, enlarging urinoma, increasing pain, ileus, fistula or infection, urinary drainage in the form of ureteral stent and augmented by percutaneous nephrostomy, if necessary, should be performed [26,35].

Notably, approximately 25% of patients with devitalized parenchyma (grade III), grade IV, and grade V injuries will require intervention for persistent or delayed bleeding (selective angioembolization or nephrectomy) [36,37]. Traditionally, delayed bleeding develops 1–2 weeks postinjury, but may occur up to a month after the initial insult as a result of ateriovenous fistula or pseudoaneurysm formation (Figure 19.1). A review of the National Trauma Data Bank showed that only 2% underwent angiography after renal injury, and although 88% of those patients required subsequent intervention, secondary angioembolization was successful in 97% of cases. Thus angioembolization successfully treated 80% of AAST IV and V cases without the need for nephrectomy [38]. Although there is no consensus regarding when to utilize angioembolization, the authors agree that it should be the first line of treatment in patients who have sustained renal trauma who have been transfused 2–3 units packed red blood cells [38].

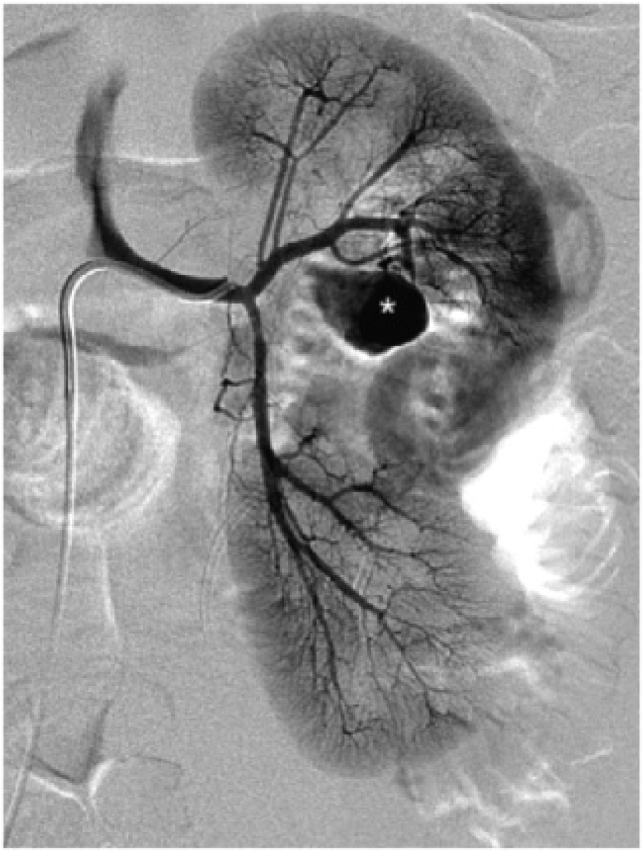


Figure 19.1 Pseudoaneurysm (*) after grade IV renal laceration trauma. The patient underwent internal double J stent placement for urinary extravasation. Approximately 1 week following discharge, he re-presented with significant gross hematuria. CT was suspicious for pseudoaneurysm. This was managed with interventional radiology embolization.

A meta-analysis showed nonoperative management was successful in 83% of nonvascular grade IV injuries. Of the patients who required interventions for symptomatic urinoma, 80% were managed with ureteral stent, percutaneous drain, and percutaneous nephrostomy, while 20% needed open repair [39].

CT imaging characteristics indicative of future operative intervention

Several recent studies have examined that CT findings are indicative of future operative intervention. In the adult literature, CT findings of increased perirenal hematoma distance, intravascular contrast extravasation, medial renal laceration site, and percentage of devitalized parenchyma were associated with increased rates of operative intervention [40,41]. However, the literature on the pediatric side is less clear, consisting of several single-institution case series. Bartley and Santucci noted in a pediatric series that medial contrast extravasation was seen in 4 of 10 patients with grade IV injuries, of which 3 ultimately required ureteral stents and/or percutaneous nephrostomy [14]. Another study noted that lack of opacification into the ipsilateral ureter, which was found in three patients, resulted in operative intervention in two patients and loss of function in the third, and that this radiologic finding should prompt operative intervention [42]. Reese et al. noted that presence of collecting system hematoma and increased urinoma size (1.5 cm with conservative management and 4.3 cm with failed conservative management) predicted failure of conservative management and children with failed conservative management had a greater incidence of dissociated renal fragments and interpolar extravasation [43]. Another study corroborated the findings of lack of opacification of the ipsilateral ureter and collecting system defects/hematoma were associated with failure of nonoperative management of high-grade blunt renal injuries [44] (Figure 19.2). A fifth study demonstrated the need for transfusion, antero-medial laceration, intravascular contrast extravasation, and large perinephric hematoma (1.8 cm with conservative management and 2.9 cm with failed conservative management) were associated with need for urological intervention [45]. With numerous single-institution series drawing different conclusions on CT characteristics associated with urologic interventions, it is difficult to pinpoint which are indeed significant and clinically impactful.

Renal exploration and reconstruction

Exploratory laparotomy for trauma involved making a vertical midline laparotomy incision from xiphoid to pubis to and allow for complete inspection of the intra-abdominal contents. Repair of major vascular, spleen, liver, and bowel injuries should be performed before renal exploration. However, if there is hemorrhage from the renal hilum then kidney exploration should be prioritized. The renal hilum is accessed by making a vertical incision medial to the inferior mesenteric artery over the aorta. The incision is extended superiorly to the ligament of Treitz and inferiorly to the inferior mesenteric artery. Once hilar control is obtained, further exposure of the kidney and the retroperitoneum can be obtained by reflecting the colon. Earlier studies demonstrated that obtaining early renal hilar control before opening Gerota's fascia can decrease renal loss from 56% to 18% [46]. In a series of 133 renal units, early vessel isolation and control was performed before opening Gerota's fascia and resulted in a renal salvage rate of 89% [47].

If the patient is hemodynamically stable, without coagulopathy, and other intra-abdominal organ injuries have been addressed, then renal reconstruction can be addressed. Basic principles of renal reconstruction after trauma include complete renal exposure, temporary vascular control if necessary, limited debridement of devitalized tissue, individual suture ligation of bleeding vessels, water tight closure of collecting system defects with absorbable suture if possible, reapproximation of the parenchymal defect, coverage with fibroadipose flaps (Gerota's fascia or omentum), and liberal use of drains. Based on experience from open nephron sparing surgery, biologic hemostatic agents such as FLOSEAL™ and TISSEEL™ (Baxter Healthcare Corp., Deerfield, IL) may be used to augment the repair [48,49].

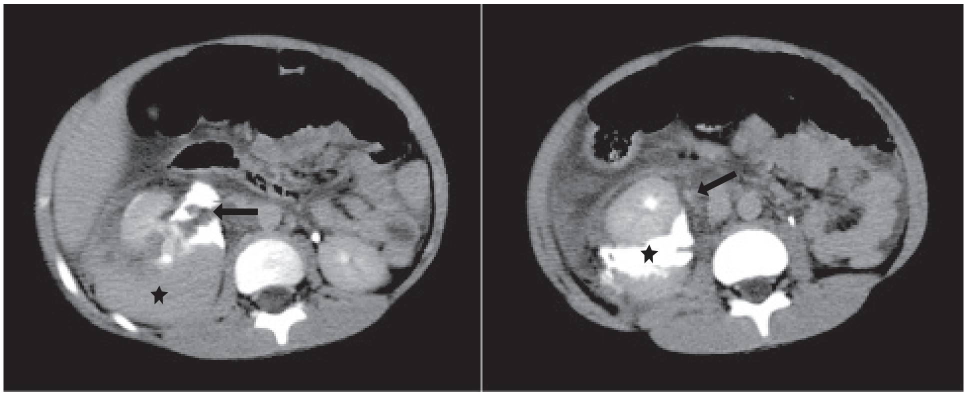

(a) (b)

Figure 19.2 Seven-year-old male sustaining blunt renal trauma. **(a)** Axial CT urogram showing clot in the right renal pelvis (blue arrow) and significant hematoma posterior to kidney (blue star). **(b)** Axial CT urogram in the same patient showing lack of ipsilateral right ureteral opacification (red arrow) and significant posterior medial contrast extravasation/urinoma.

Long-term renal function

Technetium-99 m-dimercaptusuccinic acid (DMSA) scans provide functional outcomes for children who have sustained renal trauma, but outcomes are quite variable. One study noted that high grade injuries (grades IV and V) had a normal creatinine, but definitive loss of 48% in the calculated renal activity and no compensatory hypertrophy on the noninjured side [50]. The two clinical instances in which DMSA scan are being used are when there is concern for long-term renal prognosis or with posttrauma-induced hypertension [50,51]. The most common finding in a patient with posttraumatic hypertension is a small, scarred, nonfunctioning (<20%) kidney, which is a clinical indication for nephrectomy [23,50].

Conclusions

Blunt renal trauma is much more common than penetrating renal trauma. The vast majority of hemodynamically stable blunt renal trauma patients, across all grades, can be managed nonoperatively with excellent renal salvage rates. Patients with low grade injuries, grades I through III, will likely do well without any operative intervention. Patients who are hemodynamically unstable after initial efforts of resuscitation should undergo operative intervention (angioembolization or exploratory laparotomy). Patients with high grade injuries, grades IV or V, who are initially managed nonoperatively, may ultimately require reimaging and ureteral stenting for urinoma if they demonstrate persistent fever, abdominal pain, or ileus. These high grade patients may also have delayed bleeding which should be treated with angioembolization.

Ureteral injuries

Traumatic ureteral injury in children is rare due to the small caliber of the ureter, its mobility, and protection by surrounding back muscles and retroperitoneal fat. Ureteral injury will occur in conjunction with other intraperitoneal injuries in 90% of patients and renal or bladder injuries in 10% [52,53].

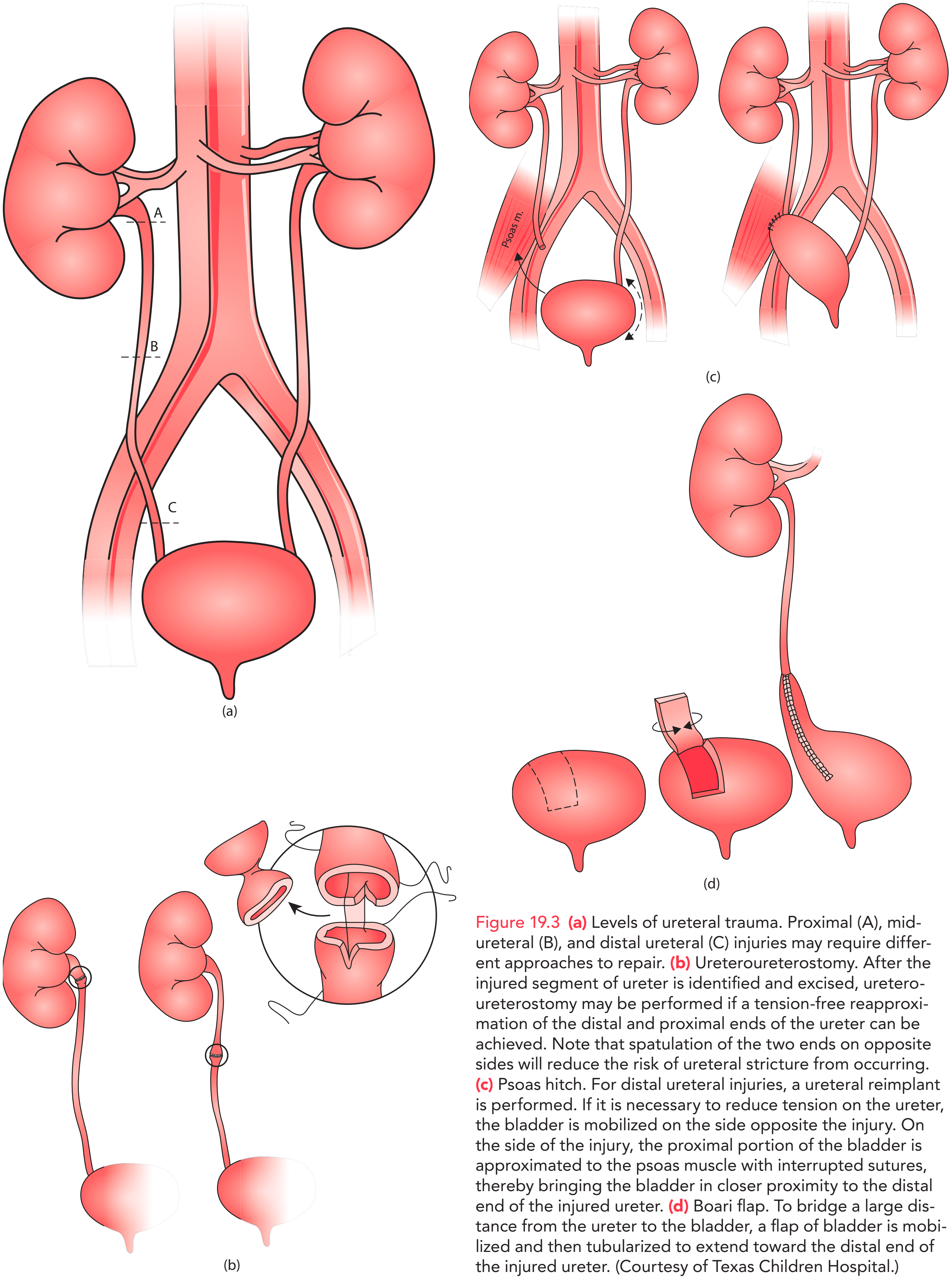
Diagnosis

A high index of suspicion is required for the evaluation of ureteral injury. A delay in diagnosis is not uncommon as hematuria may be absent in up to two-thirds of patients with ureteral injury due to blunt trauma [52,54,55]. Complications such as abscess or ileus may be presenting signs of a urine leak due to ureteral trauma [56]. The diagnosis of ureteral injury is usually made by CT urogram on the delayed series. If the CT urogram is equivocal but there is still suspicion of ureteral injury, a cystoscopy and retrograde pyelogram can be performed to aid in diagnosis. Significant findings include medial and periureteral extravasation of contrast. Nonvisualization of the distal ureter is a suspicious finding [57]. Recently, a split-bolus protocol for abdominal CT imaging has been proposed as a means to reduce exposure to ionizing radiation [15]. Although this has not been validated in large series, the imaging technique appears promising.

In the case of penetrating trauma, initial radiographic imaging may not detect a ureteral injury. Gunshot wounds caused by high-velocity missiles may cause injury to surrounding tissue at a significant distance from its path. As tissue necrosis occurs over a 3- to 5-day period following the initial injury, urinary leakage will begin to occur [58].

Management

The management of traumatic ureteral injury will depend on the location and length of the injury as well as the timing of the diagnosis in relationship to the initial injury. Surgical exploration when acute ureteral injury is suspected is warranted (Figure 19.3). IV injection of indigo carmine or methylene blue may help localize the injured ureteral segment. Proximally in the case of ureteral pelvic junction disruption, a pyeloureterostomy can be performed. Ipsilateral



(a)

(c)

(d)

(b)

Figure 19.3 **(a)** Levels of ureteral trauma. Proximal (A), mid-ureteral (B), and distal ureteral (C) injuries may require different approaches to repair. **(b)** Ureteroureterostomy. After the injured segment of ureter is identified and excised, ureteroureterostomy may be performed if a tension-free reapproximation of the distal and proximal ends of the ureter can be achieved. Note that spatulation of the two ends on opposite sides will reduce the risk of ureteral stricture from occurring. **(c)** Psoas hitch. For distal ureteral injuries, a ureteral reimplant is performed. If it is necessary to reduce tension on the ureter, the bladder is mobilized on the side opposite the injury. On the side of the injury, the proximal portion of the bladder is approximated to the psoas muscle with interrupted sutures, thereby bringing the bladder in closer proximity to the distal end of the injured ureter. **(d)** Boari flap. To bridge a large distance from the ureter to the bladder, a flap of bladder is mobilized and then tubularized to extend toward the distal end of the injured ureter. (Courtesy of Texas Children Hospital.)

ureteroureterostomy is warranted if a tension-free, spatulated, and water-tight anastomosis can be achieved. For distal injuries below the iliac vessels, reimplantion into the bladder is the best option. Extra length for reimplantation may be achieved with a psoas hitch or boari flap. Transureteroureterostomy is a consideration; however, this does place a normal contralateral kidney at risk. In the case of extensive ureteral injury with few options for repair, a temporizing nephrostomy tube may be placed and definitive repair delayed. Delayed reconstruction may include ileal or appendiceal interposition, transureteroureterostomy, ureterocalycostomy, autotransplantation of the kidney to the pelvis, and nephrectomy.

Diagnosis of ureteral injury more than 6 days after initial trauma is usually managed with a percutaneous nephrostomy tube and/or a stent. Radiographic studies including retrograde pyelogram, antegrade nephrostogram, renal ultrasound, and MAG3 scan after 12 weeks may be used to assess renal function as well as the location and length of ureteral injury. Delayed reconstruction with techniques as described above may then be planned.

Bladder injuries

The bladder is well protected by the bony pelvis; however, in younger children, the bladder occupies a more abdominal position, especially when full. The dome of the bladder is more mobile and distensible and is more susceptible to rupture from external forces. Intraperitoneal bladder rupture occurs in approximately one-third of all bladder injuries [59]. Extraperitoneal bladder rupture occurs almost exclusively in association with pelvic fractures. Interestingly, the incidence of lower urinary tract injury in association with pelvic fractures is lower in children (1%) than adults (10%–25%) [60]. A shearing injury at the anterior and lateral wall of the bladder base occurs with the disruption of the pelvic ring. Occasionally, the bladder may be lacerated by a sharp bony spicule.

Historically, bladder imaging was recommended in all patients presenting with a history of blunt abdominal trauma and either microscopic or gross hematuria. This has demonstrated low yield with high cost [61,62]. Absolute indications for bladder imaging after blunt trauma include gross hematuria in the presence of a pelvic fracture and inability to void. In the case of penetrating trauma, imaging should be performed if free fluid is noted on CT scan or if the trajectory of the missile tract courses through the expected location of the bladder [61,63].

Diagnosis

Either standard or CT cystography can be utilized to assess the bladder for injury (Figure 19.4). CT cystography has been shown to be equally diagnostic of bladder rupture as conventional cystography with an overall sensitivity and specificity of 95% and 100%, respectively [64,65]. Water-soluble iodinated contrast is instilled by gravity through a Foley catheter placed in the bladder. It is important that the bladder is adequately filled to capacity for age for the study. The bladder capacity in a child may be estimated using the formula (age + 2) × 30 cc [66]. Plugging a Foley catheter at the time of initial CT scan for trauma may not result in adequate distention of the bladder and may lead to a missed diagnosis of bladder injury.

The characteristic radiographic finding in an extraperitoneal injury is that of a starburst or flame-shaped area of extravasation that is confined to the perivesical soft tissue. A "teardrop deformity" of the bladder may be noted in the presence of a large pelvic hematoma. Intraperitoneal bladder injury is identified by the presence of contrast material in the cul-de-sac, outlining loops of bowel and occasionally outlining the paracolic gutter.

Management

All patients with traumatic bladder injury should initially receive IV antibiotics and continue with oral antibiotics until after all urinary drainage catheters are removed [67]. Management of bladder rupture depends on the extent of the injury and whether the injury is extraperitoneal or intraperitoneal. In general, extraperitoneal bladder injury may be managed nonoperatively with catheter drainage alone for approximately 7–10 days (Figure 19.3). A cystogram should be obtained prior to removing the catheter to ensure complete healing of the ruptured bladder. Operative intervention for extraperitoneal bladder rupture is a consideration if the extent of the injury is very large and has failed prior nonoperative managment, if a bony spicule appears to protrude into the bladder, or if there is a concomitant orthopedic procedure, which will necessitate placement of hardware in the pelvis [68]. Posterior bladder injuries around the trigone can be accessed via an intravesical approach. If there is injury near the bladder trigone, the ureteral orifices should be canulated and injected with methylene blue or indigo carmine to rule out a concomitant ureteral injury.

Extraperitoneal injury involving the bladder neck warrants special consideration. Bladder lacerations in children are twice as likely to extend through the bladder neck compared with adults. It should be suspected if imaging demonstrates urinary extravasation but does not demonstrate a competent bladder neck. Bladder neck injuries managed with urethral or suprapubic catheter drainage alone may result in persistent leakage of urine with urinoma/abscess formation, pelvic osteomyelitis, and the potential for long-term urinary incontinence [69]. In suspected bladder neck injury, surgical exploration is warranted. A retrograde urethrogram (RUG) or cystoscopy prior to surgical exploration may help rule out a concomitant urethral injury. Opening the bladder at the dome may help prevent a pelvic clot from being dislodged. Repair of the bladder neck in at least two layers from within the bladder is recommended.

Intraperitoneal bladder injury should be treated with prompt surgical repair (Figure 19.5). The peritoneal cavity should be opened, all urine and blood evacuated, the viscera and vasculature inspected for injury, and the appropriate therapy instituted. The bladder should be opened and

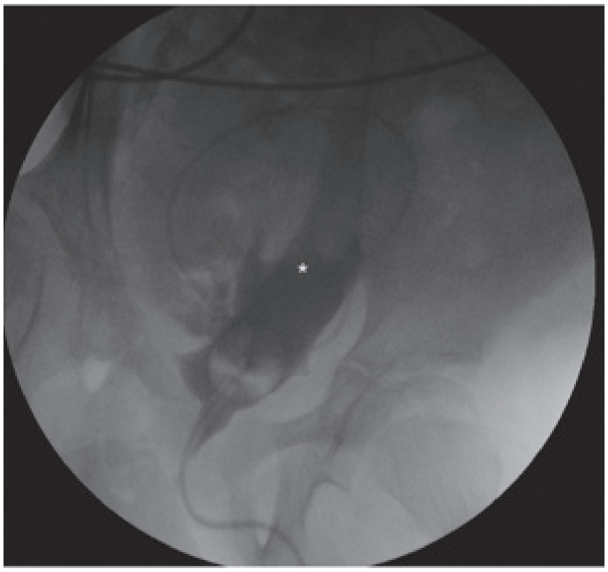


Figure 19.4 Cystogram demonstrating intraperitoneal bladder rupture (*) due to noncompliance with intermittent catheterization in a child with spina bifida status post-ileocystoplasty and bladder neck sling.

thoroughly inspected. The bladder is closed in two layers from the inside. A perivesical drain should be placed. A large-bore urinary catheter should be placed. If the urethra is too small to accommodate a large sized catheter, then a suprapubic tube may be placed. Catheter drainage should be continued for 7–10 days and a cystogram should be performed prior to catheter removal to ensure complete healing of the bladder.

Urethral injuries

Due to the immaturity of the bony pelvis, traumatic urethral injuries in children differ from adults. Combined injury to the bladder neck, posterior urethra, and sphincteric complex occurs more commonly in children. This has implications for long-term risks of urinary incontinence and erectile dysfunction [70].

The male urethra is divided into the anterior and posterior segments. The posterior male urethra comprises the prostatic and membranous urethra, which are segments above or including the urogenital diaphragm. The anterior urethra comprises the bulbous and penile urethra. Urethral injury in females is less common than in males; however, female urethral disruption is four times more common in children than adults.

Urethral injury should be considered in patients with a history of trauma to the penis, vagina, perineum, or pelvis. Injury to the urethra should be ruled out with imaging or cystoscopy if all three of the following clinical findings occur: perineal/penile hematoma, blood at the meatus or vaginal introitus, and inability to void. Additionally, a workup is indicated when one or more pubic rami are fractured, a symphyseal diastasis is present or imaging suggests a bladder neck injury.

Figure 19.5 CT cystogram demonstrating an extraperitoneal bladder perforation (*) due to trocar injury during laparoscopic appendectomy. A urethral catheter and an intraperitoneal Jackson-Pratt drain can be seen. The injury was managed with an indwelling urethral catheter for 7 days. A voiding cystourethrogram at the time of catheter removal demonstrated no leakage of urine and a normal-appearing bladder and urethra.

Posterior urethra

Approximately 5% of patients with a pelvic fracture will have an associated urethral injury [60]. High-speed blunt and crush injuries shear the attachment of the prostate and puboprostatic ligaments from the pelvic floor, while the membranous urethra, attached to the urogenital diaphragm, is pulled in another direction. This results in tearing of the posterior urethra. In females, urethral injuries are associated with pelvic fractures that result in laceration of the bladder neck and vagina.

Diagnosis

An RUG is indicated in males with suspected urethral injury. An initial anteroposterior film can identify pelvic fractures, displacement of the symphysis, or the presence of foreign objects. The patient is then placed in a 25°–30° oblique position, a catheter is inserted just beyond the fossa navicularis and the balloon is inflated with 1–2 cc of water, then contrast is injected into the urethral meatus under fluoroscopy. If a catheter was already inserted into the bladder, this should not be removed. An angiocatheter can be inserted alongside the catheter at the urethral meatus and contrast injected under fluoroscopy. In females with suspected urethral injury, cystoscopy and vaginscopy under general anesthesia is recommended due to the practical limitations of performing an RUG.

A rectal injury will be present in about 15% of children with a urethral injury. The accurate diagnosis of a concurrent rectal injury with subsequent creation of a diverting colostomy is essential. Unrecognized rectal injury in the setting of urethral injury may lead to pelvic abscess, pelvic osteomyelitis, and necrotizing fasciitis. The utility of digital rectal exam in the assessment of patients with a urethral injury due to pelvic fracture has been called into question due to its poor sensitivity [71]. Radiographic assessment of the rectum and/or endoscopy have demonstrated greater sensitivity for this injury and yield more specific information in regard to the location and severity of the injury.

Management

The ideal approach to the management of posterior urethral injuries is controversial, both in adults and children. Prompt urinary drainage in cases of pelvic fracture is recommended [34]. In general, the procedure of choice should be individualized, depending on the anatomy and the extent of the urethral injury, stability of the patient, and presence of additional injuries. Mild injuries of the urethra can be managed with catheter placement alone for 7–14 days. A voiding cystourethrogram (VCUG) is obtained when the catheter is removed. For more severe posterior urethra injuries, options for treatment include endoscopic realignment and delayed repair with immediate suprapubic drainage. Management by sutured primary end-to-end anastomosis is associated with the potential for disrupting surrounding tissue and may lead to worse outcomes in terms of continence [72,73].

Endoscopic realignment should be performed as soon as a patient is stabilized and associated intra-abdominal or pelvic injuries have been addressed. A flexible or rigid cystoscope is used to place a wire through the urethra and into the bladder. A urethral catheter can then be placed over the wire into the bladder. Catheter drainage for approximately 4–8 weeks is recommended. A VCUG should be performed at the time of catheter removal to ensure adequate healing. Long-term follow-up with flow rates and renal bladder ultrasound is recommended as stricture rates range from 14% to 45% [74–77].

If endoscopic realignment fails or if a patient is too unstable to undergo attempted realignment, a suprapubic tube should be placed. Evaluation with simultaneous retrograde urography and antegrade cystogram and VCUG approximately 3 months after injury will help delineate the location and potentially the length of the strictured urethra. Short strictures may be treated with endoscopic urethrotomy. Moderate-to-long strictures may require anastomotic urethroplasty, single-staged or two-staged flap or graft repairs.

Anterior urethra

Anterior urethal injuries are more common than posterior urethral injuries in children. Anterior urethral injury may result from straddle injuries, penetrating gunshot wounds, stabs, or urethral instrumentation. Additionally, injury to the urethra may occur during the repair of anorectal malformations. Partial or complete disruption of the urethra and its fascial coverings may occur. Urethral rupture contained by Buck’s fascia of the penis allows for blood and urine to track along the shaft only and appears as a sleeve of the penis. Urethral rupture with extravasation of blood and urine contained by Colles’ fascia produces a classic butterfly hematoma of the perineum.

Diagnosis

Physical exam findings may raise the suspicion for partial or complete disruption of the urethra and its fascial coverings. Urethral rupture contained by Buck’s fascia of the penis allows for blood and urine to track along the shaft only and appears as a sleeve of the penis. Urethral rupture with extravasation of blood and urine contained by Colles’ fascia produces a classic butterfly hematoma of the perineum. An RUG may help delineate the location and extent of injury to the urethra, but may not be necessary in all cases of anterior urethral injury.

Management

Minor contusions of the anterior urethra, without disruption, may be treated with a few days of catheter drainage. When the injury is more involved or penetrating in nature, surgical exploration, debridement, and direct repair are indicated. For distal bulbar or proximal pendulous urethral injuries, a perineal or penoscrotal incision is made. A circumcising incision with degloving of the penis is suitable for injuries of the distal urethra. Urethral lacerations may be primarily repaired with end-to-end anastomosis and catheter drainage for 7–10 days. Injuries related to gunshot wounds or extensive perineal involvement may require debridement and urinary diversion with a suprapubic tube with staged urethroplasty to be performed several months later.

In the case of iatrogenic injury to the urethra due to urethral instrumentation, management consists of establishing urethral continuity with a catheter. If an initial bedside attempt to place a urethral catheter fails, an attempt at endoscopic or radiologic guided placement of the catheter is indicated. In the event of failure to place a urethral catheter, urinary diversion with a suprapubic tube or vesicostomy may be performed. Depending on the severity of the initial injury, follow-up imaging may consist of a VCUG at the time of catheter removal and an RUS several months following catheter removal. In older children, a uroflow study with postvoid residual determination is important.

Proximal penile or bulbar urethral injury at the time of repair of an anorectal malformation can occur either due to the lack of urethral catheter at the time of surgery or due to a catheter placed through a rectourethral fistula into the rectum. Prevention of this injury with an appropriate placed urethral catheter prior to repair is ideal. This may require cystoscopy with or without a guidewire [67,78].

Testicular injuries

In boys presenting with scrotal pain, the diagnosis of testicular torsion must be ruled out. Up to 5%–8% of boys who are found to have testicular torsion have a history of scrotal trauma. If a diagnosis for scrotal/testicular pain cannot be made on clinical exam, scrotal ultrasound is the imaging modality of choice. Rupture of the testis can be seen with blunt or penetrating trauma [79]. Scrotal exploration is warranted in the acute setting if a tunica rupture is suspected. Testicular volume loss may occur with surgical exploration due to debridement and possibly pressure-related ischemia [80]. Extracellular matrix graft materials as well as the use of a tunica vaginalis flap have been utilized successfully in repair of large defects [81]. In the setting of delayed presentation (1–5 days following trauma), an observation protocol has been described consisting of scrotal support, antibiotics, and rest. Resolution of the scrotal fracture with preserved testicular architecture was seen on follow-up ultrasound imaging [82].

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20.1

Pediatric Orthopedic Trauma: An overview of pediatric musculoskeletal trauma

KATHERINE SCHROEDER and SCOTT ROSENFELD

Introduction

Musculoskeletal injury in the child differs significantly from the adult, both in injury patterns seen and in the methods of treatment. While most injuries are isolated and do well with straightforward treatment, some can be life-threatening or lead to significant long-term morbidity. Musculoskeletal injuries are also quite common in the multiply injured patient. Thus, an understanding of pediatric musculoskeletal injuries is crucial in the overall treatment of pediatric trauma patients.

Epidemiology of skeletal trauma

Skeletal injuries are common in children, with an estimated 40% of boys and 25% of girls sustaining a fracture by 16 years of age [1]. Every year, approximately 25% of children sustain an injury, with 10%–25% of these injuries consisting of a fracture [2]. Across all ages, boys are more likely to sustain a fracture than girls and the incidence of fractures increases throughout childhood and peaks at age 12 in girls and 15 in boys. Socioeconomic status, season of the year, and time of day all influence the incidence of skeletal trauma. Most pediatric fractures occur in the afternoon, after school. They are also more likely to occur in the summer, when the days are longer [3,4]. Lower socioeconomic status has been associated with increased risk of fractures and other injuries in the pediatric population as well [5].

In 2012, 12.9 million children and adolescent health care visits in the United States were a result of a musculoskeletal injury. Over 200,000 of these required hospitalization. Total hospital charges for all musculoskeletal diagnoses in 2012 totaled $7.6 billion in the pediatric population. Musculoskeletal trauma accounted for 43% of these charges [6]. Days missed from school and work, medical equipment costs, and physical therapy and rehabilitation costs also contribute significantly to the economic burden of pediatric musculoskeletal trauma.

Pathophysiology

The anatomy, biomechanical properties, and physiology of the immature skeleton differ profoundly from those of an adult. From a biomechanical standpoint, the immature skeleton, as compared to that of a mature patient, has an increased capacity to adapt to stress prior to failure, greater potential to remodel, and shorter healing time. From an anatomic standpoint, the immature skeleton has thicker periosteum than that of the mature skeleton and growth plates (physis) are present. As a result, pediatric patients have unique injury and fracture patterns including buckle fractures, greenstick fractures, plastic deformation, and physeal fractures (Figures 20.1.1 and 20.1.2). These unique patterns require different methods of treatment than the patterns seen commonly in adults.

The physis provides both longitudinal and circumferential growth to the bone. It is not only very metabolically active but also vulnerable to injury. Joint dislocations or ligamentous injuries, while common in adults, are rare in children as the weaker, nearby physis or apophysis usually fails first. Fractures involving the physis account for up to 30% of all skeletal injuries in children [7]. Physeal fractures generally heal rapidly but can lead to premature physeal closure and growth arrest with subsequent deformity and shortening.

Figure 20.1.1 AP and lateral radiographs of the wrist demonstrate a buckle fracture of the distal radius metaphysis.

Figure 20.1.2 A lateral radiograph of the forearm reveals a greenstick fracture of the radius (arrow) and plastic deformation of the ulna (asterisk).

In 1963, Salter and Harris proposed a classification system for physeal fractures, which is still used today (Figure 20.1.3) [8]. Type I fractures involve only the physis and are common and often seen in younger children. Type II fractures are the most common type of physeal fractures and are described as having a fracture line that runs through the physis and exits through the metaphysis. Type III and IV fractures extend through the physis and across the epiphysis into the articular surface and carry an increased risk of intra-articular injury, arthritis, and growth disturbance. Type V injuries involve a crushing injury to the physis and have the greatest risk of growth disturbance [8]. In 1969, Rang added type VI, indicating an injury to the periphery of the physis [9]. Specific physeal fractures that are notoriously at the greatest risk of growth arrest include distal femur physeal fractures and type III and IV fractures involving the medial malleolus (Figure 20.1.4) [10–12].

There are many ways in which fractures can be described: open versus closed, based on location in a long bone, or based on fracture pattern or alignment of the fractured bone. When classifying a long-bone fracture by anatomic location, the regions where injuries may occur include the epiphysis (closest to the adjacent joint), physis, metaphysis, and diaphysis (shaft) (Figure 20.1.5). Diaphyseal fractures can occur in multiple patterns including plastic deformation (the bone is bent but without a visible fracture line), greenstick fractures (plastic deformation on one side of the bone and a visible fracture line on the other side), or complete fractures. A greenstick fracture is so named because it is analogous to the way a young greenstick tree branch is difficult to break completely. Complete fractures can be described by their radiographic pattern and include

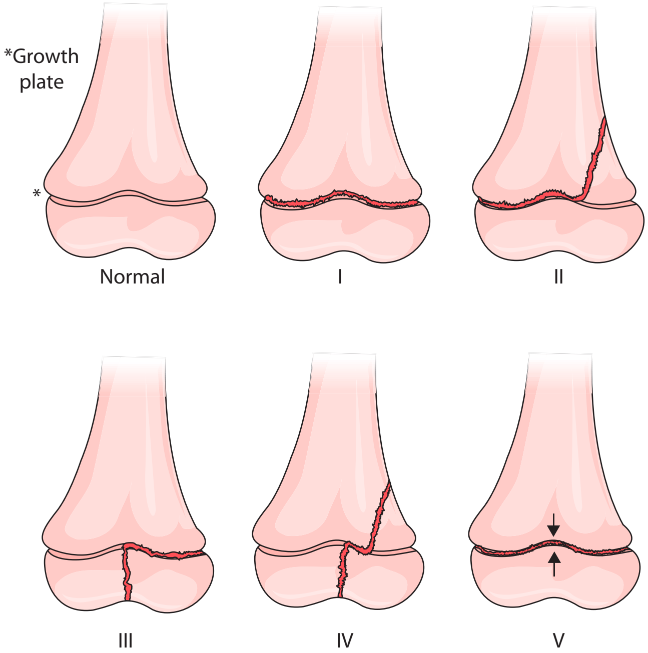


Figure 20.1.3 Salter-Harris classification of physeal fractures. (From Katherine M.S., and Scott R., *General Concepts of Pedi Ortho Trauma,* Pediatric Trauma, 2nd edition.)

Figure 20.1.4 A physeal injury to the medial malleolus can lead to growth arrest and angular deformity of the ankle.

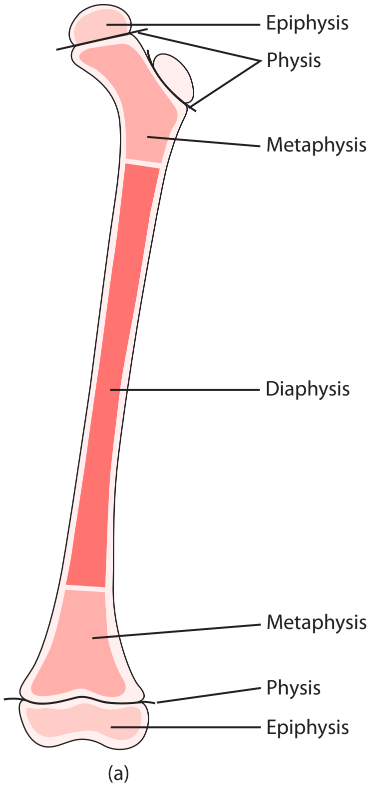


Figure 20.1.5 Anatomic regions of a long bone. (From Katherine M.S., and Scott R., *General Concepts of Pedi Ortho Trauma,* Pediatric Trauma, 2nd edition.)

transverse, oblique or spiral, and comminuted (multiple small fracture fragments). These different fracture patterns occur depending on the mechanisms of injury such as direct blows, twisting, and high-energy mechanisms, respectively. The metaphysis of a long bone contains bone that is less dense and more porous, which makes this a common location for buckle or compression-type fractures.

All fractured bones tend to remodel, or reshape, over time as they heal. However, the potential to remodel is much higher in children because growth assists in remodeling of fractures. The younger the patient and the more growth the patient has remaining, the greater the potential for a bone that heals crooked to straighten out. Fractures that most reliably remodel are those that are close to a physis and are angulated in the plane of movement of the nearest joint. For example, a distal radius fracture that is angulated either volarly or dorsally is more likely to remodel than one that is angulated radially or ulnarly. As expected, younger children have a greater potential to remodel compared with older children and adults. Distal radius and proximal humerus fractures in children show the greatest propensity to remodel (Figure 20.1.6).

Another consequence of a child's growth on fracture healing is the tendency of overgrowth. Clinically, this is most frequently seen in diaphyseal femoral fractures. Fractures of the femoral shaft will spontaneously correct shortening of up to 1–2 cm in a young child [13,14]. Overgrowth can also result in deformity. This is seen most commonly in proximal tibial metaphyseal fractures, also called Cozen fractures. In these fractures there can be asymmetric overgrowth of the medial portion of the proximal tibial physis, leading to valgus deformity about the knee [15,16].

An approach to pediatric orthopaedic trauma

While the majority of pediatric fractures are isolated and occur via a relatively low-energy mechanism of injury such as a fall or twisting, a small number occur in higher-energy circumstances such as motor vehicle collisions and may result in a multiply injured patient. These more severely injured patients should be evaluated as trauma patients and Advanced Trauma Life Support protocols should be followed. The patient should be immobilized and spine precautions enforced if indicated. Primary and secondary surveys should be completed. Imaging including anteroposterior (AP) radiographs of the chest and pelvis and a lateral x-ray of the cervical spine should be obtained. Additional studies (CT scans and/or ultrasound) should be obtained as indicated. It is important to note that the secondary survey continues for 24 to 48 hours after the initial assessment. Continuous reassessment will help identify injuries that may be missed as a result of distracting larger injuries in polytrauma patients [17,18].

An initial history, including mechanism of injury, is important to obtain. A thorough musculoskeletal examination,

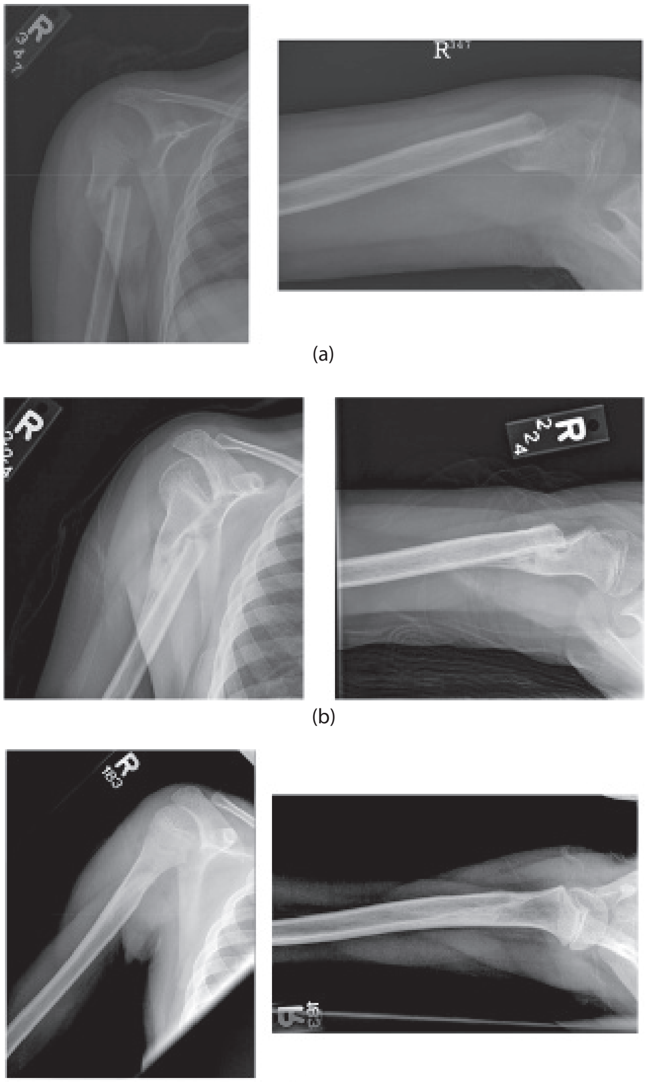


Figure 20.1.6 Radiographs showing a proximal humerus fracture in a 9-year-old patient at: **(a)** initial injury, **(b)** 6 weeks after injury, and **(c)** 9 months after injury. As demonstrated, proximal humerus fractures in children have a significant potential to remodel.

including a neurovascular exam, should be performed. If there is a high-energy mechanism of injury, an unconscious patient, or concern for spinal trauma, the patient should be immobilized on a pediatric spine board and placed into a cervical collar. It is important to note that children have a larger head-to-body ratio and smaller chest size as compared to adults. Thus, use of a standard trauma backboard causes a child's neck to be flexed. Proper immobilization of the pediatric cervical spine requires either a pediatric backboard with a cut-out occipital recess or use of a mattress pad with an adult backboard in order to elevate the child's body and remove the flexion moment placed on the neck (Figure 20.1.7). The entire spine should be palpated for tenderness or step-offs. Extremities should be examined for swelling, deformity, crepitus, or tenderness. Refusal to bear weight after a fall or accident is a frequent sign of an injury in a young child. Radiographs should be obtained of all extremities with a suspected injury. Although screening x-rays may be obtained, particularly in a very small patient, orthogonal views (AP and lateral) of an injured extremity should be obtained before definitive treatment is planned.

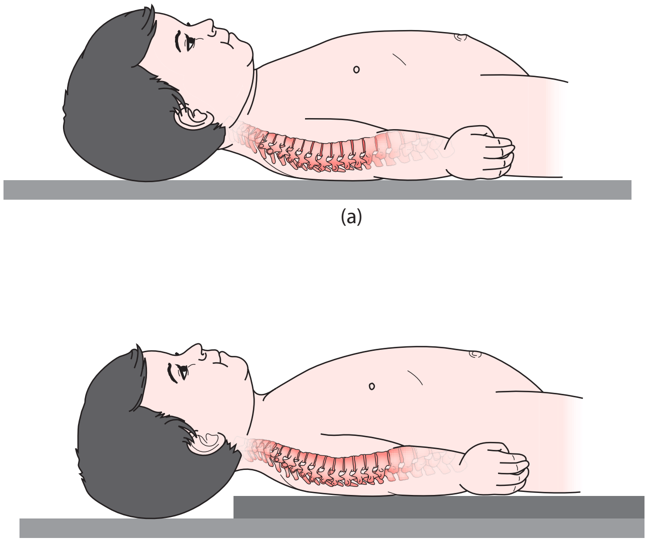


Figure 20.1.7 **(a)** Child on standard backboard resulting in flexion of the cervical spine. **(b)** Child on standard backboard with mattress under body resulting in anatomic alignment of the cervical spine. (From Katherine M.S., and Scott R., *General Concepts of Pedi Ortho Trauma,* Pediatric Trauma, 2nd edition.)

In the emergency room, a fractured extremity may be immobilized with a well-padded splint for comfort and stabilization. Patients with severe systemic and/or head injuries that will delay definitive fixation of femoral or unstable pelvic fractures may be placed in Buck's traction. If the delay is anticipated to be greater than 24 hours skeletal traction should be used as prolonged Buck's traction can lead to skin breakdown [19].

Because fractures are rarely life-threatening, splinting generally suffices as initial orthopaedic care while the patient's overall condition is stabilized. Although the importance of timing for fracture fixation in adult polytrauma patients is well recognized, there is limited research regarding the timing of definitive orthopaedic surgery in the multiply injured child. It has been shown that early fracture fixation in the first 72 hours after injury in the pediatric polytrauma patient leads to shortened hospital stays, shortened intensive care unit stays, and shorter length of time with ventilator support [20]. Overall, with regard to surgical timing, reliance on clinical judgment and effective communication between the trauma service, critical care service, orthopaedic surgery service, and the anesthesiology service is imperative.

Nonaccidental trauma

Nonaccidental trauma, or child abuse, is a serious cause of short- and long-term disability and death in the pediatric population. Abuse is second only to sudden infant death syndrome as a cause of mortality in infants 6 months to 1 year and second only to accidental injury in children over 1 year of age [21,22]. Fractures are the second most common presentation of physical abuse after skin lesions [23] and approximately one-third of abused children are seen by an orthopedic surgeon [24]. Thus, it is critically important to understand the risk factors and musculoskeletal manifestations of nonaccidental injuries.

Demographic analysis has shown that children most at risk for maltreatment include first-born children, unplanned children, premature infants, stepchildren, and children with special needs. In addition, lower socioeconomic status, single-parent homes, drug abusing parents, parents who were themselves abused, and unemployed parents have seen shown to be at increased risk [21,24]. The importance of recognizing child abuse has been well documented. It has been estimated that failure to diagnose an initial presentation of child abuse may result in a 30%–50% chance of repeated abuse and a 5%–10% chance of death in subsequent presentations of nonaccidental trauma [22,24].

A thorough history should be taken and details of the history should be compared with the physical exam and imaging for discrepancies. It is important to determine if the mechanism of injury is adequate to explain the severity of injury [25]. Additionally, the described mechanism should be developmentally appropriate for the child, for example, a 2-month-old child with a femur fracture who reportedly rolled off of the bed. This is not a developmentally appropriate scenario as infants generally do not begin rolling until 4 months of age. There are also certain fractures and fracture patterns that should raise suspicion for nonaccidental trauma. Femur fractures in children under the age of three, and particularly before walking age, are more likely to be nonaccidental. The American Academy of Orthopedic Surgeons currently recommends that children younger than 36 months with a diaphyseal femur fracture be evaluated for child abuse [26]. Other fractures often associated with abuse are posterior rib fractures, metaphyseal corner fractures, physeal separations, scapula fractures, sternal fractures, and spinous process fractures (Figure 20.1.8). A skeletal survey is recommended in any child with suspected nonaccidental trauma. This includes AP x-ray of bilateral arms, bilateral forearms, bilateral hands, bilateral femurs, bilateral legs and bilateral feet with AP, and lateral views of the axial skeleton and skull. Multiple fractures in various stages of healing are almost pathognomonic of child abuse [27]. A differential diagnosis including osteogenesis imperfecta, rickets, coagulation disorders, congenital insensitivity to pain, and leukemia should always be kept in mind and ruled out when nonaccidental trauma is suspected [28].

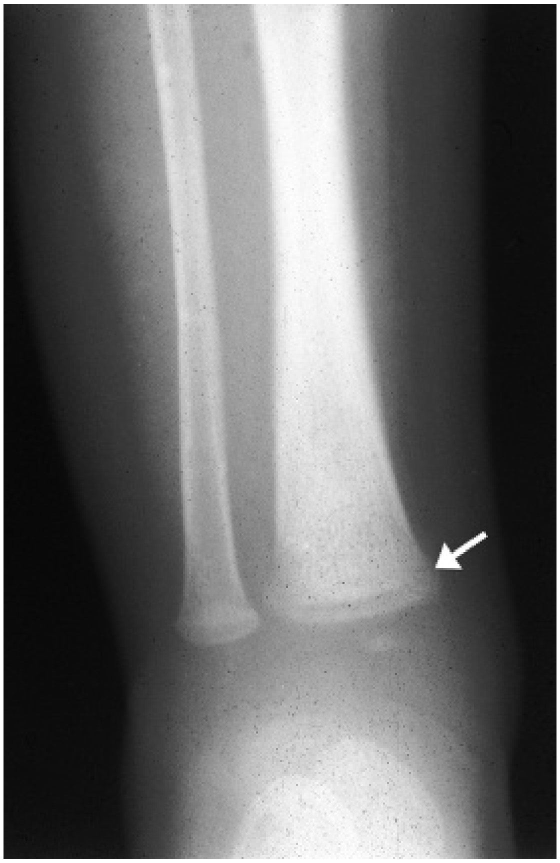


Figure 20.1.8 Subtle metaphyseal corner fracture (bucket handle-type fracture) of the distal tibia, just proximal to the physis (arrow). This is a fracture typical of child abuse.

Compartment syndrome

Compartment syndrome occurs when the pressure within a myofascial compartment increases to the point where circulation to the structures within that compartment is compromised. This can result in muscle and nerve ischemia, leading to profound disability. In addition to limb morbidity, the muscle damage can lead to rhabdomyolysis, hyperkalemia, and renal failure in severe cases. Although compartment syndrome is most commonly seen following trauma, with or without an underlying fracture, it may also occur secondary to IV infiltration, clotting disorders, septicemia, exertional rhabdomyloysis, and animal bites.

Timely diagnosis and intervention of an acute compartment syndrome is imperative in preventing permanent morbidity to a limb. Thus, an awareness of the signs of compartment syndrome is crucial. The classic teaching in the evaluation of a compartment syndrome is the five P's: pain, paresthesia, paralysis, pallor, and pulselessness. The most important of these is pain, which is often described as pain out of proportion to examination, pain at rest, or pain with passive stretch of the muscle in the suspected compartment. Pallor and pulselessness are late signs of compartment syndrome and often do not occur until irreversible ischemia has occurred. In children, these signs are less reliable and the clinical exam can be difficult in an anxious, scared, nonverbal, or obtunded child. In a series from Boston published in 2001, increasing analgesic requirements preceded the noted change in vascular status by an average of 7 h [29]. Therefore, it is important to evaluate any pediatric patient who is requiring more frequent or higher doses of medication for pain control, particularly if anxiety or agitation is present. In the pediatric population, the three A's are now recommended for consideration of a compartment syndrome: increasing anxiety, agitation, and analgesic requirement (Table 20.1.1) [30].

When evaluating a limb for a suspected compartment syndrome, any splint or circumferential dressing should be completely removed and the entire limb assessed. Since the appearance of swelling and the examiner's sense of "tightness" are unreliable, compartment pressure measurement is an important adjunct to the clinical exam, particularly in patients who are obtunded or under general anesthesia. There is no consensus for an absolute compartment pressure measurement at which fasciotomies should be performed. Both 30 and 45 mmHg have been reported in the literature as thresholds for treatment. More recently, perfusion pressure has also been used to determine the need for treatment. A ΔP (ΔP= diastolic blood pressure—compartment pressure) of less than 30 mmHg is generally considered an indication for fasciotomies [31]. It is important to note, however, that intraoperative diastolic blood pressure decreases while under general anesthesia and should be taken into consideration. Therefore, measuring compartment pressures intraoperatively may give a falsely low ΔP [32]. Overall, compartment pressure measurement should be used in conjunction with the patient's overall clinical condition and the physician's physical exam to aid in the diagnosis of compartment syndrome.

In treatment of compartment syndrome of the lower leg, all four myofascial compartments should be released: anterior, lateral, superficial posterior, and deep posterior. Although all can be released through a single lateral incision, a two-incision technique is generally recommended. In compartment syndrome of the forearm, the fasciotomy should extend, via a curvilinear skin incision, from the medial epicondyle to the distal edge of the carpal tunnel (Figure 20.1.9). Both superficial and deep muscle groups need to be decompressed. The extensor compartment can be released through a separate dorsal incision if needed. In general, fasciotomy wounds should be left open until swelling has subsided.

Table 20.1.1 The three A's of compartment syndrome in the pediatric population

Anxiety
Agitation
Increasing **A**nalgesic requirement

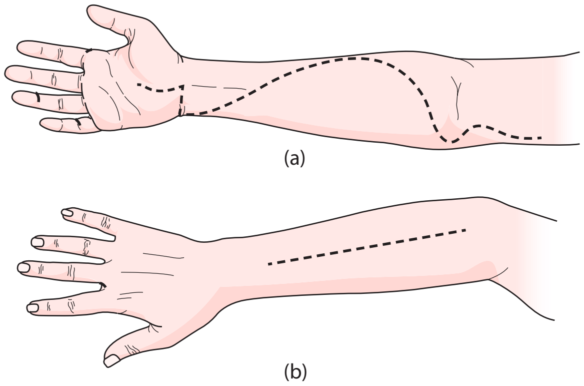


Figure 20.1.9 **(a)** Volar forearm fasciotomy incision. **(b)** Dorsal forearm fasciotomy incision. (From Katherine M.S., and Scott R., *General Concepts of Pedi Ortho Trauma,* Pediatric Trauma, 2nd edition.)

Open fractures

Open fractures make up approximately 2% of all fractures in children and, in severe cases, can be both life- and limb-threatening [33]. The goals of treatment of open fractures are to avoid infection, achieve soft tissue coverage and bony union, and restore function to the limb. In 1976, Gustilo and Anderson described a classification system for open fractures that is still used today [34]. In addition to being descriptive of open fractures, the Gustilo and Anderson classification aids in both treatment and prognosis of open fractures. Type I fractures are defined as having wounds <1 cm, type II with wounds between 1 and 10 cm, and type III fractures with wounds >10 cm. The type III fractures have been further subdivided into type A if there is adequate soft tissue coverage, type B if a soft tissue procedure is necessary for wound closure, and type C if a vascular injury is present (Figure 20.1.10).

When assessing any wound in a trauma patient, it is important to determine if the wound is superficial or if it communicates with bone. A careful history should be taken with regard to the circumstances of an open fracture and whether or not the fracture is contaminated with soil or other debris. The wound should be inspected for frank contamination and a thorough neurovascular exam should be performed. In the emergency department the wound should be superficially irrigated and obvious large debris removed. A clean dressing should be applied and the limb immobilized. Tetanus prophylaxis should be given along with appropriate IV antibiotics. A first generation cephalosporin is indicated in type I and type II open injuries. An aminoglycoside should be added for type III injuries. High-dose penicillin should be added in farm-related injuries when there is risk for Clostridial infection [35].

In general, open fractures should be treated with open surgical debridement. Even grade I open fractures with pin hole wounds have a 2.5%–4% risk of infection if treated with antibiotics alone [36,37]. In the past, it was believed that

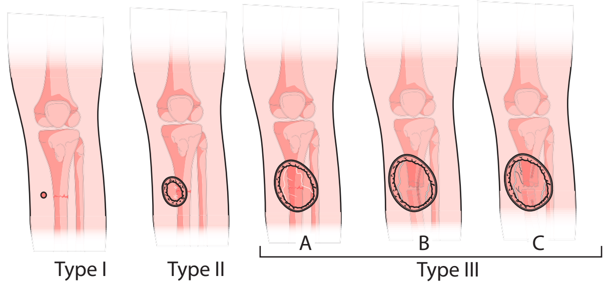


Figure 20.1.10 The Gustilo and Anderson classification of open fractures. (From Katherine M.S., and Scott R., *General Concepts of Pedi Ortho Trauma,* Pediatric Trauma, 2nd edition.)

debridement of open fractures should be done within 6 h of injury. However, recent studies have shown that surgical debridement within 6 h after the injury offers little benefit over debridement within 24 h after the injury with regard to the prevention of acute infection [38]. Therefore, current recommendation is that open fractures are treated with surgical debridement within 24 h of injury. All dead or devitalized tissue should be removed and the wound irrigated thoroughly. Bone ends should be inspected to ensure no foreign material has been impacted into them. The wound should only be closed primarily if there is confidence that no foreign material or necrotic tissue remains. Repeat debridements are often necessary for grossly contaminated wounds. Depending on the fracture type and degree of soft tissue injury the fracture may be stabilized by casting, external fixation, or internal fixation. If a wound is located near a joint, it should be inspected thoroughly to determine if the joint capsule has been disrupted, resulting in contamination of the joint. A saline load test may be used to diagnose a traumatic arthrotomy [39,40]. If the joint capsule has been disrupted, a formal surgical arthrotomy and irrigation of the joint should be performed.

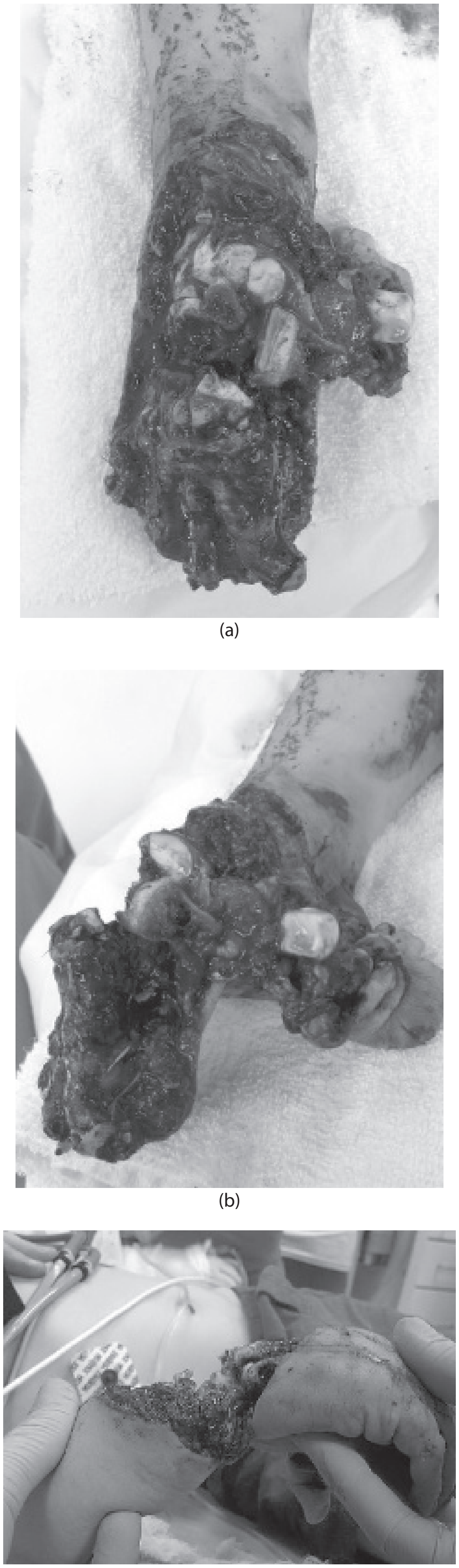
In type IIIB and IIIC open fractures, plastic surgery, and/or vascular surgery specialization is needed. Delayed closure, skin grafting, local rotational flaps, or free flaps may be needed to achieve soft tissue coverage. Patients with an open fracture and vascular injury should be treated by a multidisciplinary surgical team. Often external fixation can be used to stabilize the underlying fracture as vascular shunting or repair is performed.

Traumatic amputations and lawnmower injuries

Although representing a small percentage of pediatric injuries, traumatic amputations can lead to significant long-term disability. Loder showed that lower extremity traumatic amputations were most commonly caused by lawnmower injuries, followed by farm machinery injuries and motor vehicle and motor–pedestrian collisions [41]. Recent data show an increasing incidence of firearm-related injuries leading to amputation [42].

Although preventable, lawnmower injuries continue to be seen in the pediatric trauma population. It is estimated that over 9000 injuries occur each year in the pediatric population from power lawnmower accidents [43]. Lawnmower injuries are more common in boys, more common in the spring and summer, and involve the lower extremities more often than the upper extremities [44,45]. Children injured by riding lawnmowers, compared with those injured by push lawnmowers, are generally younger and sustain more severe injuries [44] (Figure 20.1.11).

When faced with a lawnmower injury, the principles of open fracture management should be followed with urgent assessment followed by surgical debridement. Triple antibiotics should be administered in the emergency room, including a cephalosporin, an aminoglycoside, and penicillin. In

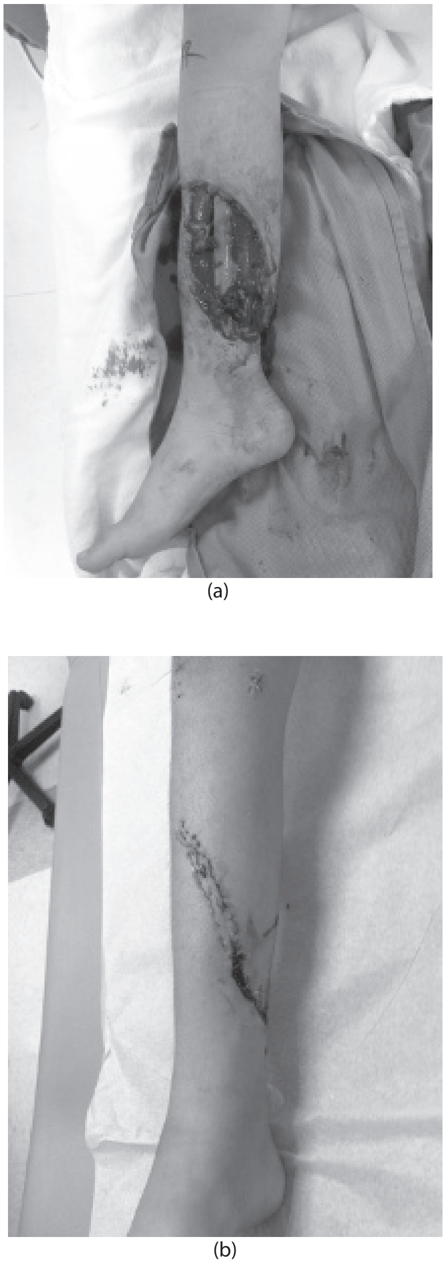

(a)

(b)

(c)

Figure 20.1.11 Lawnmower injury to right foot **(a, b)** and right wrist **(c)** of a 5-year-old boy.

general, multiple debridements are needed to assure viable tissue is present at all edges. Up to 47% of these injuries necessitate some level of amputation [44]. Coverage can be accomplished via delayed primary closure or skin grafting (Figure 20.1.12). Plastic surgery specialization should be obtained if required for wound coverage and digit replantation if indicated.


(a)

(b)


(c)

Figure 20.1.12 Grade 3A open fracture of left tibia and fibula fracture in a 10-year-old female **(a)**. There was adequate soft tissue for primary wound closure without skin graft **(b, c)**.

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20.2

Pediatric Orthopedic Trauma: Spine and pelvis trauma

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General considerations in pediatric spine trauma

Pediatric spine fractures are rare but can be devastating injuries. These injuries account for only 1%–2% of all pediatric trauma admissions, but mortality rates are reported to be as high as 5%–41% [1–4]. The discrepancy between injury and mortality rate is most likely attributed to the unique anatomic challenges of the growing spine as well as the mechanism causing these injuries that may result in concomitant injuries to other systems. Physician unfamiliarity with these injuries may also play a role. Although each child is unique, there are common injury patterns that must be recognized early and appropriately managed.

Cervical spine anatomy

The cervical spine is divided into upper (base of skull [occiput], C1, and C2) and lower segments (C3–C7).

The atlas (C1) develops from three ossification centers: the body and two neural arches or lateral masses that are connected by synchondroses or temporary hyaline cartilage growth plates [5,6] (Figure 20.2.1a). The anterior arch (body) ossifies by 1 year. The posterior arch comprises the two lateral masses and fuses by the age of 3–4 years. By 7–8 years, the posterior arch fuses to the anterior arch. Prior to fusion, these synchondroses are visualized on open mouth anterior–posterior (AP) x-rays and are often mistaken for fractures [5,6].

Similarly, the axis (C2) is formed from five ossification centers: one body, two neural arches, and each half of the dens (Figure 20.2.1b). The synchondrosis between the dens and body is often mistaken for a fracture on x-ray between the ages of 3 and 7 years [5,6]. On open mouth odontoid x-rays, the synchondrosis is predictably cup shaped and below the level of the surrounding lateral mass articular surface.

The lower segment (C3–C7) is formed from three ossification centers: the body and two neural arches (Figure 20.2.1c). The neural arches fuse posteriorly by 2–3 years and the body fuses to the neural arch by 3–6 years. The immature cervical vertebrae are wedge shaped with a horizontal facet joint orientation. During development, the vertebrae enlarge through appositional growth at the superior and inferior endplates. The junction between the endplates is more prone to fracture. At skeletal maturity, the vertebrae have a more vertical facet joint orientation (~70°) and are less resistant to fracture. Similarly, around the age of 10 years, the cervical vertebrae develop uncinate processes resulting in increased rotatory stability [5–7].

Increased ligamentous laxity, underdeveloped neck musculature, and relatively large craniums significantly contribute to cervical spine instability in children [3,4]. This allows the C2–C3 articulation to act as a fulcrum leading to approximately 50% greater flexion–extension mobility in a child less than 8 years old. As the child ages, the most mobile segments become more caudal. The immature cervical spine is predisposed to forward translation and injury

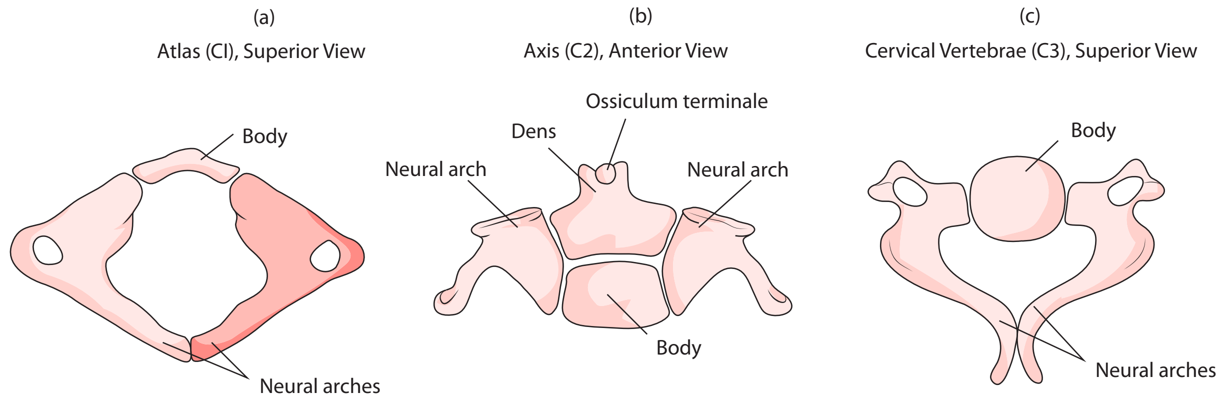


Figure 20.2.1 **(a)** The atlas (C1). **(b)** The axis (C2). **(c)** Cervical vertebrae (C3–C7). (Courtesy of Texas Children's Hospital, Houston, Texas.)

because of the three major factors: large head-to-body ratio, ligamentous laxity, and orientation of facet joint.

Thoracolumbar spine anatomy

The caudal spine is composed of 12 thoracic and 5 lumbar vertebrae that are tethered together by intravertebral discs and strong anterior and posterior longitudinal ligaments (Figure 20.2.2).

The pediatric thoracic spine, which is linked to the rib cage, has smaller intervertebral discs, and facet joints that are shallower and more horizontally oriented in the coronal plane as compared to the adult spine. The lumbar spine has a larger canal with the spinal cord terminating in the conus medullaris at L3 in the newborn and moving more caudal with age. By age 8, the conus medullaris is near the first or second lumbar vertebrae [4,7].

Before the age of 8, the nucleus pulposus has greater water content and less collagen. This increases the elasticity and flexibility of the spine and the possibility of multilevel injury. Physeal cartilage is weaker than bone, and tension forces can result in Salter–Harris I fractures [7].

Epidemiology

The mechanism of cervical spine injuries varies widely. Children less than 8 years of age are prone to upper cervical spine injuries from lower-energy mechanisms such as ground level falls and child abuse. Older and male children are more likely to present from higher-energy mechanisms including motor vehicle accidents, sports injuries, all terrain vehicle (ATV), and bicycle injuries. Although the most common presenting symptom is pain localized to the neck region, headache, reduced neck range of motion, subjective instability, and weakness are also common symptoms. Neurologic injury is rare but all patients with distracting injuries or unclear exams should be triaged as having cervical spine injuries until proven otherwise [1,2,5,6].

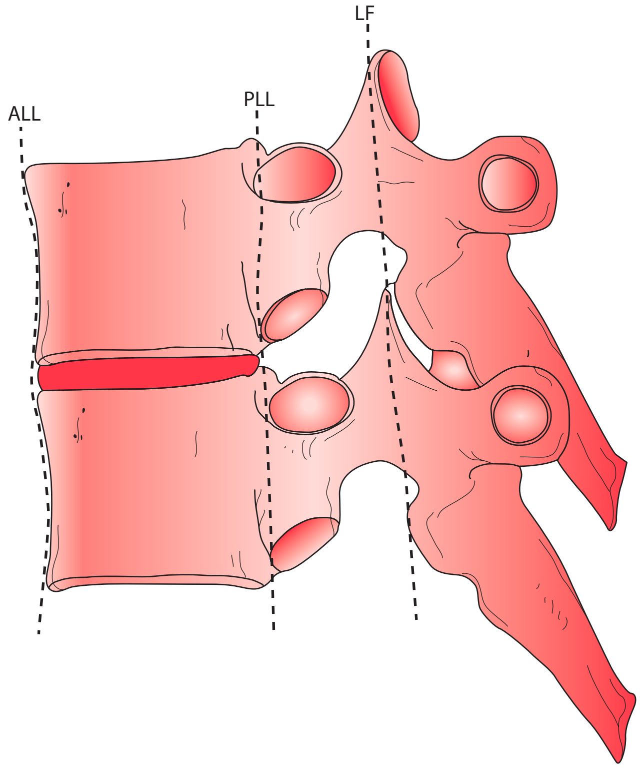


Figure 20.2.2 Sagittal view of the thoracolumbar spine. ALL: anterior longitudinal ligament, PLL: posterior longitudinal ligament, LF: ligamentum flavum. (Courtesy of Texas Children's Hospital, Houston, Texas.)

Injuries to the thoracolumbar spine are rare and most often present in older children (>8 years). Children who participate in high-risk activities such as football, rugby, skiing, and ATV accidents are at risk [7]. Motor vehicle collisions are also a common cause of spinal injury [8]. Specifically, lap belts can cause intra-abdominal and thoracolumbar spinal injury with a hyperflexion mechanism compressing the anterior structures and posterior column distraction [9]. The thoracic vertebrae with surrounding ribs are inherently more stable and less prone to injury. However, in children, these structures are not well developed. This increases the risk for intra-abdominal and intrathoracic organ damage. The most commonly present symptom is back pain that is identified with midline tenderness in an awake and alert patient. Neurologic injury can occur with high-energy mechanisms and must be ruled out in every patient [7,10].

Evaluation

Evaluation of spine injuries should start with an evaluation of the patient's airway, circulation, and breathing. Pediatric patients with suspected spine injuries should have their neck and back immobilized during the initial evaluation [5,6]. Appropriate immobilization places the head and neck region in a neutral position. Pediatric backboards have occiput cut-outs or appropriately sized padding for the child's age [6] (Figure 20.2.3). A rigid cervical collar should be placed as soon as possible. The collar and backboard prevent flexion and kyphosis through the injured segment that may result in progression of the injury.

After safely immobilizing the spine, external garments should be removed and the entire spine should be palpated in the midline to assess for tenderness while the patient is carefully logrolled onto his or her side [3,6]. Approximately 20% of patients with a cervical spine injury will have a concomitant lower cervical, thoracic, or lumbar spine fracture [3,6,11,12]. An in-depth neurologic exam should be performed to assess for muscle strength, weakness, proprioception, and reflexes [11,12]. The neurologic exam should be repeated and documented once the child is more alert and cooperative (Table 20.2.1). An adequate neurologic exam should identify the level of injury based on the presence or absence of muscle weakness, a sensory deficit, or loss of a reflex arch. The motor strength exam is graded on a five-point scale and recorded for each of the cervical and lumbar levels (Table 20.2.2). Sensation is graded on a three-point scale (Table 20.2.3). Sensory and motor examinations may be difficult depending on the age and alertness of the child, but should be attempted in all patients. Once a spine fracture or injury is identified, the orthopaedic/neurosurgical service should be consulted for further management.

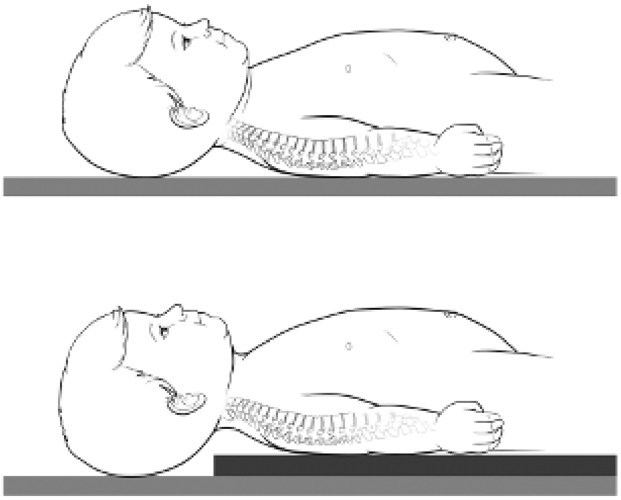


Figure 20.2.3 Young children can be immobilized on a modified backboard with either an occipital recess (less practical) or a mattress pad to raise the chest (more practical) (bottom). Top image shows a child improperly immobilized. (Courtesy of Texas Children's Hospital, Houston, Texas.)

Table 20.2.1 Upper and lower extremity neurologic exam

Nerve root	Muscle tested	Motion	Sensory	Reflex
C5	Deltoid	Shoulder abduction	Lateral upper arm	Biceps
	Biceps	Elbow flexion and wrist supination		
C6	Brachioradialis	Wrist extension	Thumb and radial forearm	Brachioradialis
	ECRL	Elbow flexion		
C7	Triceps	Elbow extension	Index, long, ring finger	Triceps
	FCR	Wrist flexion		
C8	FDS	Finger flexion	Small finger	None
T1	Interossei	Finger abduction	Medial elbow	None
T4			Nipple	
T10			Umbilicus	
L2, L3	Iliopsoas	Hip Flexion	Iliac crest	Cremasteric
	Hip abductors	Hip abduction	Groin	
L3, L4	Quadriceps	Knee extension	Lateral thigh, anterior knee, medial leg	Patellar
L4, L5	Tibialis anterior	Ankle forsiflexion	Lateral leg, dorsal foot	None
L5	Extensor hallicus longus	Great toe extension	First web space	None
S1	Gastroc-soleus	Foot planar flexion	Lateral foot	Achilles
	Peroneal longus and brevis	Foot eversion	Posterior leg	

ECRL: extensor carpi radialis longus, FCR: flexor carpi radialis, FDS: flexor digitorum superficialis.

Table 20.2.2 American Spinal Injury Association Motor Impairment Scale

Motor grading system	
Paralysis	0
Palpable or visible contraction	1
Full range of motion with gravity eliminated	2
Full range motion against gravity	3
Full range of motion with some, but not full, resistance	4
Full range of motion against normal resistance	5

Table 20.2.3 American Spinal Injury Association Sensory Impairment Scale

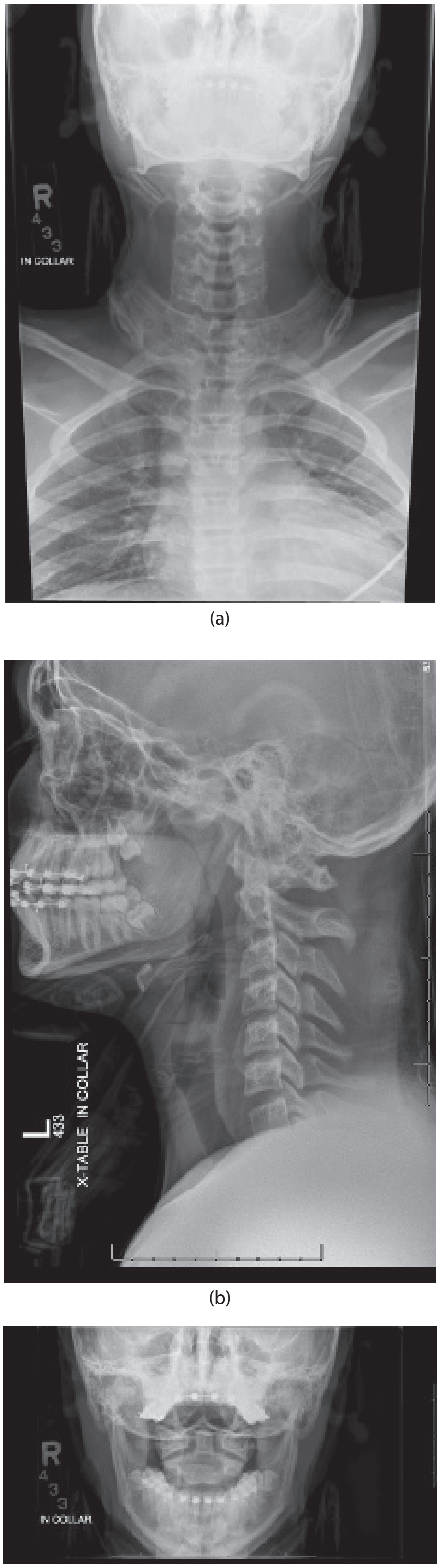
Sensory grading system	
Absent sensation	0
Impaired sensation	1
Normal sensation	2
Not testable	NT

Imaging

Plain radiographic evaluation is the gold standard for the initial evaluation of suspected spine injuries in children. Routine use of radiographic evaluation for all trauma patients is not indicated, but patients with midline tenderness, localized pain, distracting injuries, neurologic defects, visible evidence of trauma, or altered levels of consciousness may benefit from radiographic evaluation. The initial x-ray series should include at least an anterior-posterior (AP) and lateral views of the cervical spine. If the patient is cooperative and stable, then an open mouth odontoid view should be obtained (Figure 20.2.4). Flexion–extension views may be obtained to identify ligamentous injuries in awake, alert, and cooperative patients. However, they are rarely indicated in the acute trauma setting and are typically ordered at follow-up visits [11]. If a concurrent thoracolumbar injury is suspected then AP and lateral x-rays of the thoracic and lumbar spine are recommended.

AP x-rays should always be evaluated for fracture and symmetry of pedicles. In the cervical spine, open mouth odontoid views should be reviewed for fracture and status of closure of synchondrosis. Lateral C-spine x-rays should be systematically reviewed for symmetry of the anterior and posterior aspect of the vertebral bodies, symmetry of interspinous distance, congruity of spinolaminar (Swischuck's) line, atlanto-dens interval (ADI), and space available for cord (SAC) (Figures 20.2.5 and 20.2.6). Other normal findings on lateral x-rays include retropharyngeal space less than 6 mm at C3 and less than 14 mm at C6, and retrotracheal space of less than 14 mm. Vertebral wedging may be normal until age 7–8 years [5,6,11].

Pseudosubluxation is a normal radiographic finding in pediatric patients. It is defined as less than 3 mm of anterior displacement of a vertebral body on adjacent vertebrae. This subluxation most commonly occurs at C2–C3 or C3–C4 but should reduce on extension lateral x-rays.



(a)

(b)

(c)

Figure 20.2.4 C-spine trauma series in a 13-year-old male. **(a)** AP. **(b)** Lateral mouth view. **(c)** Open mouth view.

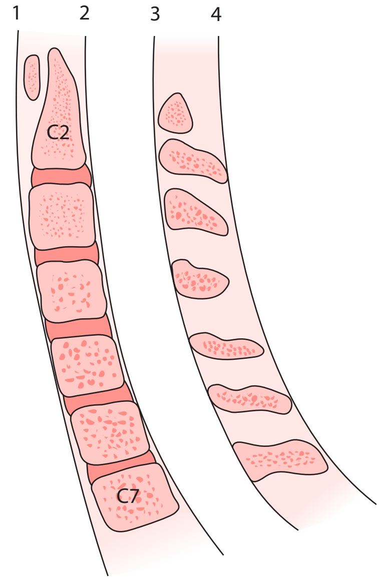


Figure 20.2.5 Normal linear relationships of the lateral cervical spine **(1)** Anterior vertebral bone line. (2) Posterior vertebral line. **(3)** Spinolaminar line. (4) Spinous processes. (Courtesy of Texas Children's Hospital, Houston, Texas.)

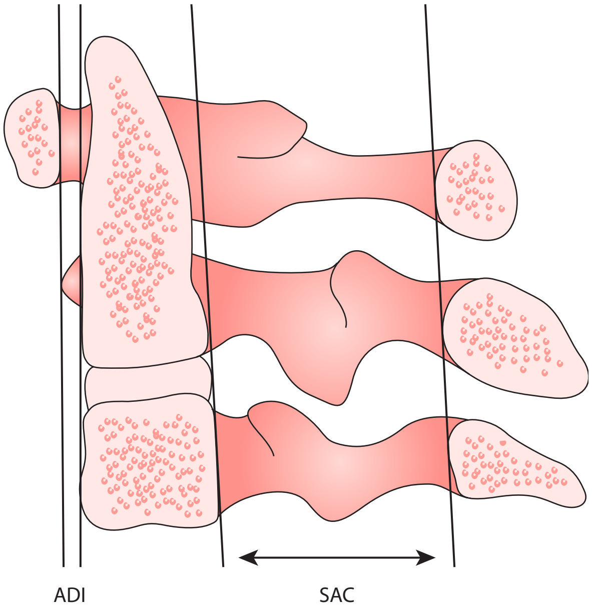


Figure 20.2.6 Upper cervical spine and occiput (C1–C3). ADI: Atlantodens interval; SAC: space available for the cord. Atlantoaxial instability should be suspected with an ADI >5 mm. If ADI ≥ 10–12 mm, cord compression occurs as a result of small SAC. (Courtesy of Texas Children's Hospital, Houston, Texas.)

Congruity of the posterior elements (Swischuk Line and less than 10 mm of spinous process widening) will confirm that the radiographic findings are representative of a pseudosubluxation and not a true subluxation [1,3–7,10].

Advanced imaging

The role of magnetic resonance imaging (MRI) and computed tomography (CT) scans in children is not clearly defined. CT scans are most commonly used for surgical planning and classification of fractures first identified on x-ray. MRI is utilized in the acute setting to rule out ligamentous or spinal cord injury when an injury is not clearly identified by x-ray [11,12].

Upper cervical spine injuries

Occipital condyle fractures are exceedingly rare fractures in children and typically result from a higher energy axial load injury or direct blow (Figure 20.2.7). Most commonly, these patients present with persistent neck pain and torticollis and normal x-rays. Often concomitant cranial nerve injuries (most commonly CN IX and XII) are present. In the setting of negative x-rays, advanced imaging will help identify the correct fracture pattern. Stable (type 1 and non-displaced type 2) injuries may be treated in a cervical orthosis. Displaced type 2 or type 3 fractures may require halo immobilization or occipitocervical arthrodesis [11,13].

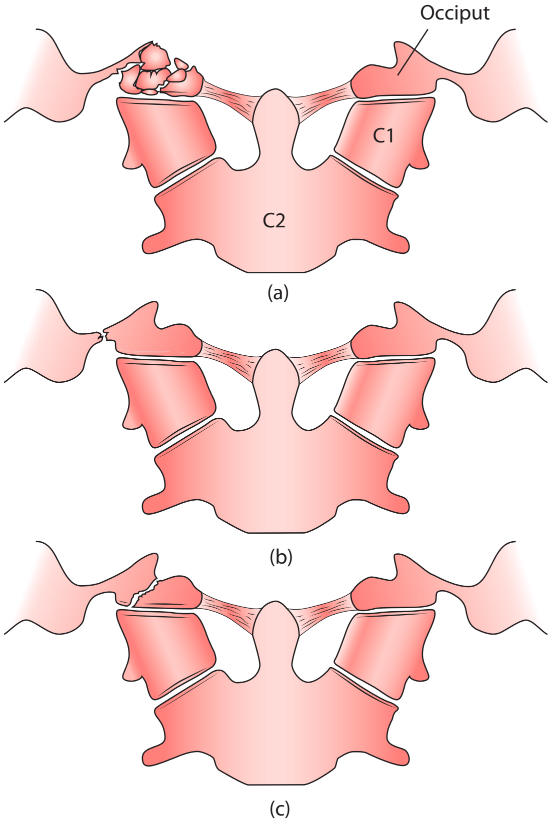


Figure 20.2.7 Illustrations of occipital condyle fracture patterns. **(a)** Type 1, comminuted impaction fracture. **(b)** Type 2, condyle fracture with associated basilar skull fracture. **(c)** Type 3, avulsion of the alar ligament attachment. (Courtesy of Texas Children's Hospital, Houston, Texas.)

Atlas (Jefferson) fractures are caused by an axial load injury and result in disruption of the stability of the C1 ring (Figure 20.2.8). Patients often present with history of axial compression or hyperextension injury and neck pain. The fracture can be identified on AP x-ray or axial CT imaging. Stable injuries (<7 mm of lateral mass widening) may be treated in rigid cervical orthosis or halo [1,12,13]. Unstable injuries may require halo brace or occiput to C1 or C2 fusion [11,14].

Axis (odontoid) fractures are one of the most common pediatric spine fractures. They result from a sudden deceleration force like those encountered in a motor vehicle or sports injury. Patients often present with a history of head trauma (both high and low energy) with cervical pain. Fractures of the dens can be classified by open mouth odontoid x-rays or coronal CT scans (Figure 20.2.9). Odontoid fractures are inherently stable due to an intact periosteal sleeve. Treatment includes immobilization in a halo or minerva brace for 3 months [4,15,16].

A hangman's fracture is a bilateral anterior subluxation of C2 on C3 (traumatic spondylolisthesis) from forced hyperextension most commonly from the weight of a disproportionately large head in children less than 2 years old. Treatment includes immobilization in a hard cervical orthosis, halo, or minerva cast (Figure 20.2.10) [4,17]

Atlantoaxial rotatory displacement (AARD) is a term that refers to a subluxation of the atlantoaxial articulation. The subluxation can be the result of trauma or more commonly infection such as upper respiratory tract infection (Grisel syndrome) or retropharyngeal abscesses. Inflammation

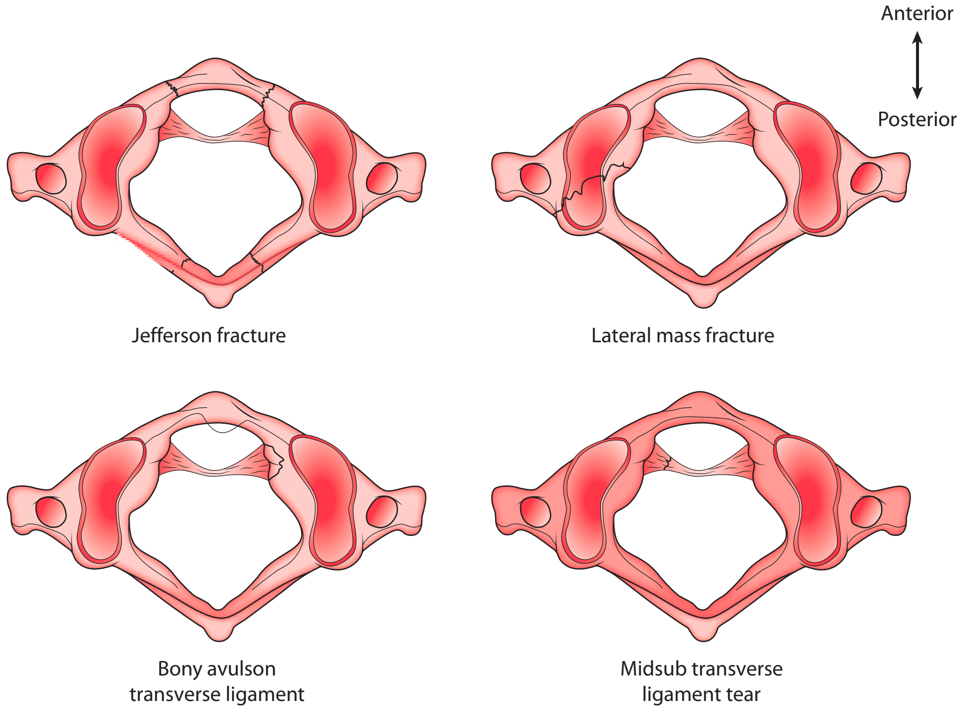


Figure 20.2.8 Atlas fractures. (Courtesy of Texas Children's Hospital, Houston, Texas.)

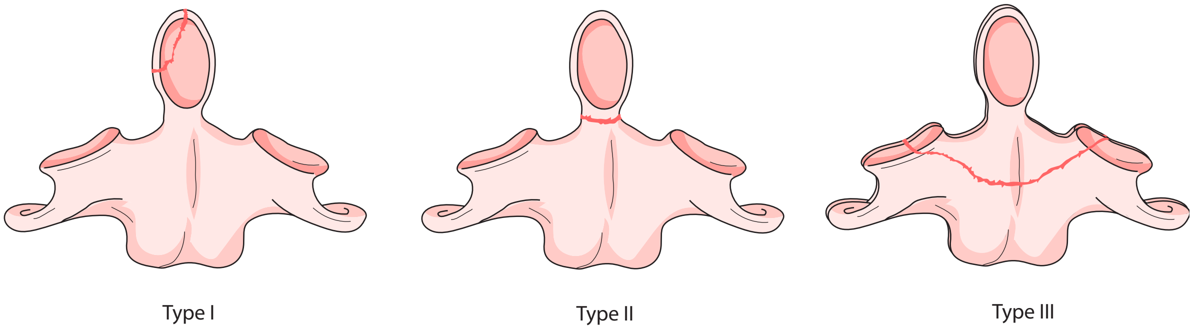


Figure 20.2.9 Axis fractures, types I–III. (Courtesy of Texas Children's Hospital, Houston, Texas.)

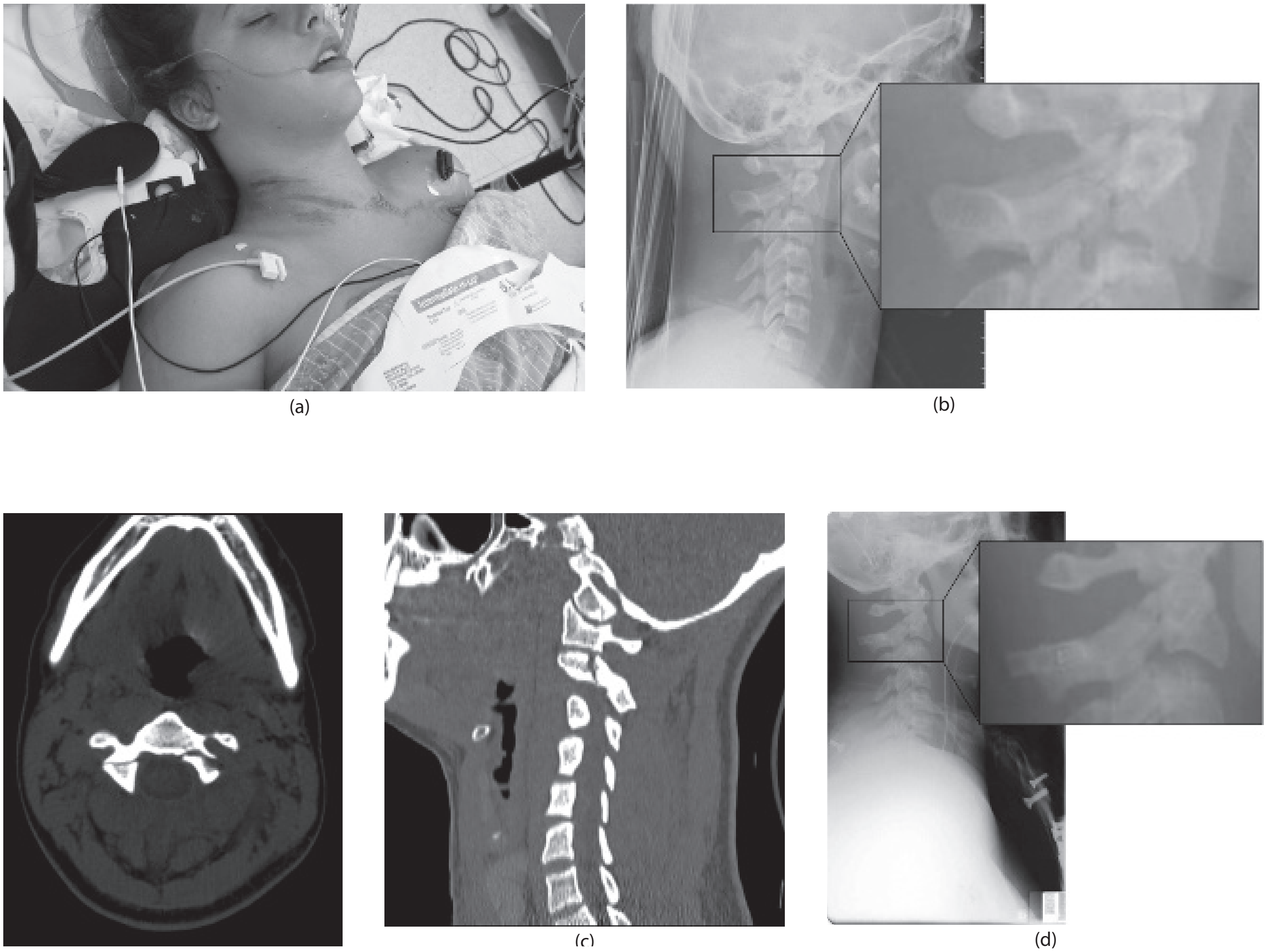

(a) (b) (c) (d)

Figure 20.2.10 Example of a patient with a hangman's fracture. **(a)** Clinical image. **(b)** Injury x-rays. **(c)** Injury CT scan. **(d)** X-ray after closed reduction and halo application. (Courtesy of Dr. John P. Dormans, Texas Children's Hospital.)

from tonsillectomy or pharyngoplasty may also result in subluxation. Patients often present with symptoms of neck pain, headache, and rotation of the head due to strong spasm of the sternocleidomastoid muscle (Figure 20.2.11). Asymmetry of the lateral masses can be appreciated on open mouth odontoid x-rays, and coronal and axial CT images and are classified based on the amount of angulation and displacement. Treatment depends on the underlying cause of the AARD and duration of symptoms. Acute cases can often be successfully treated with a cervical collar, while long standing cases may require surgery [18–20].

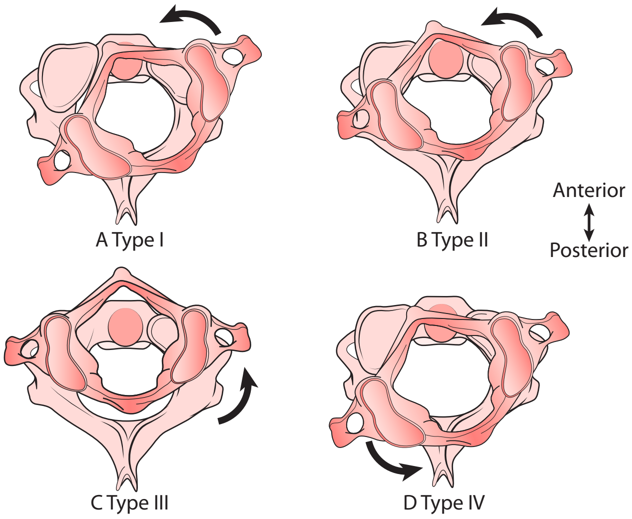


Figure 20.2.11 Atlantoaxial rotatory displacement classification, types I–IV. (Courtesy of Texas Children's Hospital, Houston, Texas.)

Subaxial cervical spine injuries

Subaxial cervical spine fractures are more common among older children and teenagers. The age of the patient, mechanism of injury, presence of neurologic injury, and stability of the resultant fracture are the main principles that guide management. The soft metaphyseal-like bone between the cartilaginous endplates and vertebral body is a common site for fracture and is unique to the growing spine. As in the adult spine, the most commonly injured segments are at C5–C7 [5,21].

Compression fractures occur after an axial compression and flexion loading high-energy trauma. Lateral x-rays will reveal loss of height in the anterior 2/3 of the vertebral body with preservation of the posterior wall. AP x-rays should be inspected for symmetry and congruity of the pedicles. A CT scan will confirm integrity of the posterior wall. Compression fractures may be treated in a rigid cervical collar [5,22,23] (Figure 20.2.12).

Burst fractures occur in older children most commonly after an axial load injury from high-energy trauma. Lateral x-rays will reveal loss of height of the entire vertebral body with or without retropulsion of body into the canal. AP x-rays will identify asymmetry of the pedicles and widening of the interpedicular distance relative to the vertebral levels above and below the injury. Lateral CT reconstructions can help characterize retropulsion of the fragments and identify canal compromise in greater detail. Neurologic injury may occur with spinal cord impingement from retropulsed fragments. Treatment depends on the stability of fracture and amount of canal compromise. Stable fractures without canal comprise may be treated with halo traction [1]. Unstable fractures may require anterior arthrodesis [5,22,23].

Unilateral and bilateral facet dislocations of the subaxial spine are more common injuries among older children and adolescents resulting from a high-energy flexion-distraction force. Perching or asymmetry of facets on AP x-ray, lateral x-ray, or CT imaging from the adjacent level facet joints are diagnostic of a subluxated or dislocated facet joint (Figure 20.2.13). Neurologic injury may suggest an entrapped disc and may need to be evaluated by MRI. Unilateral subluxations are more stable and, in an awake and alert patient, may be closed reduced by an experienced

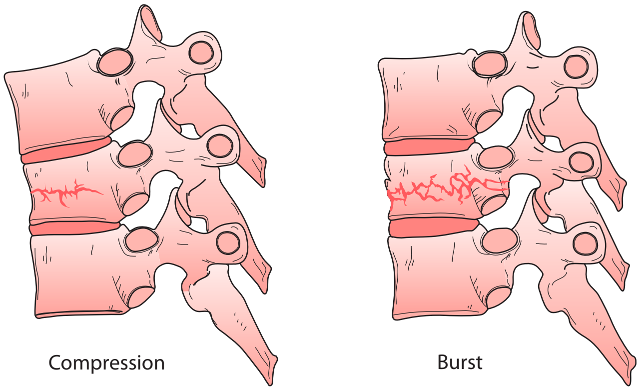


Figure 20.2.12 Illustration of compression versus burst fracture. In a compression fracture, the anterior body is shortened while the posterior column remains at full height versus in a burst fracture, the entire body loses height. (Courtesy of Texas Children's Hospital, Houston, Texas.)

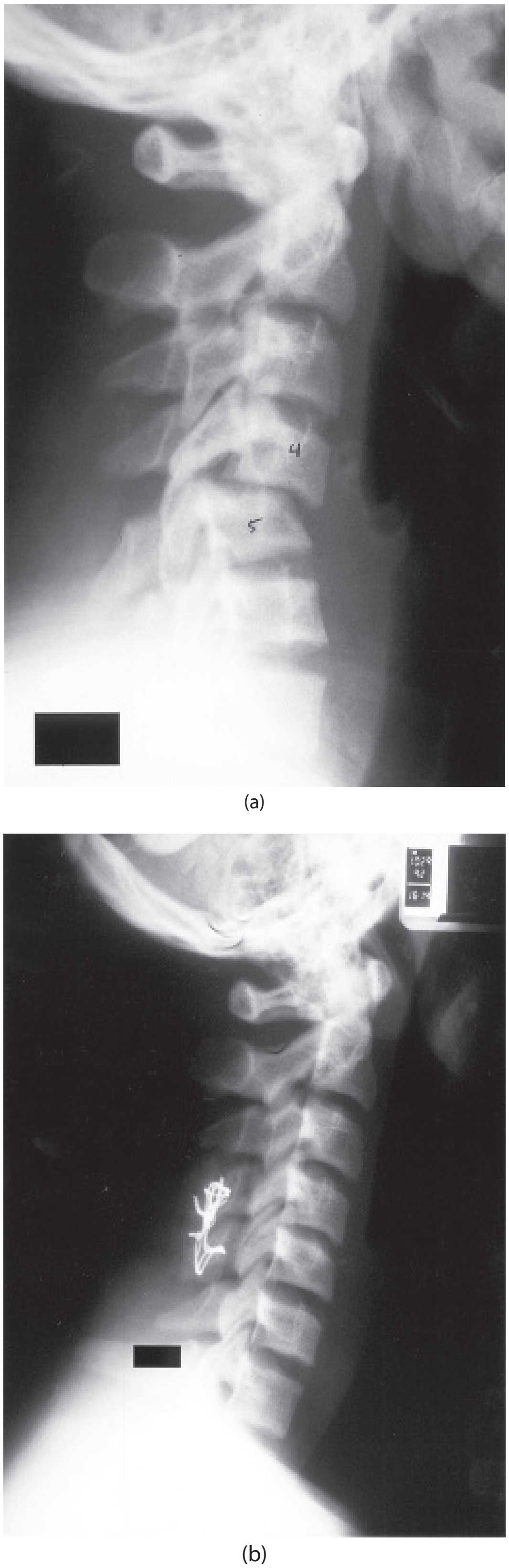


Figure 20.2.13 Clinical example of C4–C5 fracture dislocation. **(a)** Injury x-ray. **(b)** X-ray after reduction and posterior fusion. (Courtesy of Dr. John P. Dormans, Texas Children's Hospital.)

spine surgeon. Bilateral dislocations are inherently unstable and prone to neurologic injury. A closed reduction should only be attempted in an awake and alert patient by an experienced spine surgeon. Prereduction MRI may be necessary to rule out an entrapped disc in the obtunded patient. Often subluxations and dislocations cannot be closed reduced and require an open reduction with posterior arthrodesis [5,22–24].

Thoracolumbar spine injuries

Compression fractures and burst fractures are similar to those in the subaxial cervical spine. In the thoracic spine, compression fractures are inherently stable and can largely be treated with bracing. Fractures of the lumbar spine do not have the stability of the surrounding rib cage and are prone to more instability [7]. Treatment of burst fractures depends on their stability. Fractures without kyphotic wedging or neurologic injury, minimal loss of vertebral height, and intact posterior elements are deemed stable [7,25]. Stable fractures may be treated with an extension cast or thoracic lumbar sacral orthosis [7,25,26]. Unstable fractures may require arthrodesis.

Chance fractures result from a flexion-distraction injury pattern, often from a seat belt injury. If there is a seat belt mark on the abdomen, there needs to be a high level of suspicion for associated with intra-abdominal injuries (Figure 20.2.14). These injuries may be challenging to inexperienced practitioners as the force may be transmitted through the posterior joint capsule and ligaments or through the bony vertebral elements. Bony fractures have a higher union rate and may be treated in a hyperextension cast (<10 years old) or orthosis in older children. The higher degree of ligamentous involvement requires arthrodesis of the unstable spinal segment [7,27].

A limbus fracture is a fracture through the hypertrophic zone separating the vertebral apophysis from the spongiosa layer of the vertebral body (Figure 20.2.15). Similar to a disc herniation in an adult, the apophysis herniates into the canal or neural foramen. Patients present with radicular back pain and numbness or weakness of the lower legs. These fractures are often missed on x-ray and are better characterized by MRI to determine the location and size of the herniation. Surgical decompression is limited to those patients with neurologic compromise. Nonsteroidal anti-inflammatory drugs (NSAIDs) and immobilization in a thoracolumbosacral orthosis (TLSO) brace are used to treat limbus fractures without neurologic injury [7,28].

Spinous and transverse process fractures are usually the result of blunt trauma and in rare cases may be associated with visceral injury. Lower lumbar spinous process fractures may occur in association with pelvic injuries and may require a detailed trauma evaluation. Fractures that occur in isolation are stable and should be treated with pain control and activity as tolerated [7].

Figure 20.2.14 Chance fracture. Flexion distraction injury through L2.

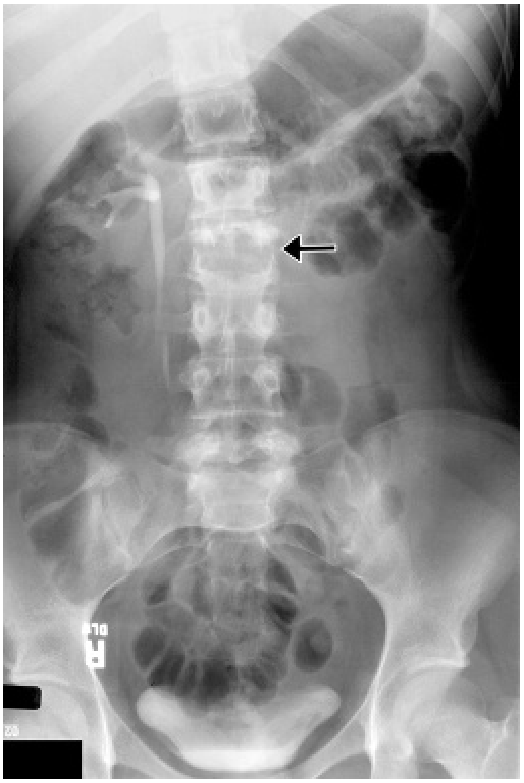


Figure 20.2.15 Chance fracture. On this anteroposterior view, note the disruption of the pedicles of L2 and the widening of the interspinous distance between L2 and L3.

Spinal cord injury without radiographic abnormality (SCIWORA)

Spinal cord injury without radiographic abnormalities (SCIWORA) is defined as an injury resulting in a neurologic deficit with normal radiographs or CT scan and is unique to children. It is attributed to a flexion or distraction injury through the vertebral disc space. MRI evaluation will reveal hemorrhage and edema within the cord (Figure 20.2.16). The incidence ranges from 5% to 67% and is most common in children less than 8 years old. Patients may initially present with transient paresthesias or subjective paralysis and should be immediately immobilized to prevent progression of their injury or deterioration of their neurologic function. In patients with an abnormal neurologic exam, but normal radiographs and CT scan, an MRI should be obtained to evaluate for SCIWORA [7,29] (Figure 20.2.17).

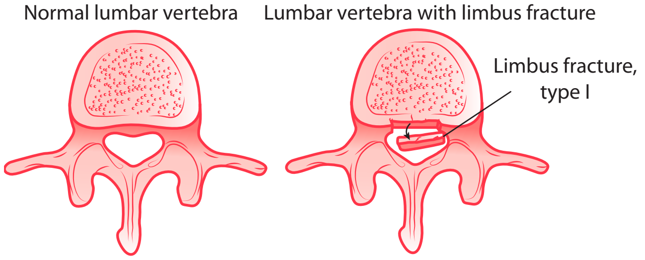


Figure 20.2.16 Type I limbus fracture. (Courtesy of Texas Children's Hospital, Houston, Texas.)

Figure 20.2.17 MRI example of spinal cord injury without radiographic abnormality (SCIWORA). (Courtesy of Dr. John P. Dormans, Texas Children's Hospital.)

Pediatric pelvic fractures

General considerations

The pelvic ring is formed from the fusion of three major ossification centers: the ilium, ischium, and pubis (Figure 20.2.18). By the age of 7 years, the pubis and ischium fuse to form the inferior pubic rami. Between the age of 13 and 16 years, the three ossification centers fuse through the triradiate cartilage. Secondary ossification centers exist at the iliac crest, ischial apophysis, anterior inferior iliac spine, pubic tubercle, ischial spine, and lateral wing of the sacrum. The time to closure varies, but ranges from 13 to 25 years on average. Muscular attachments at each site are prone to avulsion fractures due to weak cartilaginous attachment to underlying bone [30,31] (Figure 20.2.19).

Pediatric bone has a high modulus of elasticity and resists deformation more than the surrounding cartilage [32]. Therefore pelvic fractures are a marker for high-energy trauma and should prompt clinicians to look for intra-abdominal, genitourinary, thoracic, and head injuries [30–32]. Evaluation of pelvic ring fractures should start with an evaluation of the patient's airway, circulation, and breathing. A neurologic exam should be documented on arrival and should assess for muscle strength, weakness, proprioception, and reflexes. The exam should be repeated and documented once the child becomes more cooperative. A careful genitourinary exam should be performed to evaluate for bladder and urethral injuries.

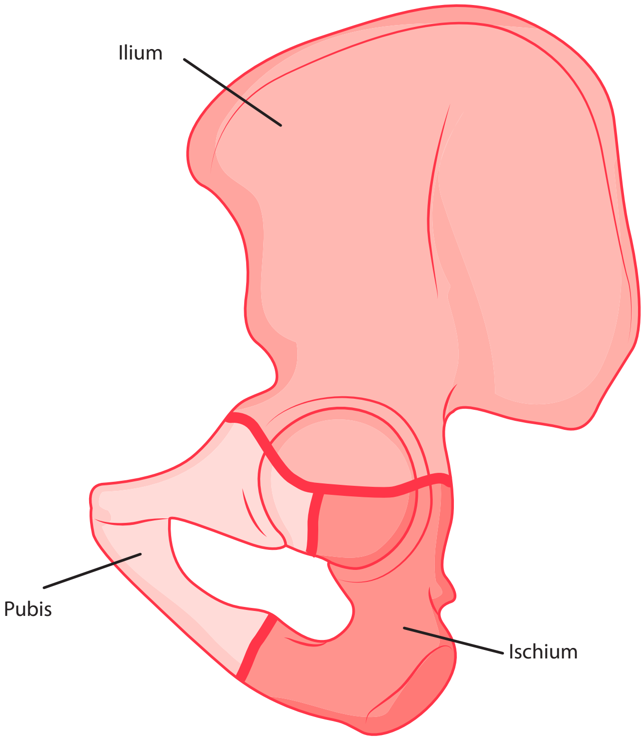


Figure 20.2.18 Immature pelvis with ossification centers. (Courtesy of Texas Children's Hospital, Houston, Texas.)

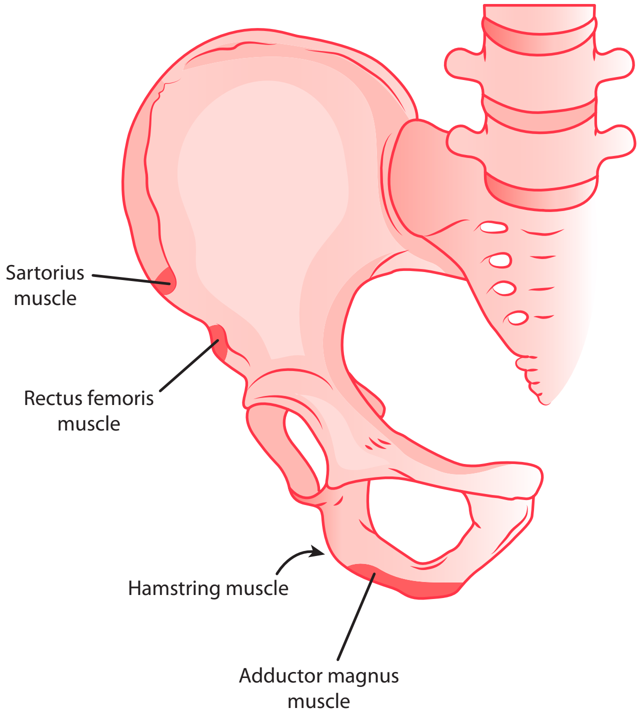


Figure 20.2.19 Illustration of major muscular attachments to bony pelvis. (Courtesy of Texas Children's Hospital, Houston, Texas.)

Children with pelvic fractures should also be evaluated for rectal and vaginal lacerations.

Exsanguination associated with pediatric high-energy pelvic fractures is rare compared to adults [33]. This may be secondary to the vasoconstrictive response in younger nonatherosclerotic blood vessels [34]. In 90% of patients with unstable fracture patterns with persistent hypotension despite adequate resuscitation, bleeding is venous and not helped by arteriography. In these injuries, a pelvic binder used to reduce pelvic volume may tamponade bleeding and eliminate or delay the need for surgery [35].

Imaging

Plain radiographs are the best initial assessment of pelvic fractures. Standard views include AP and frog lateral views of the pelvis that include the bilateral hips. Single hip x-rays are not useful in acute trauma as the uninjured contralateral side may be used for comparison. Displacement of fractures can be further defined using inlet and outlet views. Judet views are used to identify fracture of the acetabulum [30–32].

CT scans assist in the classification of fractures and injury pattern. A CT scan may be particularly helpful when assessing the displacement of fractures and congruity of sacroiliac joint, sacrum, or acetabulum. MRI has limited use in the acute pelvic fracture setting.

Specific pelvic injuries

Stable pelvic fracture patterns

In general, because of the higher modulus of elasticity of the pediatric pelvis, the incidence of ligamentous injury is more common than fractures [21–23,36].

Diastasis of the pubic symphysis or sacroiliac joints is more common in children with open triradiate cartilage (Figure 20.2.20). However, although rare, neurologic

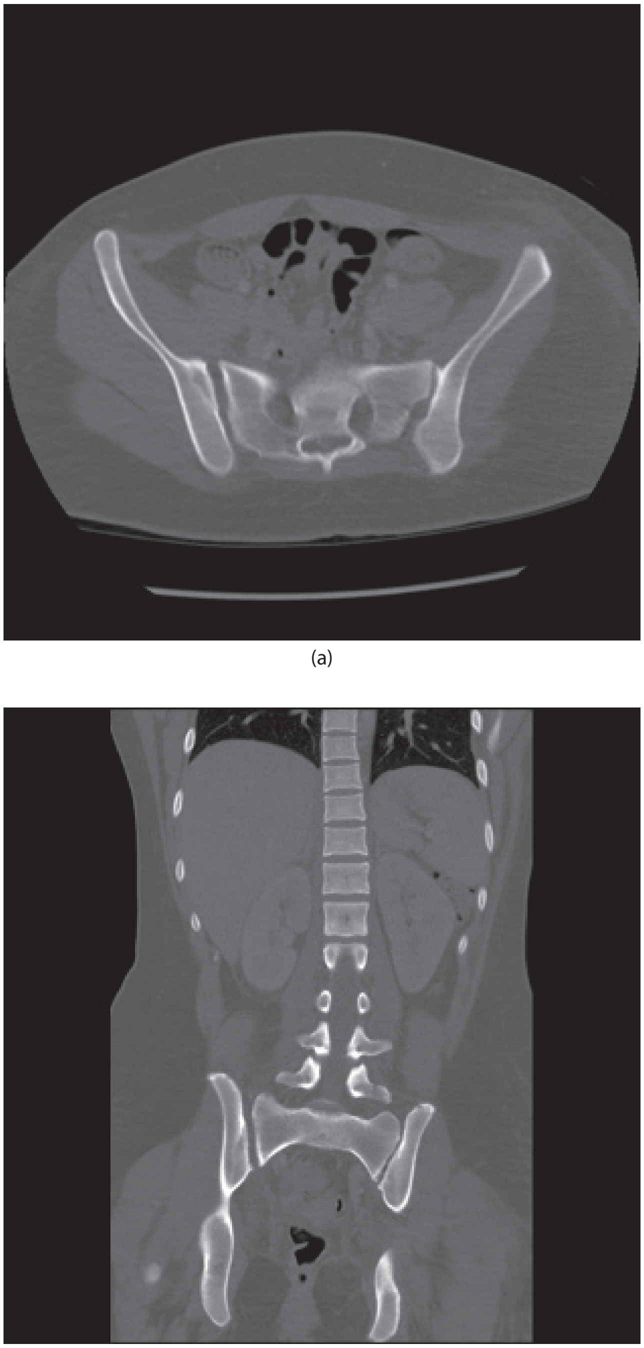

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Figure 20.2.20 CT scan of a 15-year-old status post a motor vehicle collision with right sacroiliac joint widening. **(a)** axial image. **(b)** coronal image.

injury must be ruled out with particular attention to the L5 and S1 distributions. These fractures can be evaluated by inlet and outlet x-rays and CT scan for asymmetry. Treatment is typically protected weight bearing with crutches [32].

Avulsion fractures are the result of forceful concentric or eccentric contractions of attached muscles, most commonly in adolescent athletes. The most common sites and associated avulsed muscles include anterior superior iliac spine—sartorius, anterior inferior iliac spine—direct head of rectus femorus, and ischial tuberosity—hamstring/adductors (Figure 20.2.21). AP and frog lateral x-rays of the pelvis are diagnostic. Treatment includes protective weight bearing with crutches for minimally displaced (<2 cm) avulsion fractures [32]. Although controversial, indications for surgical treatment include acute fractures displaced more than 2 cm, persistently symptomatic, or chronically painful fractures [37].

Figure 20.2.21 X-ray of a 15-year-old boy who sustained a left anterior superior iliac spine avulsion fracture while playing basketball.

Isolated pubic rami or iliac wing (Duverney) fractures are associated with high-energy mechanisms and should prompt a thorough evaluation for other pelvic and visceral injuries (Figure 20.2.22). AP and frog lateral x-rays should be obtained during initial evaluation. A CT scan can be used to rule out concomitant ring injuries. Isolated fractures may be treated with progressive weight bearing with crutches as tolerated and pain control [32].

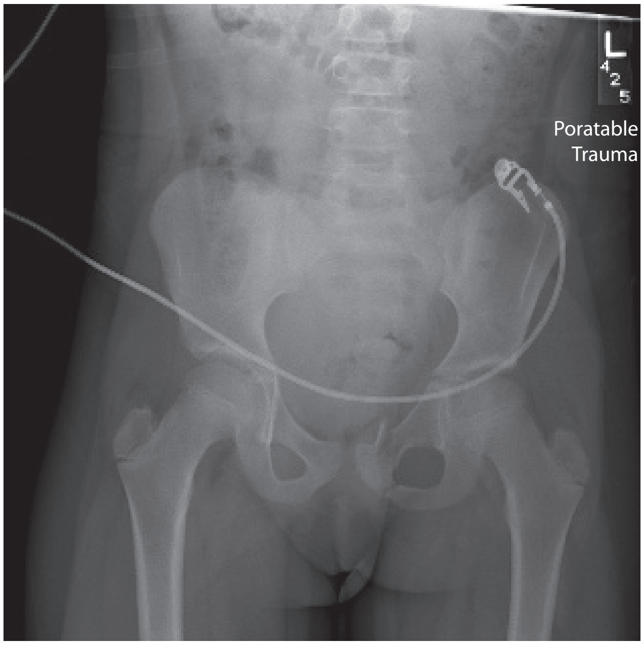

Figure 20.2.22 X-ray of an 8-year-old girl with left superior and inferior pubic rami fractures sustained in a motor vehicle collision.

Unstable pelvic fractures

Unstable pelvis fractures are characterized by a break of the pelvic ring in two or more places [30–32].

Bilateral superior and inferior pubic rami (straddle) fractures result in a complete disruption of the anterior ring and can be associated with urethral or bladder injury. Inlet and outlet x-rays demonstrate superior displacement of the floating segment. Treatment is bed rest in a supine position with the hips flexed (semi-Fowler position) to relax the abdominal muscles and reduce the floating segment [30].

Disruption of the anterior and posterior ring occurs when there is a fracture through the bony pelvis, sacroiliac joints, or the pubic symphysis that results in displacement of the hemipelvis (Figure 20.2.23). Evaluation should include assessment of leg length discrepancy and neurologic status. Inlet and outlet x-rays and CT scan demonstrate the fracture pattern and pelvic displacement. Hemorrhage, intra-abdominal, or retroperitoneal injuries are uncommon but can occur. In rare cases operative stabilization with an external fixator or internal fixation may be necessary [30,32].

Acetabular fractures are rare in children but occur as result of a high-energy force transmitted through the femoral head into the pelvis. Fractures should be evaluated with pelvic x-rays including Judet views and a CT scan. Stable acetabular fractures are small (<1 mm of displacement) and do not extend to the weight-bearing portion of the pelvis (Figure 20.2.24). Stable fractures can be treated with restricted weight bearing and crutch ambulation [32]. Unstable fractures are larger (>2 mm displacement) and are usually associated with subluxation or dislocation of the hip. Unstable fractures should be placed in temporary external traction and evaluated for definitive fixation [31].

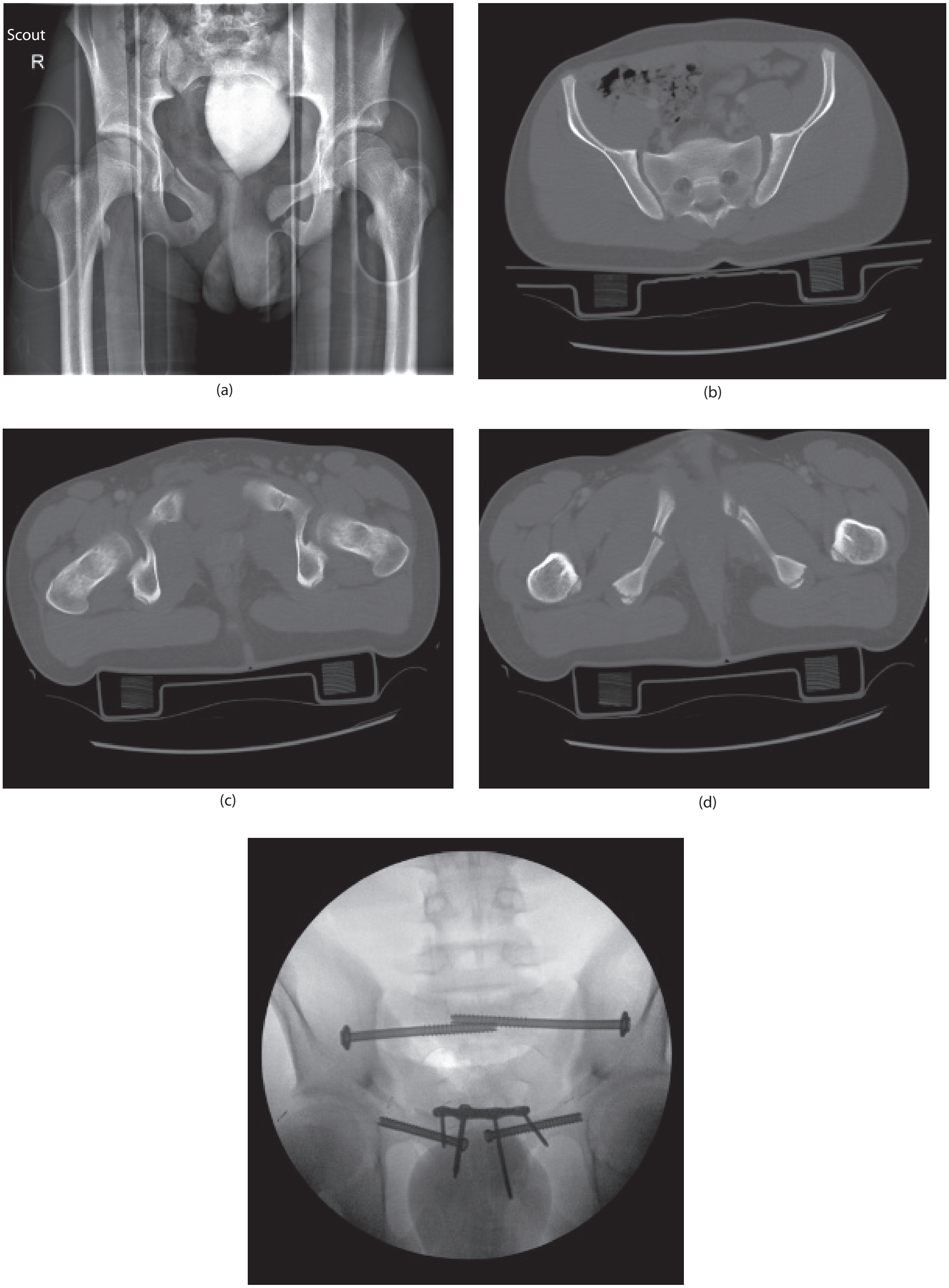

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Figure 20.2.23 A 13-year-old male who sustained an unstable pelvic fracture after falling off a play structure from 30 ft. **(a)** Injury pelvic x-ray. **(b–d)**. Injury CT scans demonstrating anterior and posterior pelvic widening. **(e)** Postreduction and fixation x-ray.

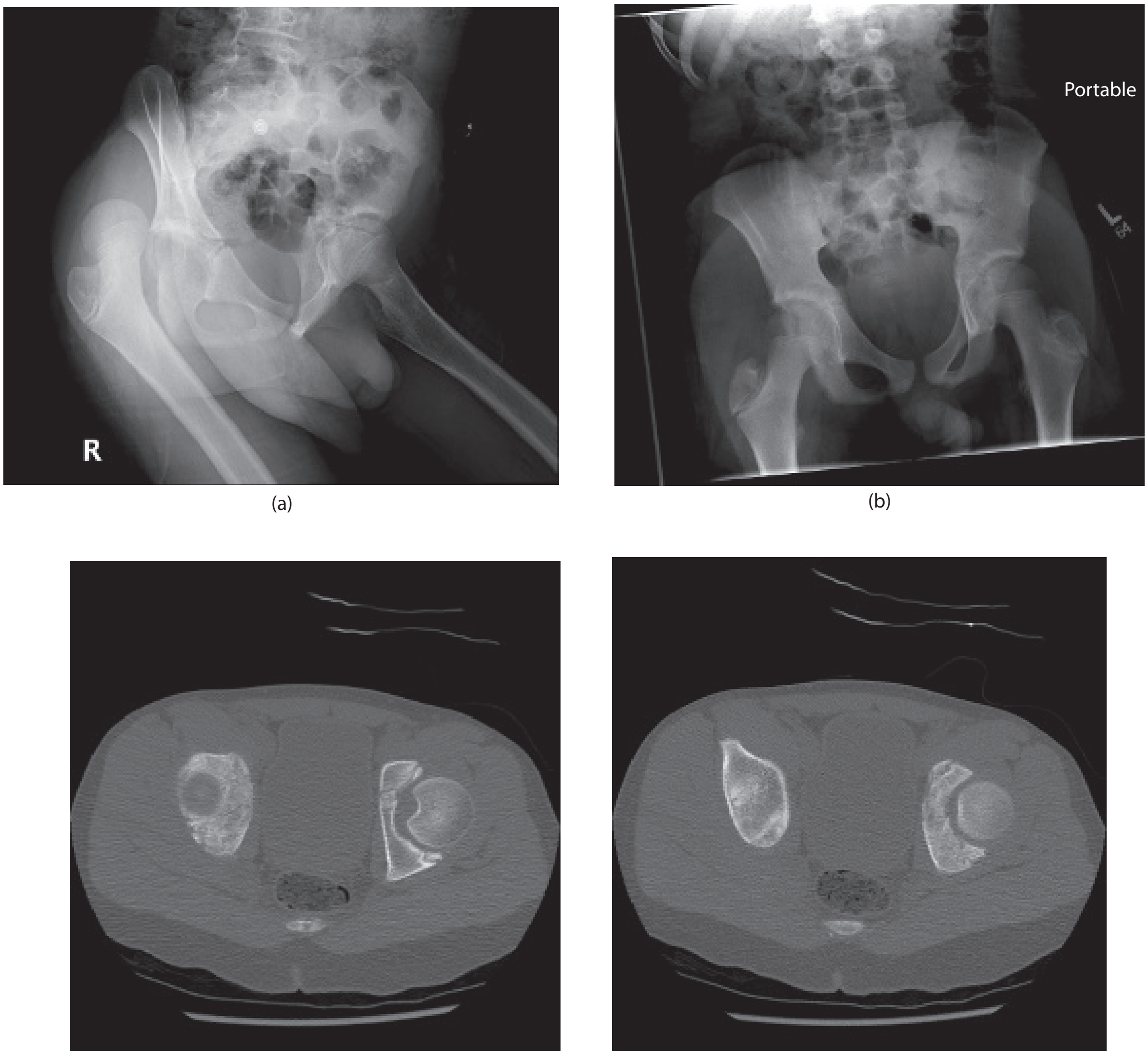

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Figure 20.2.24 A 13-year-old male who sustained a right dislocated hip associated with a posterior wall acetabular fracture. Hip was reduced in the emergency department. On stress testing in the operating room, the hip was found to be stable, so no operative intervention was indicated for the fracture. **(a)** Initial pelvic x-ray showing right hip dislocation. **(b)** Pelvic x-ray after hip reduction. **(c** and **d)** Pelvic CT demonstrating small posterior wall acetabular fracture (<25%).

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20.3

Pediatric Orthopedic Trauma: Upper Extremity Fractures

VINITHA R. SHENAVA and MEGAN M. MAY

Introduction

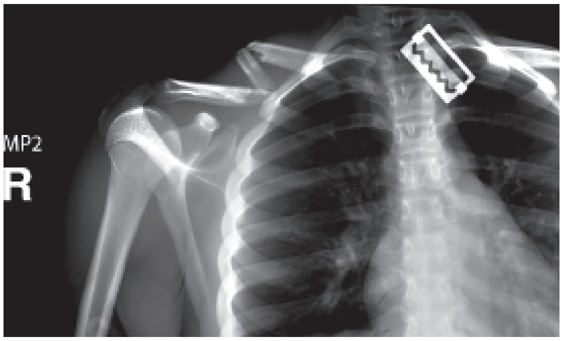
Injuries in the skeletally immature patient represent a major public health challenge as this impacts both the patient and the patient's family. The incidence of pediatric trauma in the United States appears to be increasing. The most common causes of musculoskeletal injury are sports or recreational activities, motor vehicle accidents, nonaccidental injuries (abuse), and occasionally gunshot and firearm injuries. Sports and recreational injuries contribute the most to musculoskeletal trauma and the incidence of these injuries is increasing due to greater youth participation. Younger children are becoming involved in organized athletic activities and are participating in these activities year round. In addition, recreational activities such as skateboarding and bicycling have changed to more extreme activities with higher speeds and stunts [1].

Clavicle

The clavicle is an S-shaped bone that articulates with the sternum medially and the scapula at the acromion process laterally. Clavicle fractures are the most frequent childhood fracture [2]. Eighty-five percent of these fractures occur in the shaft. The majority can be treated with a sling for 2–3 weeks. Clavicle fractures due to high-energy trauma may result in more comminuted fractures and fractures with greater displacement (Figure 20.3.1a). This could pose potential injury to surrounding structures such as the brachial plexus, neighboring vessels, or apex of the lung. In the rare circumstance of an open fracture or an impending open fracture with tenting of the skin it is reasonable to perform an open reduction and internal fixation of the fracture (Figure 20.3.1b).

Distal clavicle fractures account for 10% of clavicle fractures [3]. As the distal clavicle epiphysis does not ossify until the teenage years this can be mistaken for an acromioclavicular (AC) joint injury. However, because the periosteal sleeve surrounding the distal clavicle is so thick this injury can usually be treated with a sling.

Medial clavicular fractures and pseudo-sternoclavicular joint dislocations account for 5% of clavicle fractures [4]. This is usually the result of a direct blow. With anterior displacement there is usually an obvious prominence in the area. Posterior displacement can be associated with respiratory distress, dysphagia, dysphonia, or distended neck veins from compression of the trachea, esophagus, recurrent



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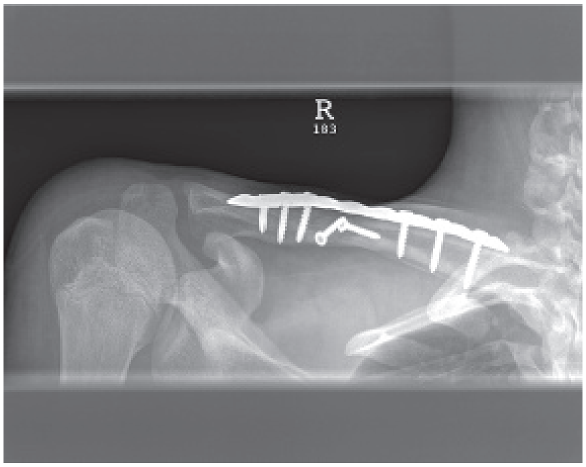

(b)

Figure 20.3.1 **(a)** AP chest x-ray reveals a comminuted open clavicle fracture in a 15-year-old trauma patient. **(b)** This patient was treated with surgery due to the severe displacement and large segmental fragment.

laryngeal nerve, or great vessels. CT scan is the most useful imaging modality. Anteriorly displaced fractures are usually managed with a sling. Posteriorly displaced fractures resulting in respiratory distress can be life-threatening and require operative treatment with a thoracic or cardiac surgeon available for potential assistance.

AC joint injury

A true injury to the AC joint is rare in children as the clavicle is the last bone to ossify. This typically results from a blow or a fall on the point of the shoulder. Treatment is a sling for 2–3 weeks. Operative treatment is considered in AC injuries associated with scapulothoracic dislocation, injuries in which the clavicle becomes subcutaneous and has buttonholed through the trapezius or open fractures.

Scapular body fractures

Fractures of the scapula are rare and occur as a result of high-energy trauma. Due to surrounding musculature, clinical deformity is rarely evident. X-rays and CT are useful in determining the extent of injury. There is often significant injury to the underlying chest. Once the patient is stable this fracture can be treated with a sling for 2–3 weeks.

Scapulothoracic dislocation

This is an extremely rare injury and has been reported in two children—one aged 8 and another 11 years old [5]. This can be diagnosed on an AP chest x-ray in which asymmetry of the shoulder girdle will be noted with the affected side being laterally displaced. This injury is also associated with injury to the brachial plexus, vascular structures, and chest wall. Operative treatment involves repair of the detached suspensory muscles and stabilization of the scapula articulation with the clavicle.

Glenohumeral joint dislocation

The shoulder joint has the most freedom of movement compared to all other joints and this is what predisposes it to dislocation. In young children, a traumatic injury to the shoulder will more commonly result in a fracture involving the proximal humeral physis as this is the weakest link in the glenohumeral articulation. In adolescents, the physis begins to close and strengthen so glenohumeral dislocations occur. Dislocations are based on the direction of the humeral head relative to the glenoid. Eighty-five percent of shoulder dislocations are anterior (Figure 20.3.2a and b) and result from a force on the outstretched hand with the shoulder in abduction, external rotation, and elevation. Posterior dislocations are rare and are associated with seizures or electrocution, which result in overactivity of the internal rotators which lever the humeral head posteriorly [6]. Dislocations are treated by prompt reduction. Following reduction patients are treated with a sling for 3 weeks. Anterior should dislocations have a high risk for recurrence, so arthroscopic or open stabilization is often considered in adolescent athletes.

Proximal humerus fractures

The proximal humeral physis contributes 80% of the longitudinal growth of the humerus and thus fractures in this location have tremendous remodeling potential [7]. The majority of these are Salter–Harris (SH) I or II fractures (Figure 20.3.3). In children 12 years of age or less, the treatment of choice is a sling. For older children who have less growth remaining and thus ability to remodel the fracture, operative treatment with closed reduction, and percutaneous pinning or open reduction are considerations [8].

Humeral shaft fractures

Fractures of the humeral shaft account for 2%–5% of all fractures in children [9]. Direct trauma to the arm is the most common mechanism. Isolated closed humeral shaft

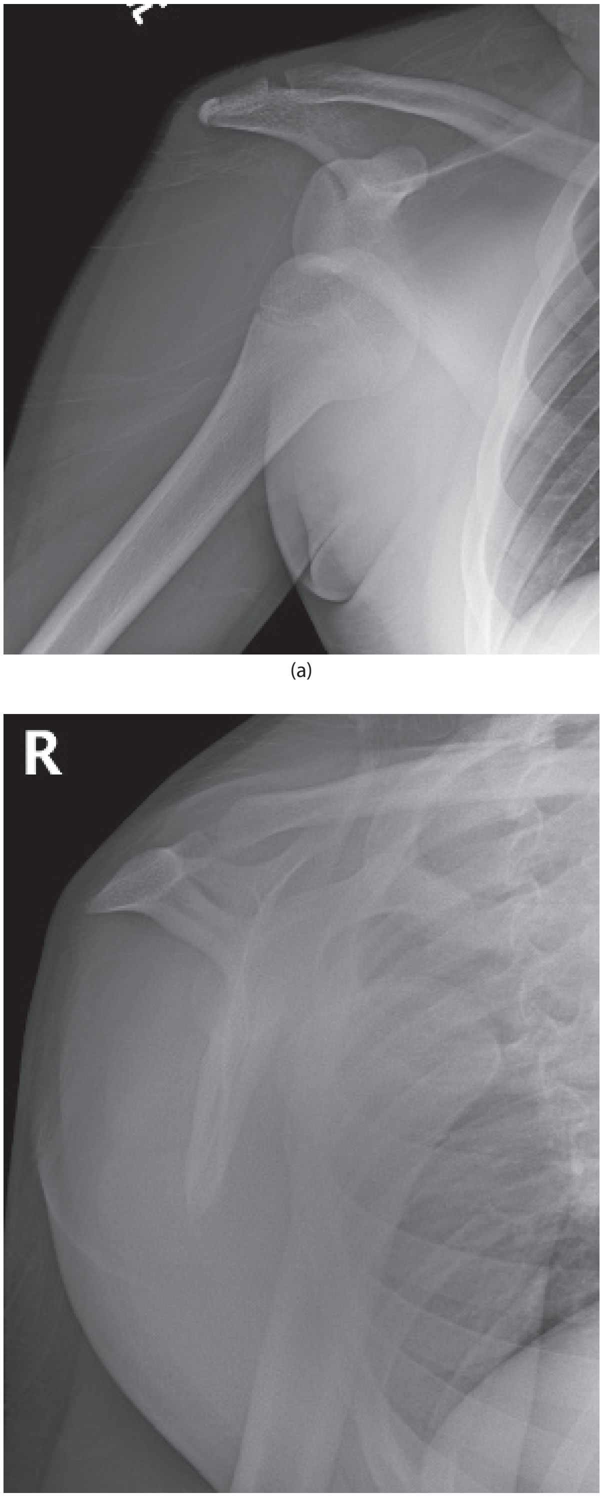

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Figure 20.3.2 **(a, b)** AP and scapular Y x-rays reveal an anterior shoulder dislocation in a 15-year-old male.

Figure 20.3.3 AP shoulder x-ray reveals an Salter-Harris II fracture with approximately 60° of varus angulation.

fractures are typically managed by a coaptation splint or a prefabricated splint. Rare indications for operative treatment are open fractures that require irrigation and debridement, fractures associated with a vascular injury, and polytrauma patients in which operative stabilization of the fracture allows easier nursing care of the patient, greater ease in mobilizing the patient, and early functional use of the extremity.

Humeral shaft fractures, specifically fractures in the distal third of the shaft, can have associated radial nerve injuries (Figure 20.3.4). These are typically traction injuries and should be observed for 4 months. However, if upon presentation, the radial nerve function is intact, but the function is lost after closed reduction, the nerve should be explored as it can be entrapped at the fracture site [10].

Fractures and dislocations about the elbow

Fractures about the elbow occur more often in the skeletally immature than they do in adults. The collateral circulation about the elbow is abundant and often times is sufficient to maintain adequate circulation to the forearm and hand even if the main blood supply from the brachial artery is interrupted. Due to the many ossification centers about the elbow, it is easy to misinterpret elbow radiographs and comparison x-rays can be useful to aide in the diagnosis of fracture. When evaluating radiographs of the elbow, subtle findings of fracture can be the appearance of the anterior and posterior fat pads (Figure 20.3.5a and b). When an elbow effusion is present, which can result from bleeding from a fracture, the fat pads become elevated from the distal humeral surface and can be seen on a lateral x-ray (Figure 20.3.5c) [11]. This may be the only evidence of an occult elbow injury until follow-up x-rays are obtained 10–14 days later when there is evidence of healing and callous formation.

Figure 20.3.4 AP x-ray reveals a transverse humerus fracture at the junction of the mid to distal 1/3 shaft. This patient sustained a radial nerve palsy that spontaneously recovered 2 months after the injury.

Supracondylar humerus fractures

The distal end of the humerus consists of strong medial and lateral columns but a central portion that is wafer thin. This thin central portion is produced by the olecranon fossa posteriorly and the coronoid fossa anteriorly. Supracondylar humerus fractures occur in this area and typically are seen in the first decade of life. They account for 30% of all limb fractures in children less than 7 years of age [12]. Supracondylar humerus fractures are the most common type of elbow fracture, accounting for 60% of fractures about the elbow in children [13]. There are two types of supracondylar humerus fractures depending on the mechanism of injury: extension and flexion type. The extension type fracture (Figure 20.3.6a and b) occurs in 96% of patients with a supracondylar humerus fracture and typically is the result of a fall on an outstretched hand. The flexion type (Figure 20.3.7) occurs in 4% of supracondylar humerus fractures and is a result of a fall onto the olecranon with the elbow flexed.

Nerve injury is reported to occur in approximately 15% of supracondylar humerus fractures and is associated with fractures with greater displacement. Reports vary according to which nerve is most commonly injured. Anterior injured. Anterior interosseus nerve, median nerve, and radial nerve injuries are associated with extension type fractures and ulnar nerve injuries are associated with flexion type fractures.

Permanent vascular injury is seen in less than 1% of supracondylar humerus fractures. The brachial artery is protected by the brachialis muscle but if the muscle is torn, the anterior spike of proximal fracture fragment can occlude flow.

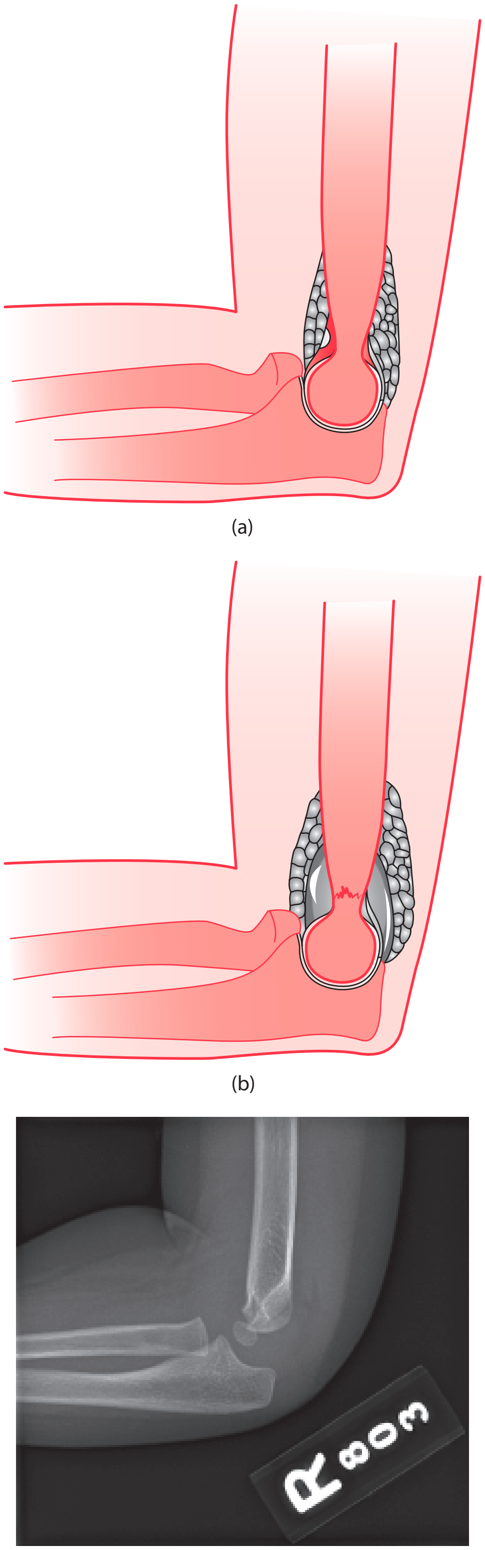
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Figure 20.3.5 **(a)** Normal elbow without trauma. **(b)** Elbow following trauma with resulting hemarthrosis. Hemarthrosis fills the elbow joint and displaces the fat pads which on x-ray will result in a soft tissue shadow. **(c)** Lateral elbow x-ray demonstrating a posterior fat pad sign indicative of hemarthrosis and thus fracture. (Courtesy of Texas Children's Hospital, Houston, Texas.)

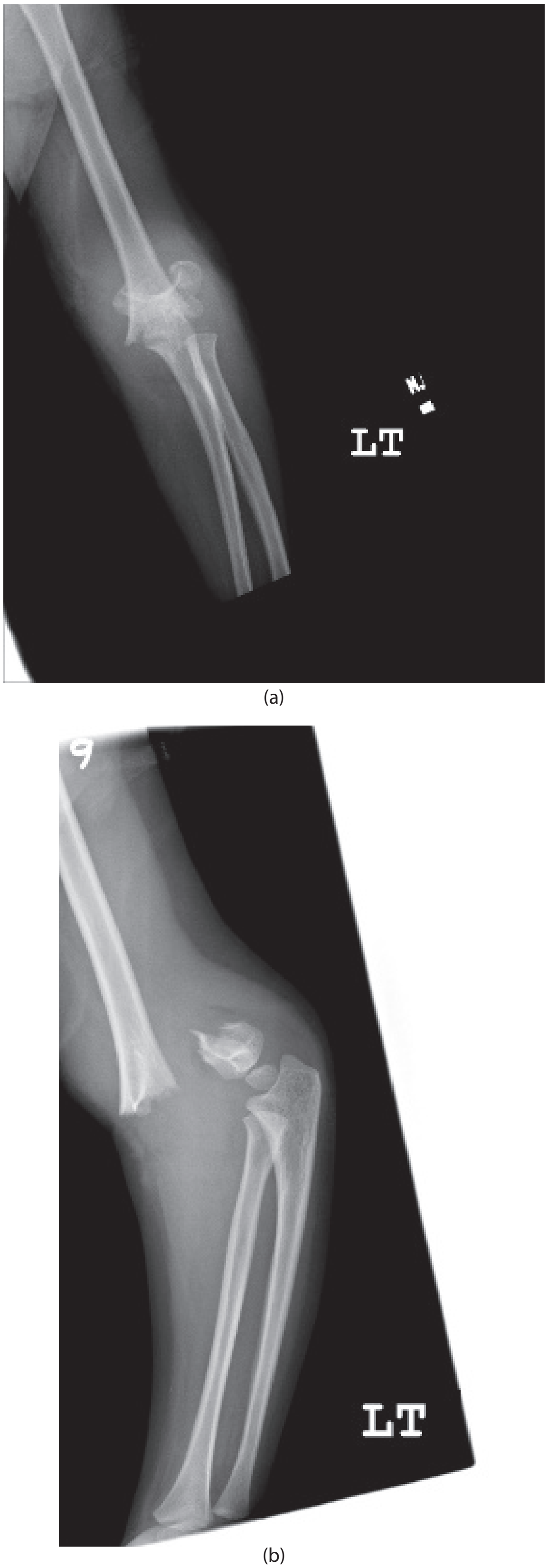


Figure 20.3.6 **(a)** AP elbow x-ray reveals supracondylar humerus fracture with overlapping fracture fragments. **(b)** Lateral elbow x-ray reveals the true displacement of this extension type supracondylar humerus fracture in a 4-year-old child who fell from the monkey bars.

Figure 20.3.7 Lateral elbow x-ray reveals a flexion type supracondylar humerus fracture in a 6-year-old male who fell directly on his elbow.

The artery can also rarely become entrapped within the fracture site upon reduction of the fracture. If this occurs, oftentimes the median nerve is also entrapped necessitating open reduction of the fracture with removal of the neurovascular structures from the fracture site. The management of supracondylar humerus fractures with an absent radial pulse is closed reduction after general anesthesia. If circulation returns the fracture is pinned, splinted, and observed. If following the reduction the limb is truly dysvascular then arterial exploration is indicated. If the hand is perfused but the radial pulse does not return, this is observed as this is typically the result of vasospasm and collateral flow to the arm is abundant.

The Gartland Classification system (Figure 20.3.8) is the most useful method of describing extension type supracondylar humerus fractures and is based on the amount of displacement of the two fragments [14]. A type I fracture is nondisplaced. A clear fracture line may or may not be visualized. Lateral x-rays will typically show evidence of a fat pad sign. The anterior humeral line which is a line drawn on the lateral x-ray down the thick anterior cortical bone of the distal humerus will pass through the central one-third of the capitellum. A type II fracture is angulated but the posterior cortex is intact and acts as a hinge. The anterior humeral line does not bisect the capitellum but may touch the anterior aspect. A type III supracondylar humerus fracture is completely displaced with disruption of the anterior and posterior cortices.

Treatment of type I fractures is a long arm cast for 3–4 weeks. Type II and III fractures are treated with closed reduction and percutaneous pinning or open reduction and pinning. Type III supracondylar humerus fractures are typically treated within 24 h to avoid complications such as compartment syndrome.

Occasionally a supracondylar humerus fracture may be associated with a fracture of the forearm. This injury

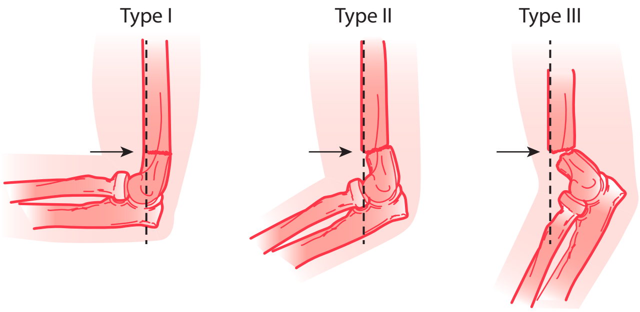


Figure 20.3.8 Gartland classification. Type I is a nondisplaced fracture with the anterior humeral line (dotted line) passing thru the capitellum. A type II is a minimally displaced fracture in which the posterior cortex is hinged and the anterior cortex is displaced. The anterior humeral line may touch the capitellum but will not pass through the center. A type III is a completely displaced fracture with disruption of both the anterior and posterior cortex. (Courtesy of Texas Children's Hospital, Houston, Texas.)

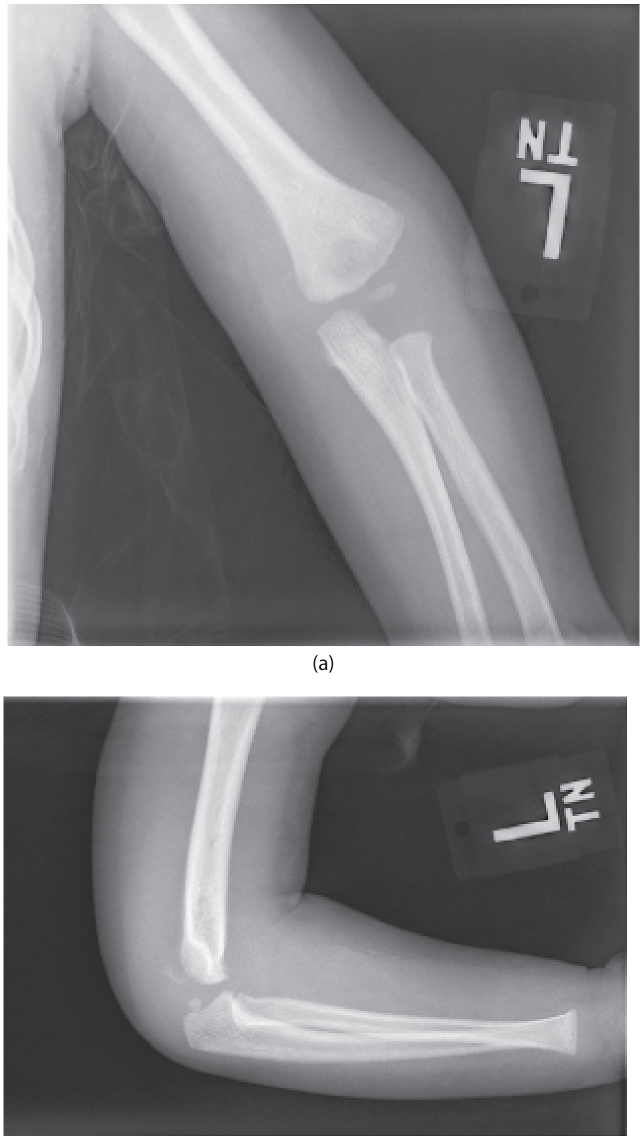
pattern is considered a floating elbow and frequently requires operative stabilization of both fractures.

Fracture separation of the distal humeral physis

This is a rare injury and the true incidence is unknown. This fracture can be difficult to diagnose as it is seen in very young children in whom much of the distal humerus has not ossified. The typical mechanism is either abuse or a fall from a height. The patient will present with diffuse swelling of the elbow and the elbow may even appear dislocated. X-rays may also be misinterpreted as a dislocation but upon careful evaluation the capitellum will be noted to be displaced with the proximal radius and ulna (Figure 20.3.9a and b). If the fracture is acute, treatment is typically with a closed reduction and pinning. However, if the fracture is subacute and shows evidence of healing, immobilization in a long arm cast is all that is required [15].

Lateral condyle fractures

This fracture is relatively common and occurs in 12%–16% of elbow fractures in children [16]. This is a fracture that begins in the distal lateral humeral metaphysis and exists into the distal humeral articular surface (Figure 20.3.10). Many classification systems have been described but treatment is based on the extent of displacement, particularly at the articular surface. Nondisplaced fractures (fractures with <2 mm of displacement) can be treated with a cast but require close follow-up to ensure that the fracture does not displace in the cast. Displaced fractures are treated with closed reduction and pinning with an arthrogram or open reduction and pinning in order to ensure the articular surface is well aligned.



(a)

(b)

Figure 20.3.9 **(a, b)** AP and lateral elbow x-rays of a 13-month-old infant reveal a transphyseal distal humerus fracture. Critical evaluation of the x-rays reveals the elbow is not dislocated as the distal humerus and radio-ulnar joint are well aligned; however, the capitellum (and unossified distal humerus) are displaced medial to the humerus.

Medial epicondyle fractures

Medial epicondyle fractures occur in about 10% of elbow fractures in children and are most commonly seen in children between the ages of 10 and 14 [17]. More than 75% of these occur in males [18].

The mechanism of injury is an avulsion of the medial epicondyle due to a valgus force in combination with a contraction of the forearm flexor muscles [19]. If the valgus force is severe, it will also result in an associated elbow dislocation [18]. Treatment is based on displacement. Fractures

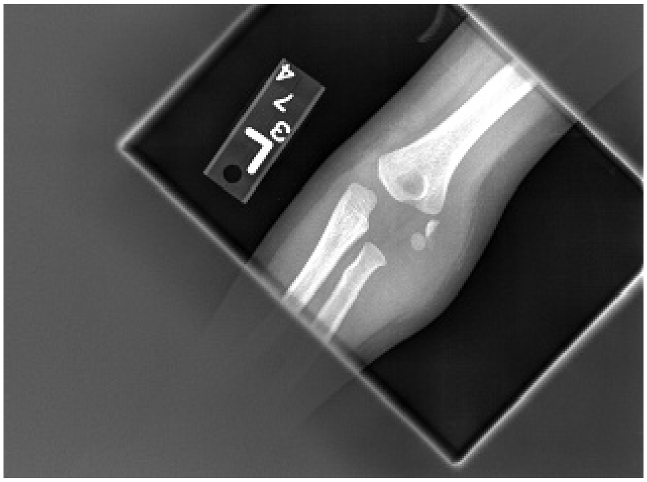


Figure 20.3.10 AP x-ray of a 2-year-old male reveals a displaced lateral condyle fracture with the fragment rotated greater than 90°.

Figure 20.3.11 AP elbow x-ray demonstrates a displaced medial epicondyle fracture. Note the significant soft tissue swelling as this injury was associated with an elbow dislocation that was reduced.

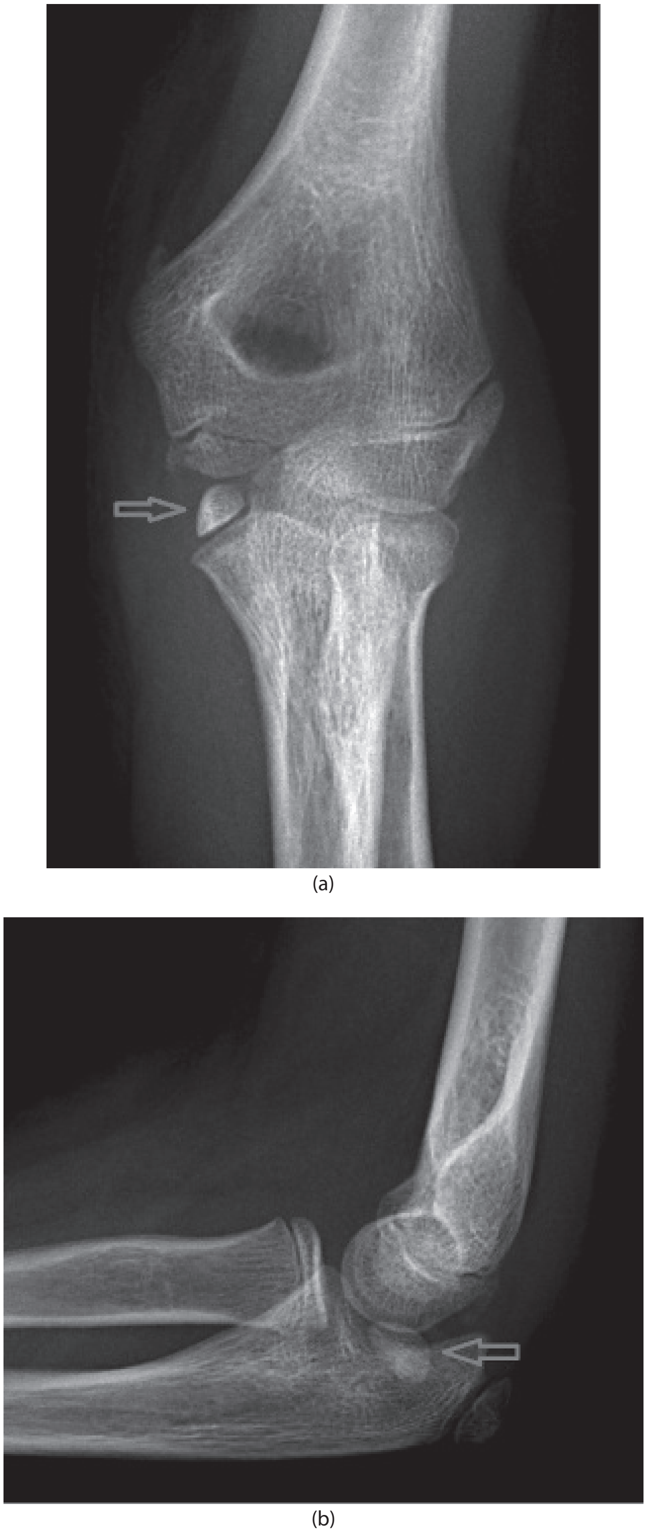


Figure 20.3.12 **(a, b)** AP and lateral elbow x-rays reveal a displaced medial epicondyle fracture incarcerated in the elbow joint in a 10-year-old male.

displaced less than 5 mm are treated with immobilization in a cast and displaced fractures are treated with open reduction internal fixation (Figure 20.3.11). Occasionally the medial epicondyle can become entrapped in the joint when it is associated with an elbow dislocation. This must be recognized so the injury can be treated appropriately with open reduction and stabilization of the fragment (Figure 20.3.12a and b).

Figure 20.3.13 Displaced radial neck fracture in 9-year-old male.

Proximal radial fractures

These fractures account for 8% of children's elbow fractures [20] and is typically seen between the ages of 9 and 12 [21]. These fractures result from one of two mechanisms: a fall onto an outstretched arm or associated with a posterior elbow dislocation. There are many classification systems and much debate as to acceptable amounts of displacement for these fractures. The most common injury pattern is a radial neck fracture that typically will involve the proximal radial physis (Figure 20.3.13). Rarely will a radial head (articular) fracture occur. Several methods of treatment have been described and include closed reduction, pin-assisted reduction, and open reduction for displaced fractures. This pattern of injury is prone to loss of elbow range of motion, and patients and families should be informed of this in order to have appropriate expectations for recovery following this injury.

Olecranon fractures

Olecranon fractures account for 5% of elbow fractures and are relatively uncommon [13]. The typical mechanism is a fall on the olecranon with the elbow flexed. Most of these fractures are nondisplaced and require only immobilization. If the fracture is displaced and involves the articular surface, this fracture is treated with open reduction and internal fixation similar to treatment undertaken in adults (Figure 20.3.14a through d). Olecranon fractures can also be associated with injuries to the radial head/neck. An olecranon fracture associated with a radial head dislocation, also is also known as a Monteggia fracture dislocation, is discussed in further detail later in this chapter.

Elbow dislocations

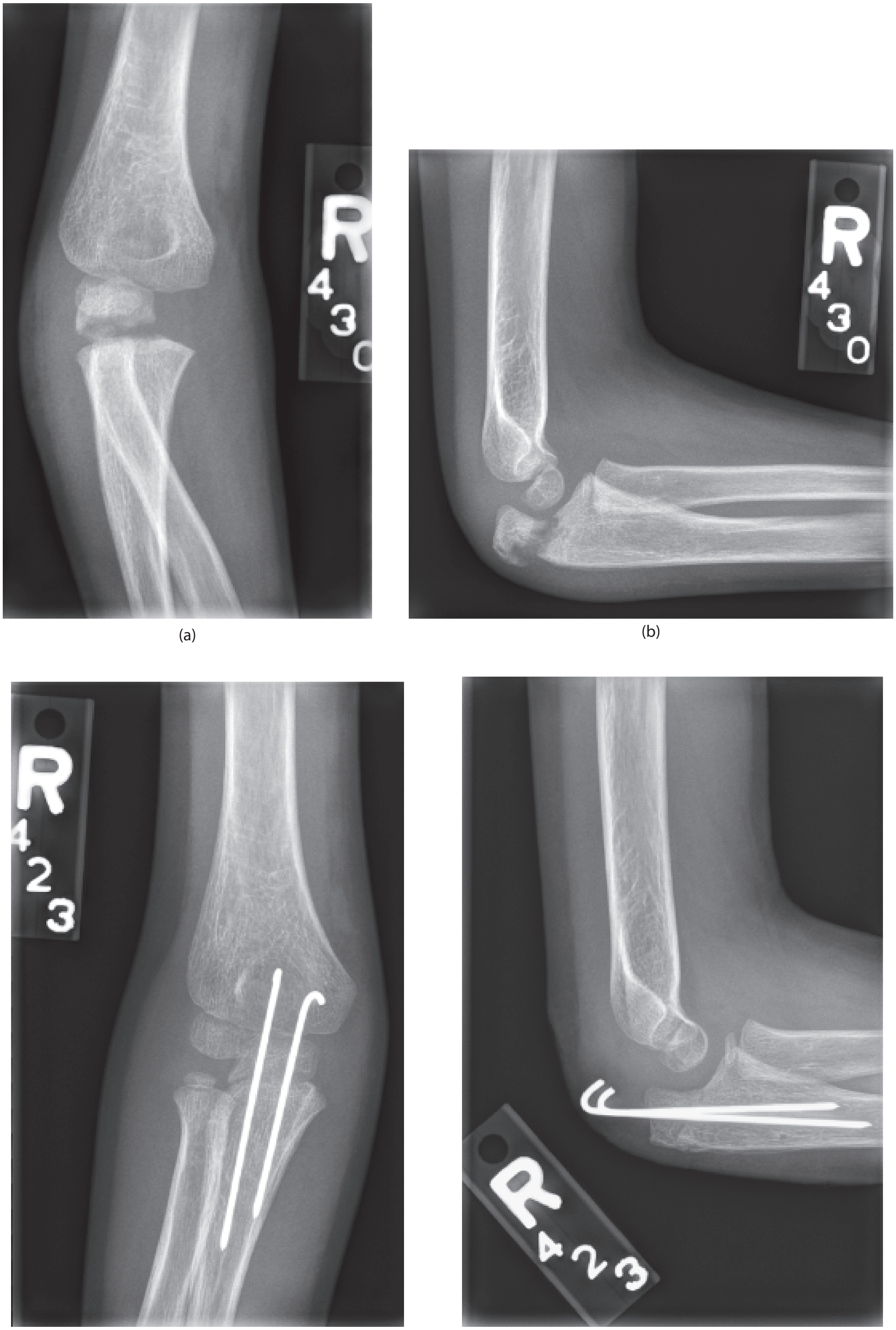
This is a rare injury in children and typically seen in the second decade of life [22]. The classification of elbow dislocations is determined by the direction of the ulna in relation to the humerus. The dislocation may be purely posterior (Figure 20.3.15a and b) or may also be in a medial or lateral direction. Elbow dislocations may also be associated with medial epicondyle fractures or fractures of the radial neck.

Treatment involves a careful neurovascular exam with documentation of median and ulnar nerve function and vascular perfusion to the hand. Closed reduction should be performed as soon as possible. Reduction involves first correction of any medial or lateral displacement followed by longitudinal traction with the elbow flexed. Following reduction, x-rays should be obtained to confirm a concentric reduction with no entrapped fragments in the joint (Figure 20.3.16a and b).

Brachial artery injury has been described with open elbow dislocations and requires immediate arterial exploration and repair. Ulnar nerve injuries have been described and are usually transient injuries. Median nerve injuries have also been described but can have profound implications as the nerve may be entrapped in the joint. These injuries are often associated with medial epicondyle fractures. If following a reduction of an elbow dislocation a patient has median nerve dysfunction, exploration of the nerve is necessary as it may be entrapped within the joint [23].

Nursemaid elbow

Nursemaid elbow is also known as a "pulled elbow." This injury results from longitudinal traction on the arm that results in subluxation of the radial head (Figure 20.3.17). It is estimated to occur in 15%–27% of all elbow injuries in children younger than 10 years old [24] and the typical age of injury is 2–4 years of age. The injury results from longitudinal traction with the forearm in pronation. This results in a partial tear of the annular ligament, which then becomes interposed between the radial head and capitellum. This typically occurs when a parent grabs the child's arm to prevent the child from walking out into traffic or to help the child climb up a step. The child will keep the elbow flexed and the forearm pronated. The subluxation is reduced by supinating the forearm with the elbow in 60°–90° of flexion and then maximally flexing the elbow while applying digital pressure over the radial head. One is usually able to palpate a reduction of the radial head. Following the reduction most children will resume use of the arm. Occasionally, in cases in which children do not resume use of the arm, it is reasonable to apply a long arm splint for a week.



(a)

(b)

(c)

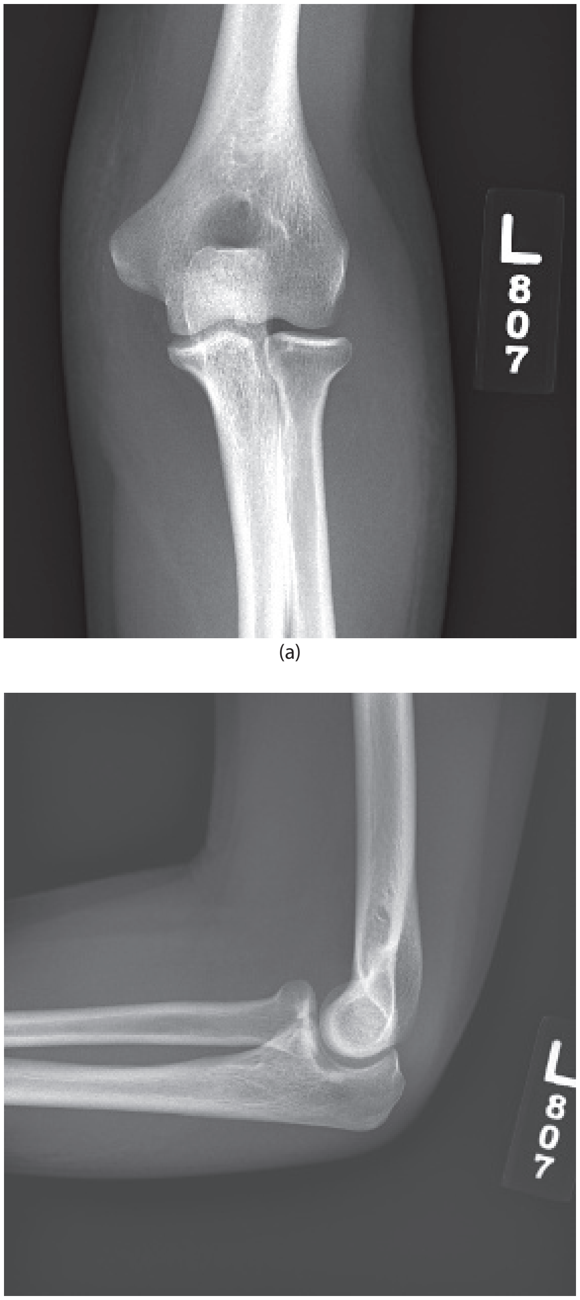
(d)

Figure 20.3.14 **(a, b)** Displaced olecranon fracture in 6-year-old male. **(c** and **d)** Due to the displacement at the articular surface, operative intervention is indicated.

(a)

(b)

Figure 20.3.15 **(a, b)** Posterior-lateral elbow dislocation in a 16-year-old male who was injured while wrestling.



(a)

(b)

Figure 20.3.16 **(a, b)** Postreduction x-rays reveal a concentric elbow joint.

Forearm fractures

Fractures of the forearm represent 40% of all fractures in all age groups of children [25]. Males have a slightly greater incidence than females. The most common location of injury is the distal metaphysis and physeal region. Diaphyseal fractures are more common in prepubescent children and physeal fractures are more common among adolescents. The majority of forearm fractures are the result of a fall on an outstretched hand during sports or play but can also occur with higher mechanism of injury such as motor vehicle accidents. Classification of theses fractures is based on the following characteristics:

1. Bone or bones involved
2. Direction of displacement (apex volar or dorsal)
3. Fracture location (diaphyseal, metaphyseal, epiphyseal)
    a. Physeal involvement
    b. Articular involvement
4. Fracture pattern (plastic deformation, buckle or greenstick fracture, complete fracture)

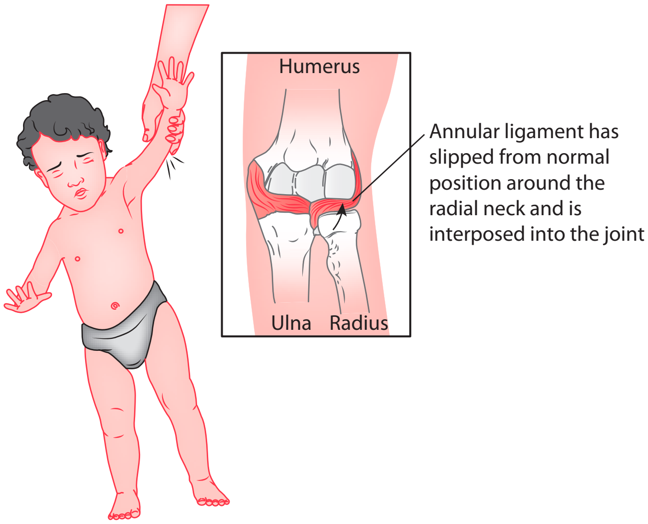


Figure 20.3.17 Typical mechanism of injury of parent "pulling" patient arm which results in subluxation of radial head and displacement of annular ligament. (Courtesy of Texas Children's Hospital, Houston, Texas.)

The goal of treatment is to correct any bony malalignment or malrotation to acceptable standards to allow for healing and remodeling of the fracture. These goals in children can often be achieved with casting but occasionally will need operative intervention. Generally speaking, malrotation is poorly tolerated as this does not remodel. There are various operative methods to achieve reduction of fractures when closed means fail. These include closed reduction and percutaneous pinning, external fixation, and open reduction internal fixation.

Proximal forearm fractures can be challenging as closed reduction can be difficult and malalignment in this region is poorly tolerated. Rarely does a proximal radius or ulna fracture occur in isolation because of the intimate anatomic relationship of the proximal radius and ulna at the elbow joint. Therefore, there should be a high level of suspicion for an associated dislocation, physeal separation, or plastic deformation of the other bone. When recognized, these injuries are amenable to treatment, but if the diagnosis is delayed chronic deformity and long-term problems can result.

Fractures of the proximal radius and ulna diaphysis can be treated with a cast as long as the angulation is less than 10°. Remodeling of the proximal forearm is limited so angulation of greater than 10° can lead to loss of forearm rotation. With angulation greater than 10°, closed reduction and/or open reduction and stabilization with plates or intramedullary rods is indicated.

Fractures of the diaphysis of the radius and ulna are extremely common injuries, and treatment varies greatly on the age of the patient. Nondisplaced fractures are typically treated in a long arm cast for 3–4 weeks and then the patient will be transitioned to a short arm cast for an additional 2–4 weeks. Generally older children require longer immobilization compared to younger children who heal faster. Most children less than 10 years of age can be treated with closed reduction and casting. Bayonet apposition without angulation or malrotation heals and remodels predictably in children less than 10 years of age (Figure 20.3.18a through f). However, if angulation or malrotation is greater than 20° in the diaphysis of a child less than 10 years of age, then operative treatment with open reduction and internal fixation with either intramedullary nails or plate and screw construct is needed. In children older than 10 years of age the acceptable angulation and malrotation is only 10° as these children have less remodeling potential and thus are more likely to require operative treatment (Figure 20.3.19a through d). Other considerations for remodeling are the location of the fracture and plane of displacement. Fractures closer to the growth plate and fractures which are displaced in the plane of joint motion have greater remodeling potential.

Fractures of the distal radius and ulna are the most common forearm injuries. These fractures are classified as buckle or torus fractures, greenstick fractures, or complete fractures. Torus fractures are inherently stable and are treated with a removable wrist splint for 3–4 weeks for comfort. Displaced fractures have tremendous remodeling potential due to the proximity to the distal radius and ulna physis as 70%–80% of the growth of these bones arises from the distal physis (Figure 20.3.20a through d). Thus, in children with greater than 2 years of growth remaining, closed reduction and casting is acceptable treatment. If residual angulation greater than 20° persists, operative treatment with closed reduction and pinning or open reduction is indicated.

Distal radius and ulna physeal fractures are treated in a similar fashion to metaphyseal fractures as previously described (Figure 20.3.21a through d). The one caveat is that physeal fractures should be treated within 5–7 days. The risk of growth arrest from radial physeal fracture is low and reported at 3%–5%; however, that risk increases if the fracture is reduced beyond 7 days as late reduction of these fractures can compound the injury to the growth plate [26]. Distal ulna physeal fractures have a higher rate of growth arrest, reported at 20%–50% [27]. An arrest of either of these bones can result in significant deformity of the forearm and wrist [28].

Monteggia fracture-dislocations

This injury pattern is defined as a fracture of the ulna with an associated radial head dislocation. Despite the known need for vigilance in diagnosing this injury it is often missed by competent orthopedic surgeons, radiologists, emergency, and primary care physicians. Quality AP and lateral radiographs of the forearm and elbow are required to appropriately diagnose this injury and failure to do so can

(a) (b) (c) (d) (e) (f)

Figure 20.3.18 **(a, b)** A 5-year-old female with a displaced radius fracture with overriding fragments and a buckle fracture of ulna. **(c, d)** Three months after injury x-rays reveal complete healing and early remodeling. **(e, f)** Six months after injury fracture remodeling is complete.

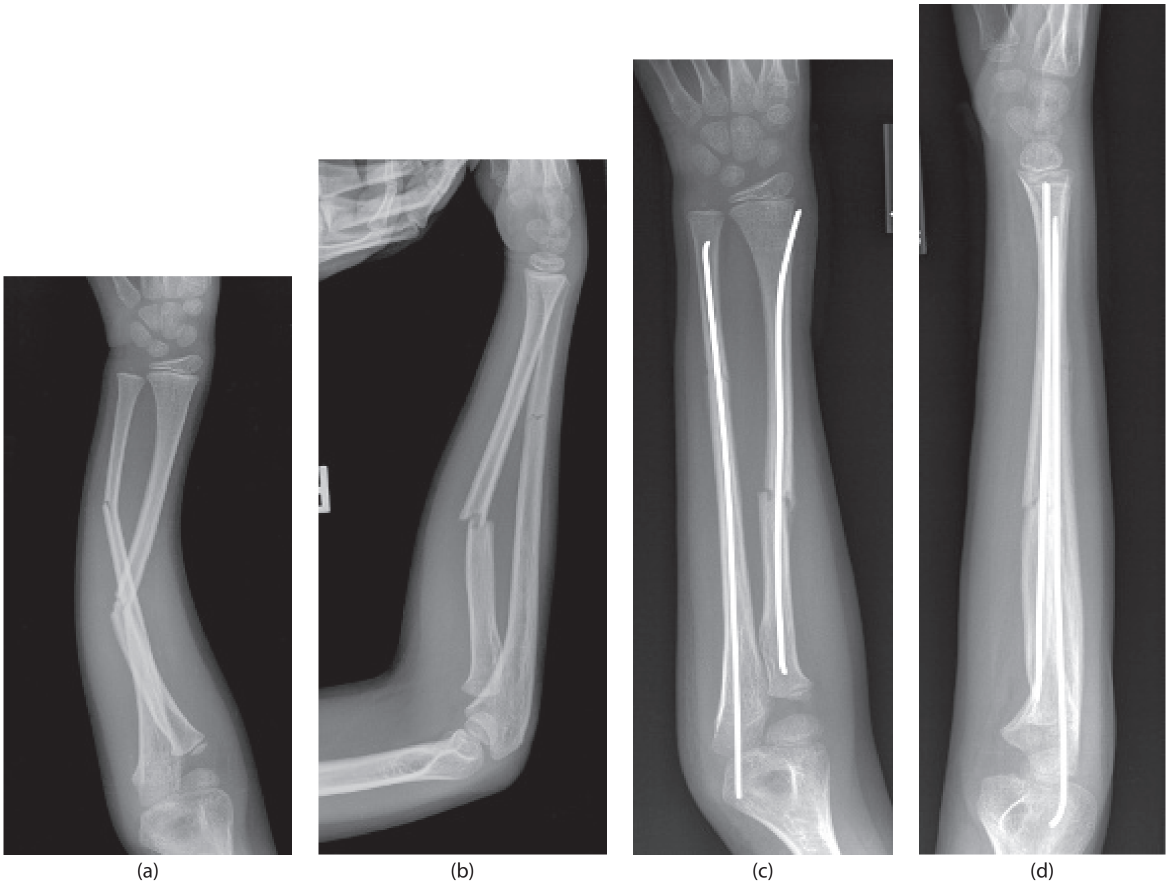


Figure 20.3.19 **(a, b)** An 8-year-old male with moderate displacement of midshaft radius and ulna fractures after a fall on the playground. **(c, d)** Closed reduction and casting did not result in adequate alignment, so the fractures were stabilized with intramedullary rods.

result in permanent impairment to the patient. In all radiographic views, the radius should line up with the capitellum (Figure 20.3.22a and b) [29].

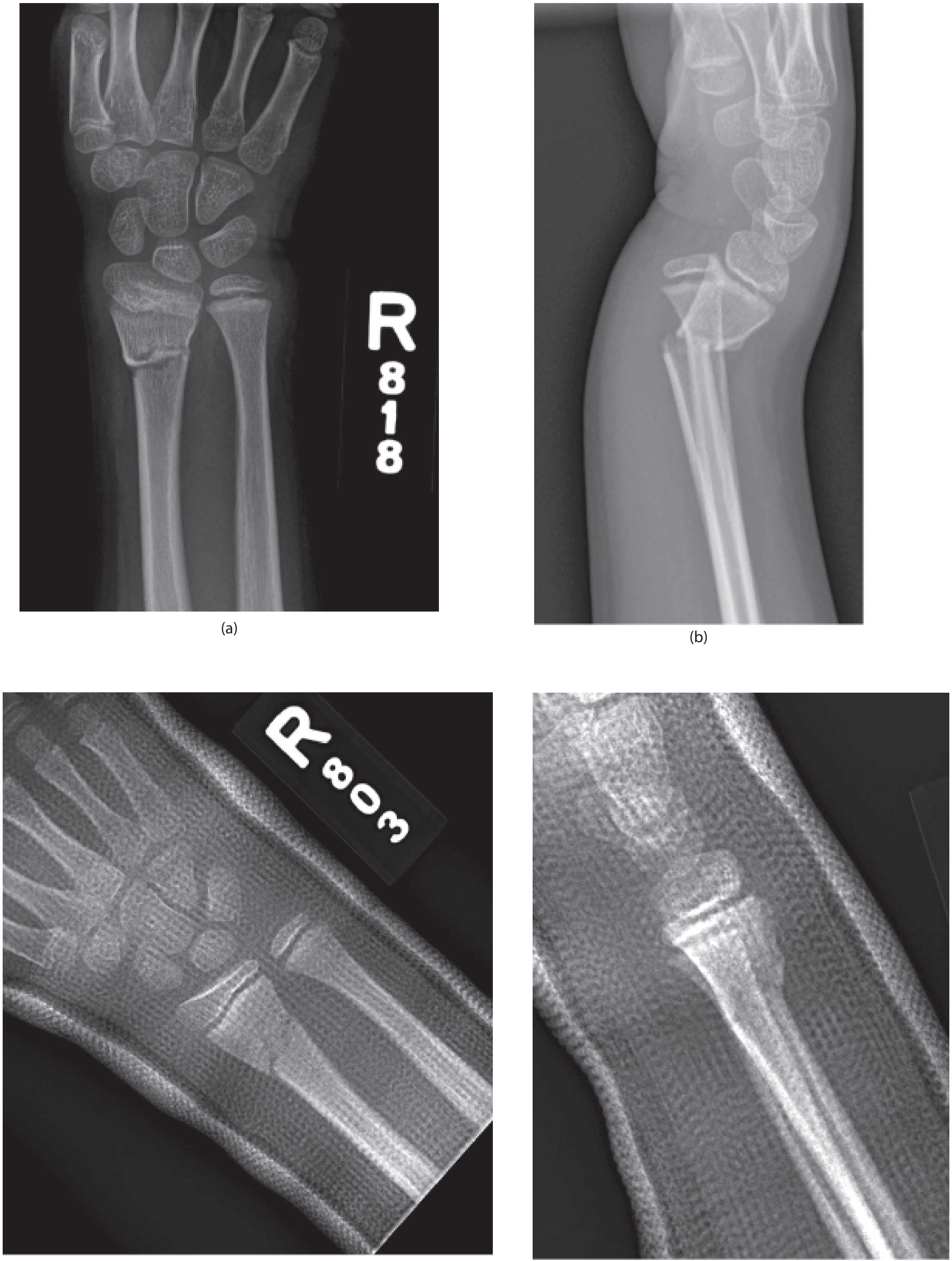
Monteggia fracture-dislocations are classified by direction of displacement of the radial head (anterior, posterior, and lateral) [30] and the type of forearm fracture. The ulna fracture can be further categorized as plastic deformation, incomplete or complete. Treatment of the injury requires anatomic reduction and stabilization of the ulna. The problem with plastic deformation or incomplete fractures of the ulna is that the injury is not recognized and thus not addressed. In the young child, treatment can be achieved by reducing the ulna fracture. The radial head then will reduce simultaneously. The patient is then placed into a long arm cast. In older children or unstable ulna fractures, treatment requires operative stabilization of the ulna with an intramedullary rod or plate and screws and rarely open treatment of the radial head dislocation.

Galeazzi fracture-dislocations

Pediatric Galeazzi fracture-dislocations are rare. They are defined as a displaced distal radius fracture with a distal radio-ulnar joint (DRUJ) dislocation or displaced ulnar physeal injury (Galeazzi equivalent) (Figure 20.3.23a and b). In adults, this injury pattern typically requires operative treatment; however, in the pediatric population, closed reduction with application of a long arm cast restores anatomic alignment and stability to the DRUJ. In the older child, open reduction of the distal radius fracture may be required to obtain an anatomic reduction (Figure 20.3.23c and d). Upon reduction of the radius, the DRUJ is stressed. If it is unstable in both supination and pronation of the forearm, a pin is placed across the DRUJ for 4–6 weeks.

Carpal fractures

Scaphoid fracture is the most common carpal injury in children [31]. Scaphoid fractures are classified by location (distal pole, waist, and proximal pole), degree of displacement, and direction of fracture. Waist fractures are the most common scaphoid fracture. Displacement greater than 1–2 mm is a risk factor for malunion or nonunion [32]. Treatment varies and can involve placement of a short arm or long arm thumb spica cast for nondisplaced



(a)

(b)

(c)

(d)

Figure 20.3.20 **(a, b)** A 10-year-old female with a displaced distal radius fracture and nondisplaced ulna fracture following a fall from a trampoline. **(c, d)** The fracture was reduced with sedation in the emergency room and treated in a short arm cast.

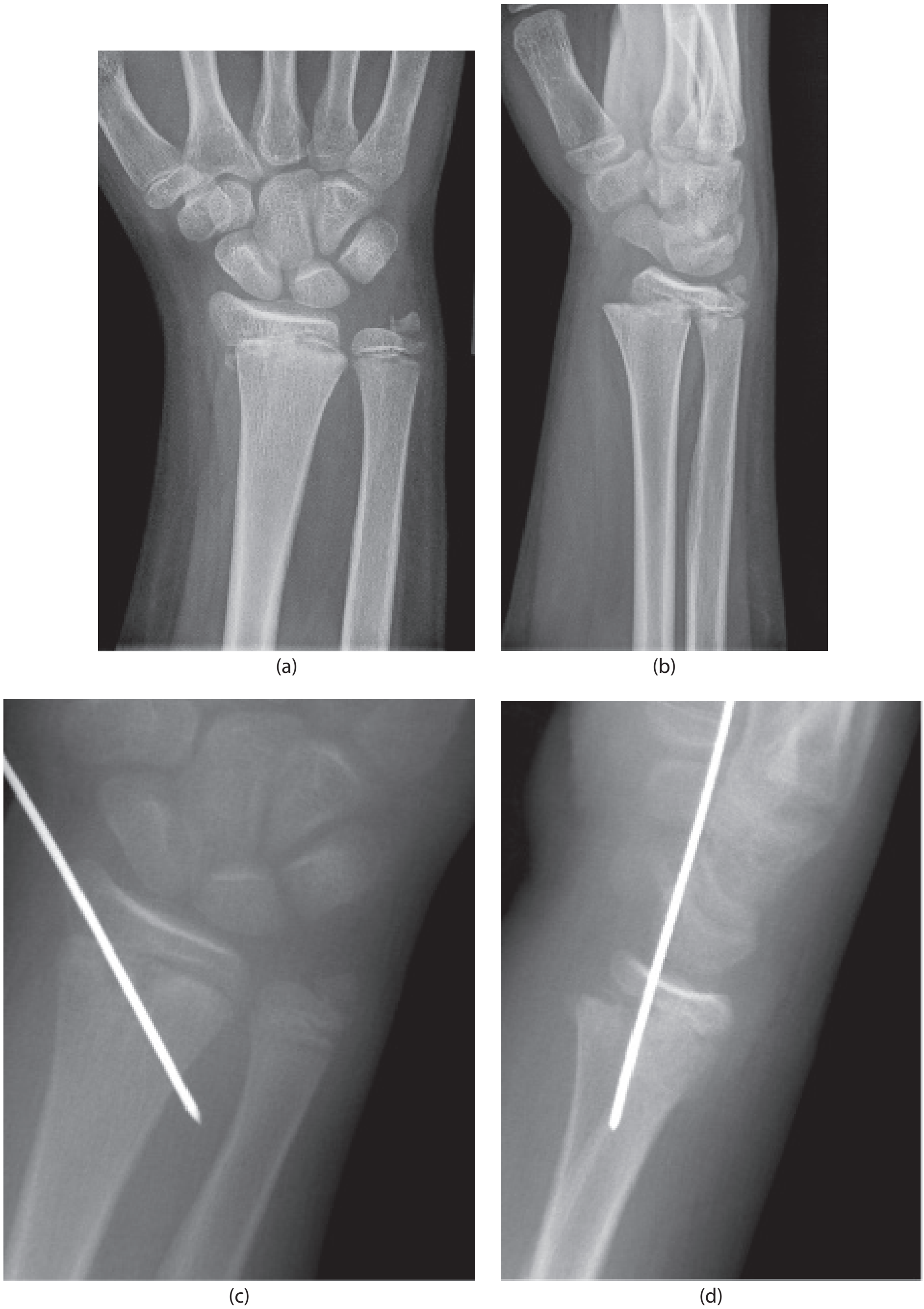
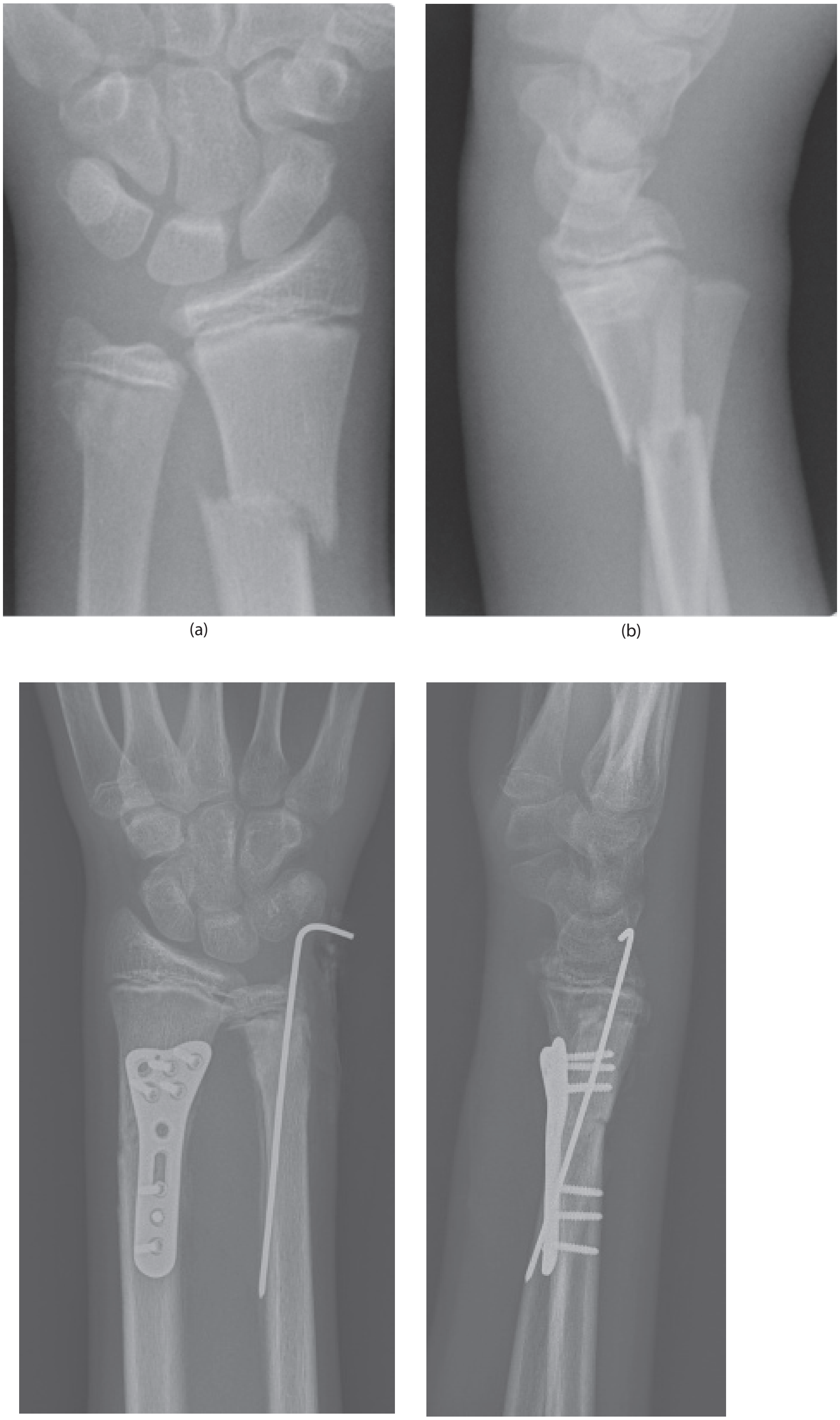


Figure 20.3.21 **(a, b)** A 10-year-old male with displaced Salter Harris II distal radius fracture and ulnar styloid fracture following a fall. **(c, d)** Closed reduction with pinning was performed to stabilize this unstable fracture.

Figure 20.3.22 **(a, b)** AP and lateral forearm x-rays reveal a chronic Monteggia fracture-dislocation. The radial head is anteriorly displaced and there is a healed ulna fracture. The dislocation of the radial head was not originally appreciated.



(a) (b) (c) (d)

Figure 20.3.23 **(a, b)** A 13-year-old male who fell from skateboard resulting in a Galeazzi equivalent injury (displaced distal radius fracture with Salter Harris II distal ulna fracture). **(c, d)** Patient underwent open reduction internal fixation of the distal radius fracture and pinning of the ulna fracture to ensure adequate healing.

fractures and operative treatment with cannulated screw fixation for displaced fractures. Avascular necrosis and nonunion can occur in children as seen in adults.

Hand fractures

The hand is commonly injured in children. In toddlers, this is often a crush injury from a door and in the older child the mechanism of injury is from sports. Approximately 80% of these injuries heal without complications; however, a small subset of fractures, dislocations, and soft tissue injuries can have dire complications if not treated appropriately.

Distal phalanx injuries usually are a result of a crush injury. Partial or complete distal tip amputations may occur as well as nail bed or plate injuries. Many of the fingertip amputations can be treated with irrigation and a sterile dressing as long as there is no exposed bone. If bone is exposed, it can either be debrided with a rongeur or an advancement flap or composite graft can be considered.

Mallet injuries occur when there is a disruption of the terminal extensor tendon insertion onto the distal phalanx epiphysis. This can occur as an intrasubstance tear of the tendon or as a bony avulsion. Both are treated with extension splinting of the distal interphalangeal joint while allowing motion of the proximal interphalangeal joint.

A Seymour fracture involves a physeal separation of the distal phalanx associated with a disruption of the overlying skin resulting in an open fracture. The germinal matrix of the nail bed can become interposed at the fracture site. Left untreated the open wound can become infected. Treatment involves removal of the nail plate, extraction of the entrapped germinal matrix at the fracture site, reduction of the fracture, and repair of the nail bed.

Figure 20.3.24 A 12-year-old female sustained a displaced Salter Harris II proximal phalanx fracture when a basketball struck her hand.

Phalangeal neck fractures

These fractures occur at the middle and proximal phalanx and if they are not recognized can result in limitation of motion or malrotation of the digit. The fracture can be underappreciated due to the small fracture fragment and the fracture often displaces into extension. This fracture typically requires operative treatment with reduction and stabilization with a pin as a reduction cannot be maintained in a cast.

Physeal phalangeal fractures

These fractures occur at the proximal phalanx and most commonly involve the small finger (Figure 20.3.24). The finger will have excessive abduction as the fracture travels through the physis and is typically a Salter Harris II injury. These injuries are treated with a closed reduction and are typically stable in a cast.

Metacarpal fractures

Fractures of the metacarpal can occur at the shaft or distally in the metacarpal neck. Shaft fractures should be assessed for malrotation. This can be assessed by inspecting tenodesis. Passive wrist extension results in passive digital flexion and allows for evaluation of digital alignment. Malalignment requires anatomic reduction and operative stabilization. Fractures of the metacarpal neck typically are the result of an altercation and occur most commonly at the fifth metacarpal. Treatment varies, but 40° of angulation at the fracture site is readily acceptable.

Dislocations

Dislocations most commonly occur at the proximal interphalangeal joint or metacarpal phalangeal joint. Dorsal dislocations are most common and are treated with a gentle reduction followed by early motion and buddy tapping. Occasionally a dislocation may be irreducible due to entrapment of the volar plate or instability. In these circumstances operative treatment is required.

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Lower extremity fractures

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Hip fractures

Unlike in the elderly population, hip fractures in children are rare and are most commonly the result of high-energy trauma. A trauma evaluation should always be considered to identify other associated injuries, such as head injuries, abdominal injuries, and other fractures [1,2].

A metabolic or structural problem with the bone should be suspected if a proximal femur fracture occurs in a young patient with a low-energy mechanism. Femoral neck stress fractures can occur as a result of osteoporosis in patients with eating disorders or low-body-weight athletes who overtrain [3,4]. Simple bone cysts are common in the trochanteric region and can also weaken the bone, predisposing it to fracture. If there is any suspicion for a pathologic fracture, further work-up should occur prior to definitive treatment of the fracture.

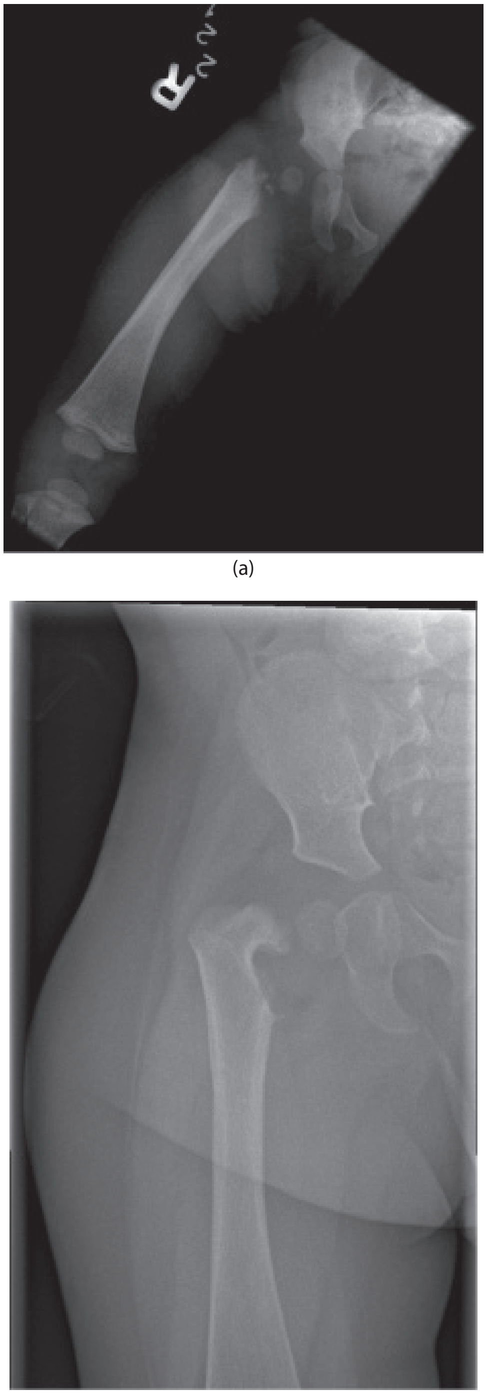
Regardless of the mechanism, the complication rate following hip fractures in children is high. The unique anatomy of the proximal femur and its blood supply contribute to this high complication rate. As with any physeal fracture, premature physeal closure is possible after a fracture through the proximal femoral physis. Depending on the age at which this occurs, a leg length discrepancy, coxa vara (Figure 20.3.25) or coxa breva, can develop [1,5,6]. The same complications can develop if an extra-physeal proximal femoral fracture requires fixation across the proximal femoral physis in order to adequately stabilize the fracture.

In addition, disruption of the vascular supply to the femoral head is common following proximal femur fractures in children and can result in avascular necrosis of the femoral head. At birth, the blood supply to the femoral head is primarily intraosseous through metaphyseal vessels from the femoral neck. As the proximal femoral physis develops, these intraosseous arteries decrease in size and the physis becomes a barrier to these vessels. The intracapsular lateral epiphyseal vessels and branches of the medial femoral circumflex artery run along the neck of the femur and become the primary blood supply to the femoral head in the older child since they bypass the physis [7,8]. There is essentially no collateral blood supply to the femoral head, so disruption of the lateral epiphyseal vessels with a fracture or occlusion of flow through these vessels due to high intracapsular pressure from a hemarthrosis can decrease the blood supply to the femoral head, leading to avascular necrosis.

The Delbet classification (Figure 20.3.26) is used to describe proximal femur fractures and is prognostic for their risk of avascular necrosis and poor outcome [2,6]. A Delbet type I fracture is a transphyseal fracture with or without dislocation of the proximal femoral epiphysis from the acetabulum. It has the highest risk for avascular necrosis. A Delbet type II fracture is an intracapsular fracture through the neck of the femur (transcervical) and is the most common proximal femur fracture (Figure 20.3.27). A Delbet type III fracture occurs at the junction of the femoral neck and the trochanteric region (cervicotrochanteric). This fracture is generally thought to be extra-capsular, but given that there is still a low risk of AVN associated with it, some of these fractures may be intra-capsular. A Delbet type IV fracture is an extra-capsular fracture through the trochanteric region of the proximal femur and has the lowest risk for AVN.

Evaluation of a patient with a proximal femur fracture usually begins with a standard trauma workup. The patient's affected extremity will usually be shortened and externally rotated. An anteroposterior (AP) pelvis radiograph with as much traction and internal rotation on the affected extremity as the patient will tolerate should be obtained. A cross table lateral x-ray should be considered over a frog lateral view to decrease the risk of further displacing a proximal femur fracture. In most circumstances, the patient will have had a computed tomography (CT) of the pelvis as part of the trauma evaluation which should always be reviewed for a possible femoral neck fracture. In cases of a suspected femoral neck stress fracture or pathologic fracture, magnetic resonance imaging (MRI) is the best imaging modality for further evaluation [9,10].

Because of a high rate of coxa vara, delayed union, and nonunion with cast treatment, most proximal femur fractures are treated with open or closed reduction and internal fixation. Timing of surgery is controversial and most studies support surgical treatment within 24 hours of injury [11–13]. In Delbet type I and II fractures, fixation will most often cross the physis in order to adequately stabilize the fracture. In



(a)

(b)

Figure 20.3.25 **(a)** Radiographs of an 8-month-old who sustained a femoral neck fracture after getting his foot stuck in his crib. **(b)** Coxa vara was seen on radiographs taken at 4 months after his injury.

young children, smooth 2.0-mm pins can be used to minimize iatrogenic injury to the physis. These children are most commonly placed in a spica cast following stabilization of their fractures. In older children with less growth remaining, cannulated screws are used to stabilize the fracture and also usually cross the physis (Figure 20.3.27). Type III fractures can usually be stabilized with similar methods but fixation can often stop short of the physis. Supplementary protection with spica casting may be considered. A pediatric hip screw and side plate are often used for fixation of a displaced type IV fracture. Postoperatively, patients are generally kept toe touch weight bearing for at least 6 weeks and possibly longer depending upon the degree of healing seen on follow-up x-rays.

Hip dislocations

Hip dislocations are also rare in children. In younger children, hip dislocations can occur with only minor trauma [14,15], but in adolescents, a hip dislocation usually occurs as a result of high-energy trauma [16]. Football and motor vehicle collisions account for the majority of hip dislocations in the adolescent group. Posterior hip dislocations are most common and occur when a posteriorly directed force is applied to a flexed and internally rotated femur. Although spontaneous reduction is possible, examination of a patient with a posterior hip dislocation usually finds that the hip is slightly flexed, adducted, and internally rotated. Careful neurologic examination is necessary, as up to 20% of posterior hip dislocations have an associated sciatic nerve injury [17,18]. Ipsilateral knee injuries are also common [19]. A posterior hip dislocation can usually be seen on a standard AP pelvis radiograph (Figure 20.3.28). Radiographs should also be carefully reviewed for a femoral neck fracture or injury to the proximal femoral physis, as this may influence whether the reduction of the hip dislocation is performed in the emergency department or in the operating room. Reduction under general anesthesia should be strongly considered in adolescents following high-energy trauma due to their increased risk for epiphyseal separation during reduction [20]. Prompt reduction (within 6 hours) is required in order to decrease a patient's risk for avascular necrosis [15,21]. If reduction is undertaken in the emergency department and proves to be difficult, the procedure should be aborted and moved to the operating room where full anesthesia, muscle relaxation, and fluoroscopy are available. If closed reduction under anesthesia is unsuccessful, open reduction is indicated [16,22]. Following reduction, a CT or MRI should always be obtained to confirm a concentric reduction, to evaluate for loose bodies within the joint, and to assess the acetabulum for fracture [21–24]. For younger children whose acetabulum is not completely ossified, an MRI should be considered to evaluate the posterior wall of the acetabulum if there is concern for an injury [23,24]. Following reduction, young patients are often immobilized in a spica cast. Adolescents should be instructed to avoid hip flexion and internal rotation, and may be placed in a hip orthosis, knee immobilizer, or given an abduction pillow to encourage compliance with these precautions.

Femoral shaft fractures

Femoral shaft fractures occur in a bimodal age distribution with peak incidence in toddlers and in adolescents [25,26]. The mechanism of injury in these two age groups is significantly different [26]. Toddlers' femurs

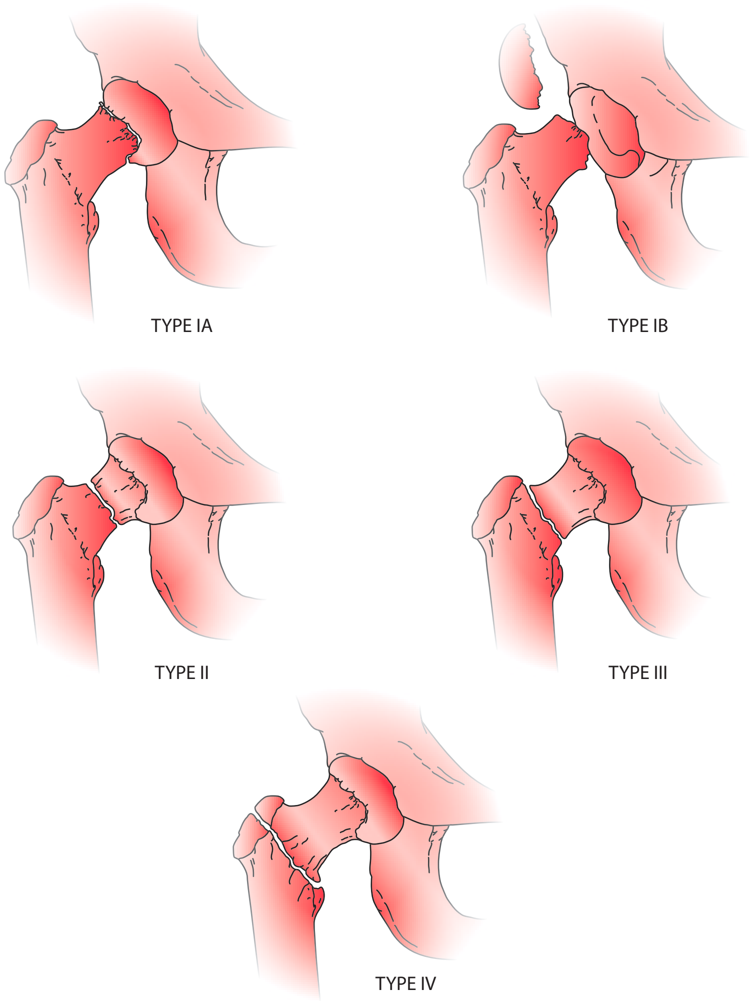


Figure 20.3.26 Delbet classification. (Courtesy of Texas Children's Hospital, Houston, Texas.)

are relatively weak, and fractures occur most commonly with falls occurring during normal play [26,27]. In contrast, high-energy trauma is usually the cause of femur fractures in adolescents [26]. Abuse must be suspected in a child who sustains a femur fracture before he has started walking [27–29]. Due to the high association of nonaccidental trauma with femur fractures in young children, the American Academy of Orthopaedic Surgeons recommends that a child abuse workup be considered in all children under 36 months of age who have sustained a femur fracture [30].

Treatment of pediatric femur fractures is highly dependent on the age of the patient. Femur fractures in infants usually occur with birth trauma and can be treated in a Pavlik harness [31,32] or a splint. Most femur fractures in children under 5 years of age can be treated with spica casting [33], usually for 4–8 weeks (Figure 20.3.29). Because of the significant remodeling potential in this age group [34], up to 2 cm of shortening [35] and 15°–30° of angulation may be accepted. Single leg spica casting, which does not immobilize the well extremity, is becoming more popular, since it allows the child to walk as his pain improves [36–38] and allows the child to be more easily cared for by parents.

Treatment of femur fractures in the 6- to 11-year-old age group is usually operative, using flexible nails (Figure 20.3.30) or a submuscular plate. Use of a rigid nail, as would be used in older adolescents and adults, requires a starting point for entry of the nail at the greater trochanter, putting the medial femoral circumflex artery at risk for injury. Iatrogenic avascular necrosis of the femoral head in children with open proximal femoral physes could result from injury to the medial femoral circumflex artery [39]. Because flexible nails do not provide rigid fixation, alternative fixation methods, such as submuscular plating, should be considered in "length unstable" fractures [40], such as comminuted fractures and long spiral fractures, which have a higher likelihood of shortening or angulation when treated with flexible nailing [32,41,42].

Femoral shaft fractures in children over 12 years old are generally treated with rigid locked intramedullary nails (Figure 20.3.31) [43]. The risks of shortening and angulation seen with flexible nails are minimized with rigid intramedullary nails, because they are "locked" with screws proximally and distally.

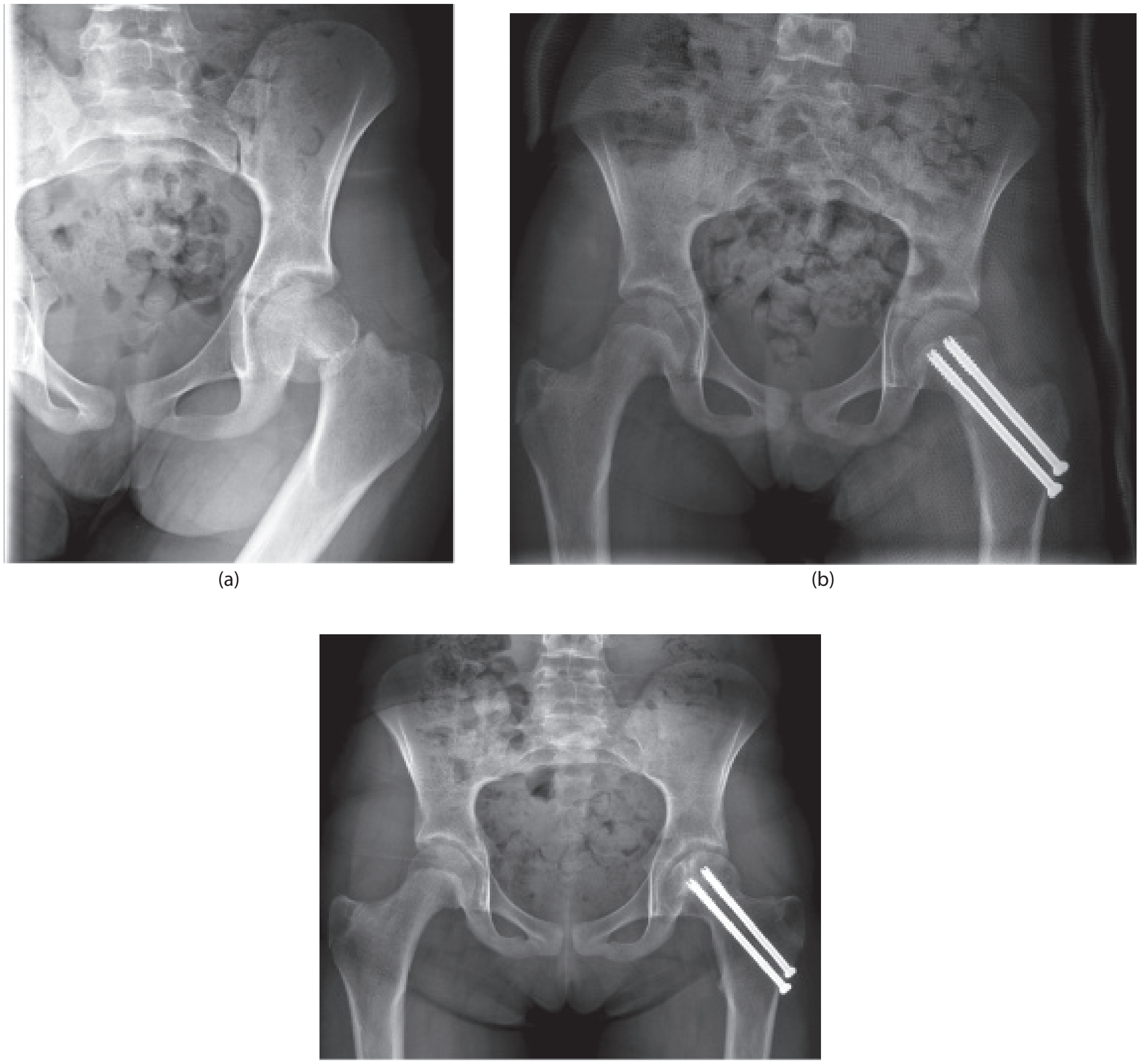

(a) (b) (c)

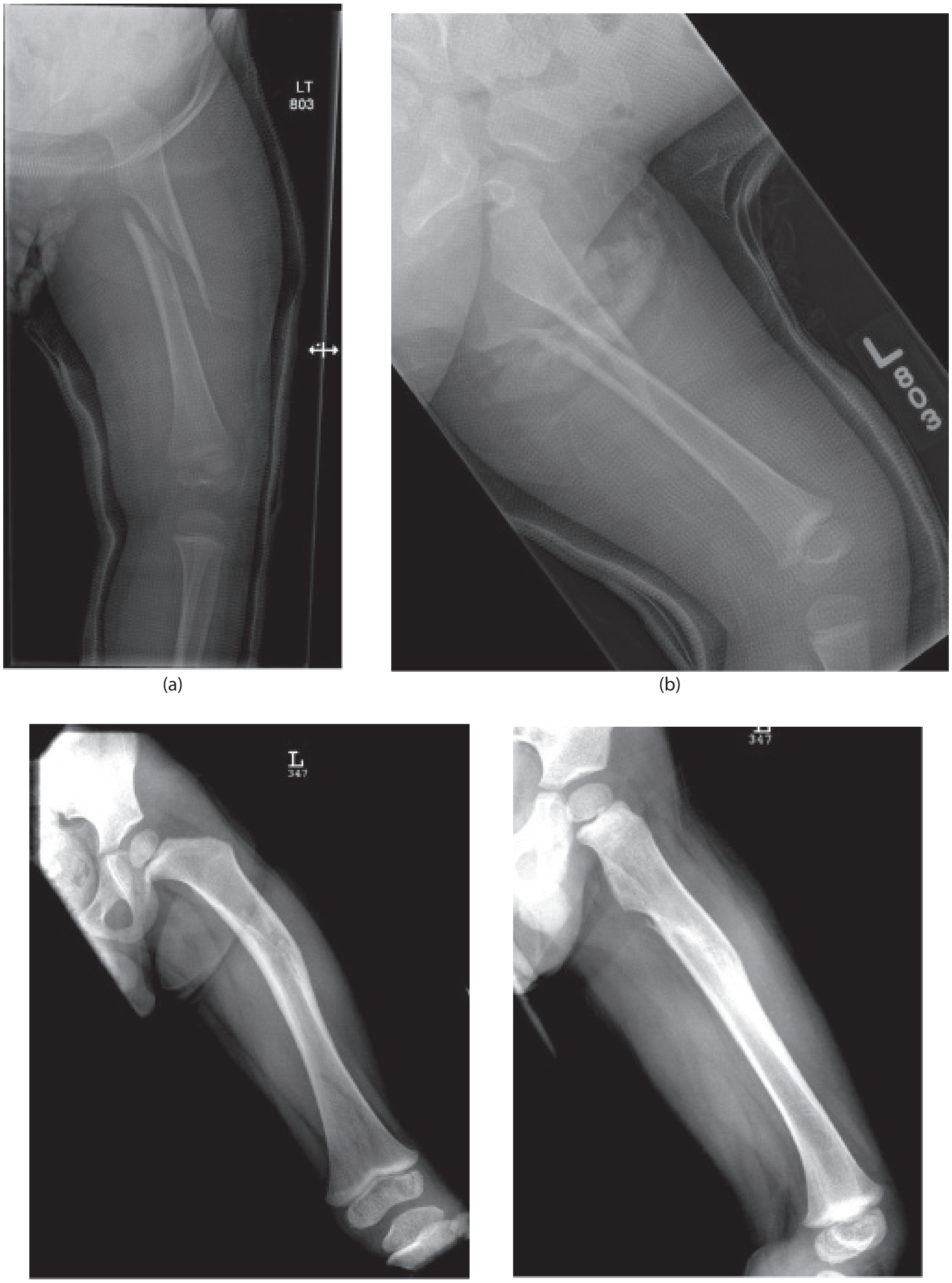
Figure 20.3.27 **(a)** Radiographs of a 9-year-old female with a transcervical femoral neck fracture sustained after falling while playing on a trampoline. **(b)** Transcervical femoral neck fracture was treated with open reduction and screw fixation. **(c)** Evidence of avascular necrosis at 2 months after her injury.

Figure 20.3.28 Hip dislocation.

In unusual circumstances, such as significant soft tissue injury, an unstable fracture in a patient with open physes or a patient who is not stable for surgery, external fixation and/or traction may be considered [44–47].

Distal femoral physeal fractures

Distal femoral physeal fractures typically occur during high-energy trauma or sports. They have a high complication rate, particularly with growth arrest [48,49]. Depending on the type of fracture, growth arrest may result in a leg length discrepancy or an angular deformity. These fractures are described using the Salter-Harris Classification (Figure 20.3.32). Type I fractures occur through the physis itself without extension into the metaphysis or epiphysis. These fractures can be nondisplaced and difficult to detect on x-rays. Because a child's physis will



(a) (b) (c) (d)

Figure 20.3.29 **(a)** and **(b)** Radiographs of a 3-year-old male with a femoral shaft fracture treated in a single leg spica cast. **(c)** and **(d)** Radiographs showing remodeling of his femoral shaft fracture 1 year after injury.

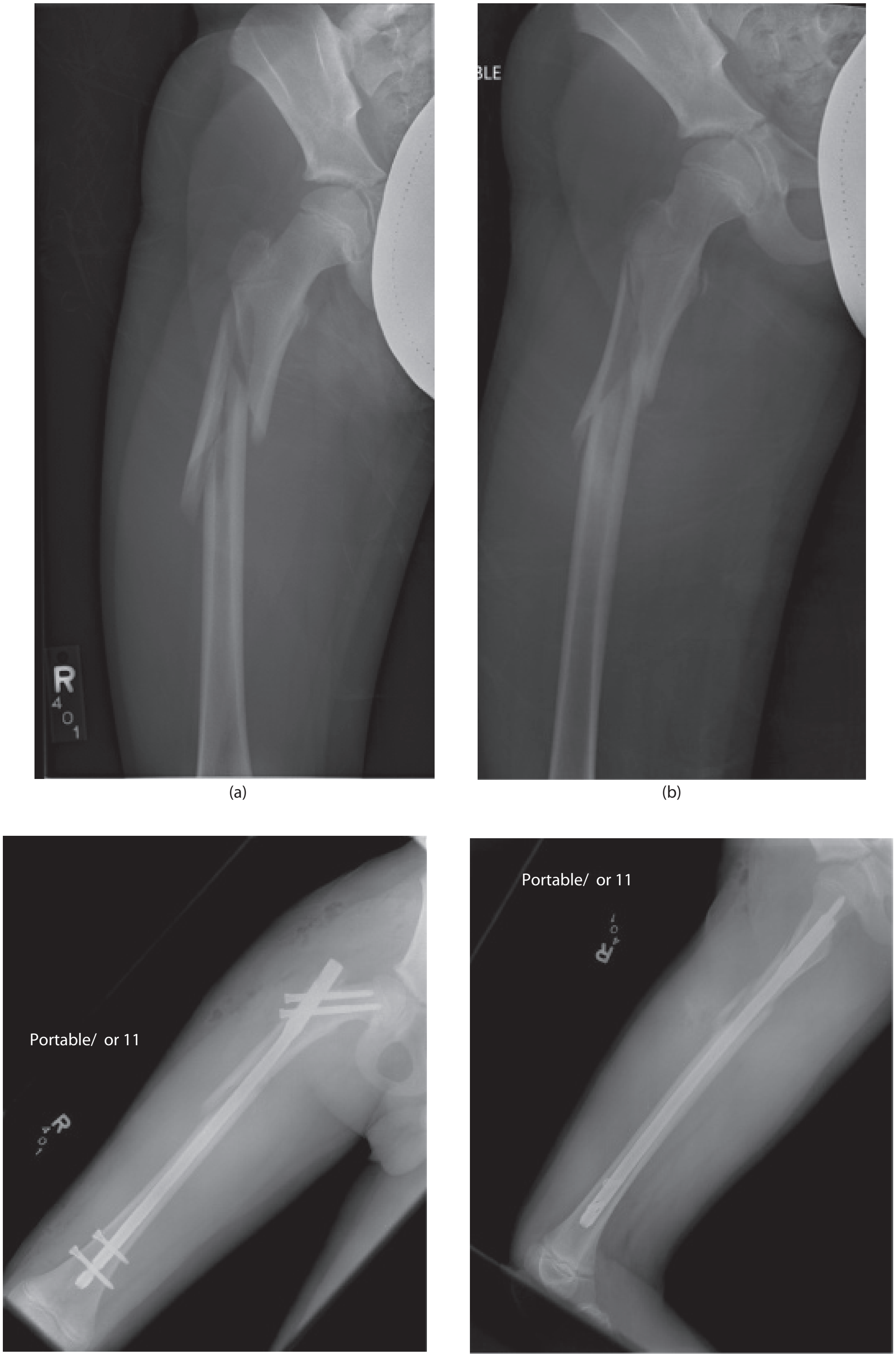
usually fail before his or her ligaments, a Salter-Harris I fracture should be considered with relatively normal appearing x-rays and a mechanism that would be concerning for a medial collateral ligament in an adult (i.e., child is struck in the lateral knee). Stress x-rays of the knee can be considered but are not generally recommended due to further potential injury to the physis. Subtle widening of the physis on x-rays and tenderness circumferentially over the distal femoral physis are findings that should raise suspicion for this injury. An MRI can be obtained to confirm diagnosis [50]. Nondisplaced fractures can be treated with a long leg cast. Displaced and/or unstable fractures are usually treated operatively with closed or open reduction and pinning.

Salter-Harris II fractures occur through the physis but extend into the metaphysis with a Thurston Holland

(a) (b)

(c) (d)

Figure 20.3.30 **(a)** and **(b)** Radiographs of an 11-year-old male who sustained a femoral shaft fracture on a trampoline. **(c)** and **(d)** Radiographs showing healing of his femoral shaft fracture at 6 months after treatment with flexible nails.



(a) (b) (c) (d)

Figure 20.3.31 **(a)** and **(b)** Radiographs of a 12-year-old male who sustained a comminuted subtrochanteric femur fracture after falling from his bicycle. **(c)** and **(d)** Radiographs showing treatment of his fracture with a rigid locked intramedullary nail.

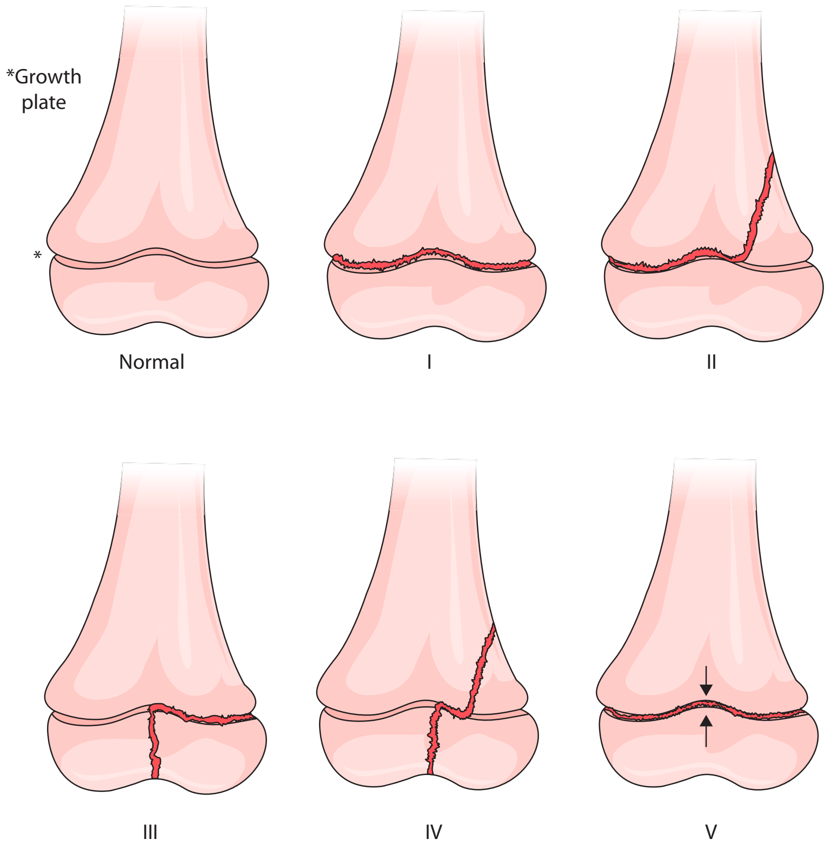


Figure 20.3.32 Salter-Harris Classification of distal femur fractures. (Courtesy of Texas Children's Hospital, Houston, Texas.)

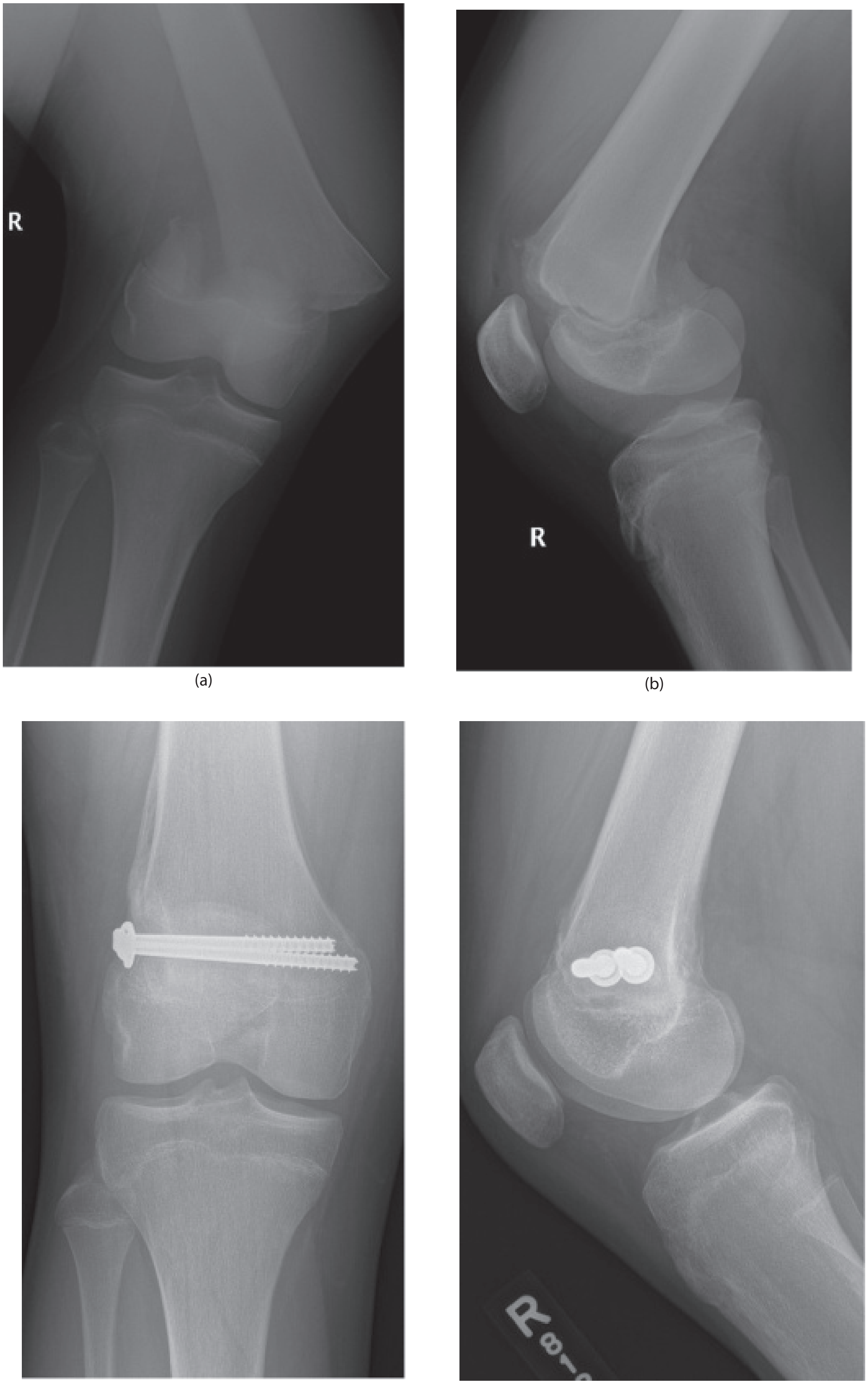
fragment. The Thurston Holland fragment can be of varying sizes. If large enough, operative treatment involves closed or open reduction and screw fixation within the Thurston Holland fragment to avoid additional injury to the distal femoral physis (Figure 20.3.33). If the Thurston Holland fragment is small, smooth pins may be used as in a Salter-Harris I fracture to stabilize it (Figure 20.3.34).

Salter-Harris III fractures involve the physis but exit through the epiphysis as an intra-articular fracture. These fractures are sometimes difficult to see on x-rays. A CT or MRI is often helpful in diagnosing the fracture and in surgical planning. Treatment usually involves closed or open reduction and screw fixation of the epiphyseal fragment (Figure 20.3.35).

Salter-Harris IV fractures are rare and are treated in a similar fashion to other distal femoral physeal fractures. Postoperatively, patients with distal femoral physeal fractures are kept in either a cast (cylinder or long leg) or brace and kept toe touch weight bearing for 4–6 weeks.

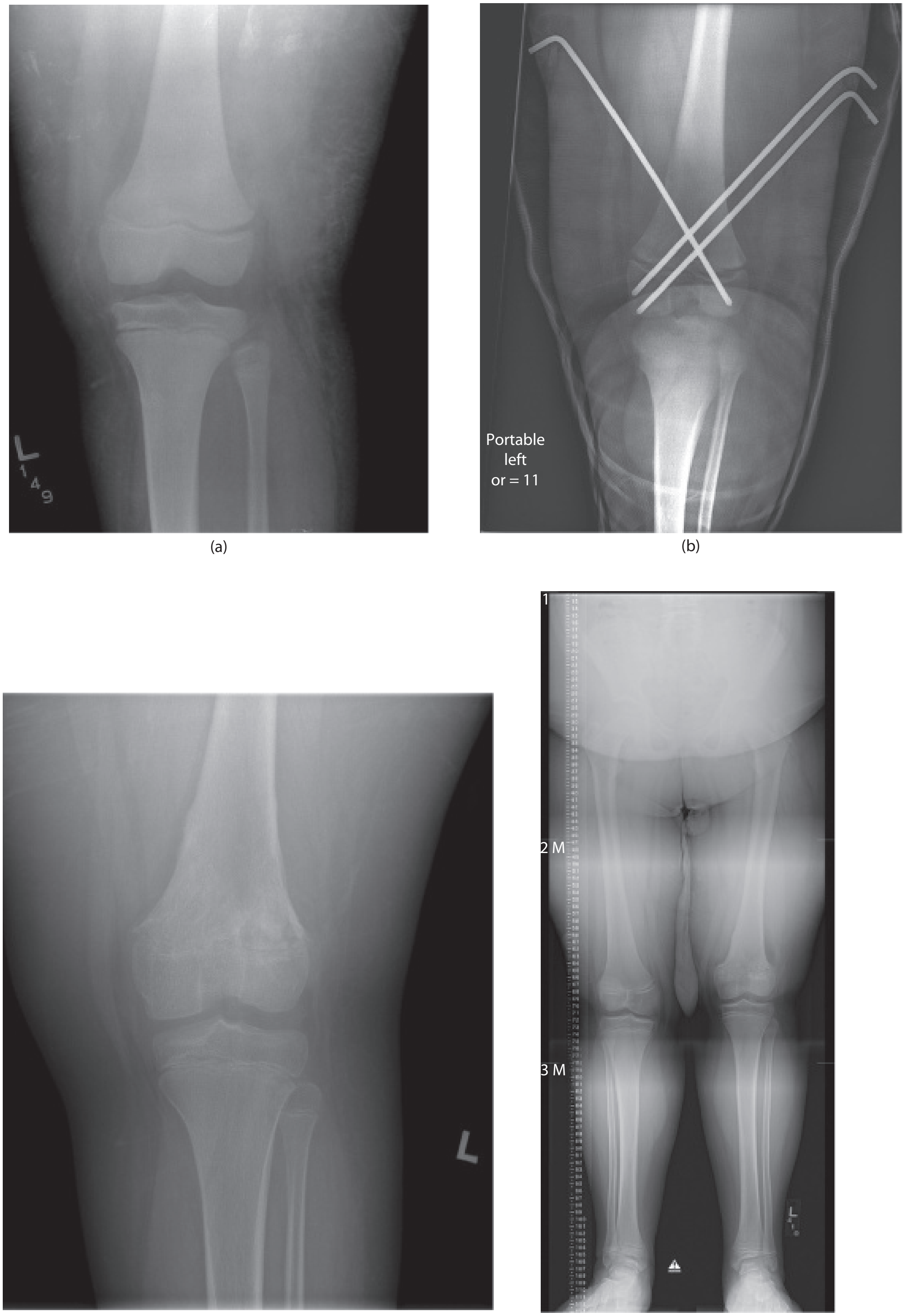
Knee injuries

After a fracture is excluded, the most common causes of traumatic knee effusions in children are anterior cruciate ligament (ACL) tears and patellar dislocations [51]. ACL tears frequently occur with a noncontact twisting mechanism during sports. A higher-energy mechanism, such as a motor vehicle collision or a contact injury during sports, may result in concomitant collateral and/or posterior cruciate ligament injuries. While a knee dislocation occurs when at least three ligaments are disrupted, bicruciate injuries have equally high rates of associated neurovascular injuries [52]. Because there may not be a significant deformity associated with a knee dislocation [52], the physician must have a high suspicion for the presence of these injuries. A careful ligamentous exam should be performed on all patients with lower extremity trauma. Laxity with varus or valgus stress with the knee in full extension suggests at least a combined cruciate and collateral ligament injury. The knee with an isolated collateral ligament injury should be stable to varus, and valgus stress with the knee extended with increased laxity detected only when flexed to approximately 30°. A significant knee effusion may not be present with a knee dislocation due to capsular disruption with more significant swelling seen in the soft tissues around the knee and leg. Knee dislocations are complicated by nerve injury in 25% and popliteal artery injury in 18% [53]. Multiple methods have been described to evaluate for arterial injury associated with knee dislocations, including angiography, duplex ultrasound, ankle brachial index, and MR angiography [53]. An MRI should be obtained to confirm diagnosis of a knee dislocation and to determine which



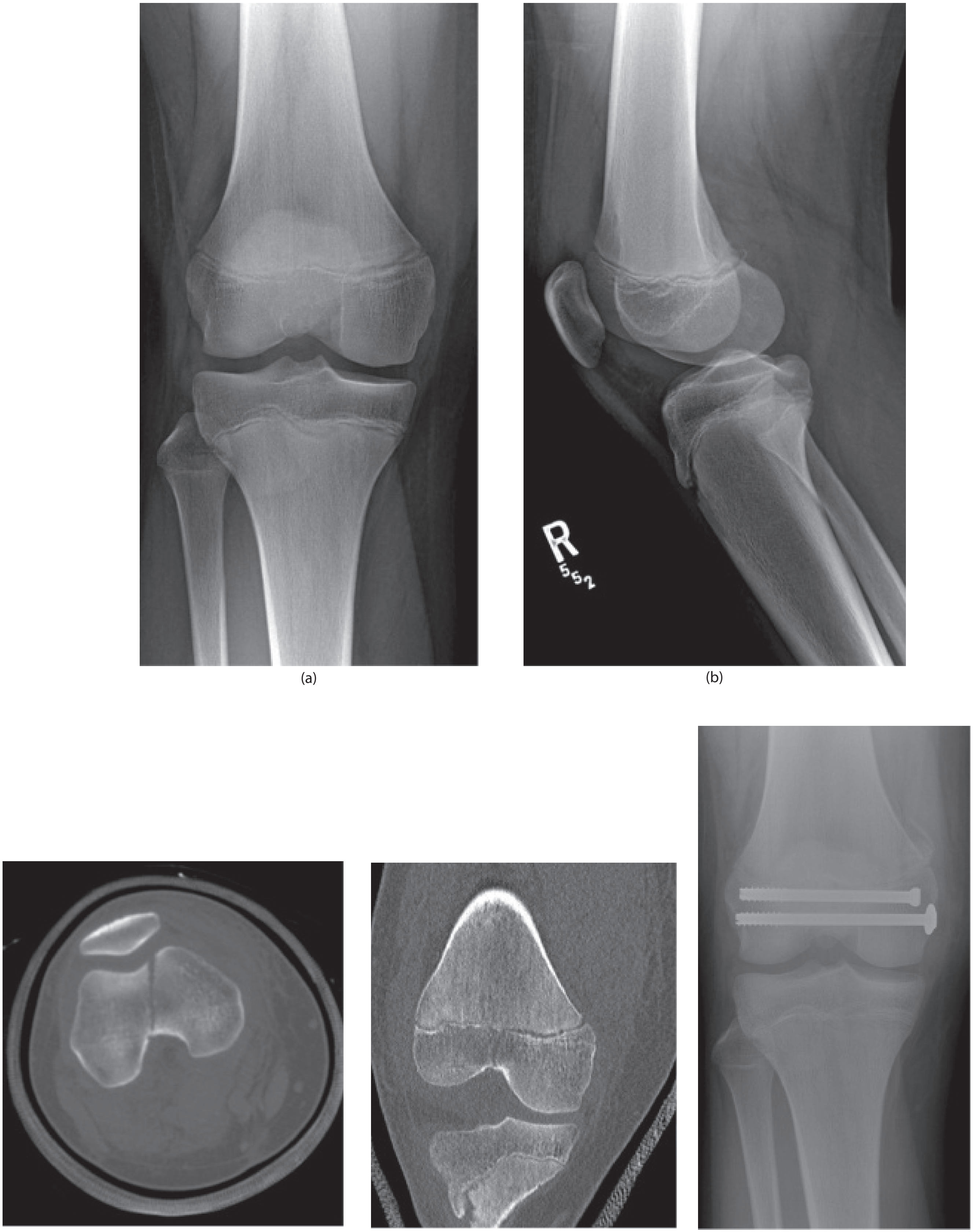
(a) (b) (c) (d)

Figure 20.3.33 **(a)** and **(b)** Radiographs of a 15-year-old male who sustained a Salter-Harris II distal femur fracture while playing football. **(c)** and **(d)** The fracture was treated with open reduction and screw fixation.



(a) (b) (c) (d)

Figure 20.3.34 **(a)** and **(b)** Radiographs of a 9-year-old male who sustained a Salter-Harris II distal femur fracture with a very small Thurston-Holland fragment that was treated with closed reduction and pinning. **(c)** and **(d)** Radiographs at 1 year after injury showed that he had developed premature physeal closure resulting in a leg length discrepancy.



(a) (b)

(c) (d) (e)

Figure 20.3.35 **(a)** and **(b)** Radiographs of a 14-year-old male who injured his knee while playing football show no obvious fracture. **(c)** and **(d)** A CT was obtained which showed a Salter-Harris III distal femur fracture. **(e)** The fracture was treated with percutaneous screw fixation.

ligaments are disrupted. After reduction, the knee should be stabilized in a splint or brace. Occasionally, an external fixator is required to keep the knee reduced until ligament reconstruction can be performed on an elective basis.

Patellar dislocations should not be confused with knee dislocations. Patellar dislocations usually occur as the result of a low-energy trauma that forces the patella to dislocate laterally. The patella often spontaneously reduces with extension of the knee. Occasionally, the patella has to be reduced manually by extending the knee and pushing the patella medially. In patients with a large effusion, an MRI should be considered to evaluate for an osteochondral fracture of the patella and/or lateral femoral condyle that has resulted in a loose body within the knee [54–57]. Patients are often predisposed to patellar dislocation due to their alignment (increased femoral anteversion, genu valgum, high Q-angle, high tibial tuberosity to trochlear groove distance), patella alta, trochlear dysplasia, young age, and hyperlaxity [58–61]. First-time patellar dislocations are usually treated conservatively with immobilization in a knee brace followed by therapy to improve the patient's range of motion and strength. The physician must be aware, however, of the high risk of redislocation in younger patients [61–63]. Surgery is usually reserved for those patients with recurrent patellar dislocations or those who sustain an osteochondral fracture at the time of injury resulting in a loose body within the joint.

Proximal tibia fractures

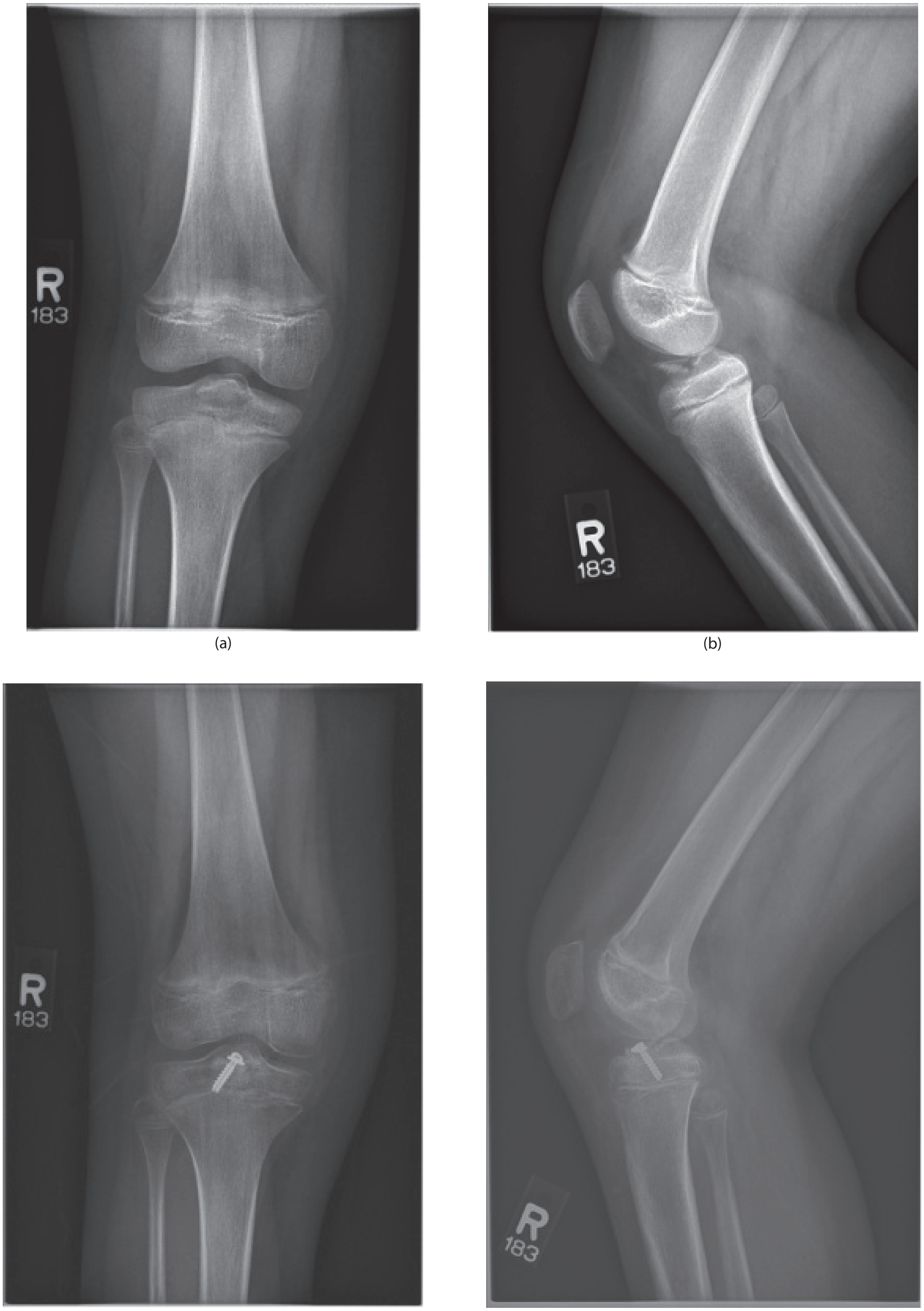
Tibial spine fractures occur when the ACL is avulsed with a portion of bone at its tibial insertion. These injuries most commonly occur during sports [64,65] and bicycle accidents [66]. Examination of these patients usually reveals a large knee effusion or hemarthrosis and increased anterior translation on Lachman and anterior drawer testing. X-rays show a fracture of the tibial spine which is classified according to its displacement on the lateral view [66,67]. A type 1 fracture is nondisplaced. A type 2 fracture is one that is extended anteriorly, hinging on its intact posterior border. A type 3 fracture has complete separation of the fragment from its bed and is displaced. Treatment is based on fracture classification. Type 1 fractures are treated nonoperatively with a long leg or cylinder cast in relative extension (0°–20°). Type 3 fractures are most often treated operatively with arthroscopic or open reduction and internal fixation either with screws or sutures (Figure 20.3.36). Treatment of type 2 fractures is surgeon dependent. An attempt at reduction of these fractures may be performed by aspirating the hemarthrosis and immobilizing the knee in full extension. If unsuccessful, surgery may be considered using a technique similar to that described for type 3 fractures [64]. Closed reduction will be unsuccessful if the meniscus and/or intermeniscal ligament is interposed between the fracture fragment and its bed [64,68]. An MRI is often obtained when evaluating these injuries as there is a high association with other concomitant intra-articular injuries, such as meniscus tears [64,65,69].

Tibial tuberosity fractures occur most often during jumping or landing from jumping [70], causing the extensor mechanism to avulse the apophysis at the patellar tendon's insertion. Following this injury, patients usually have significant swelling and bruising overlying the proximal tibia and a large effusion. A mobile fracture fragment or a defect may be palpable. X-rays usually show a displaced bony fragment and possibly patella alta, depending on the degree of fracture displacement. An ossicle seen on x-rays at the tibial tuberosity with Osgood-Schlatter disease should be differentiated from a tibial tuberosity fracture based on history, mechanism of injury, and exam. Because the fracture often involves the articular surface of the proximal tibia, a CT or MRI may be considered during the evaluation of these patients [70]. The anterior recurrent tibial artery lies close to the fracture and can be avulsed at the time of injury. Bleeding from this artery into the anterior compartment of the leg can result in compartment syndrome [70,71]. Treatment of displaced fractures usually consists of open reduction and internal fixation with cannulated screws followed by immobilization for 4–6 weeks (Figure 20.3.37).

Proximal tibial physeal fractures are rare injuries that usually occur with a high-energy mechanism, often during sports [72,73]. Because the popliteal artery is tethered posteriorly and the spike of the metaphyseal fragment in these fractures displaces posteriorly, arterial injury should be evaluated whenever this fracture is encountered [72,74,75]. X-rays should be obtained. The diagnosis is easily made if the fracture is displaced, but it is possible for the fracture to have spontaneously reduced or to have been reduced by coaches, parents, or medical personnel prior to presentation to the emergency department (Figure 20.3.38) [72,74,75]. Due to the risk of arterial injury at the time of injury, promp diagnosis of this fracture is important. Ankle-brachial index measurement and frequent monitoring for arterial insufficiency is important. Angiography should be considered if there are any concerns for arterial injury. Compartment syndrome and peroneal nerve injury are also potential complications of these injuries [72]. Reduction in the emergency department may be considered if there is no neurovascular compromise. If there is concern for a vascular injury, reduction should be performed in the operating room under anesthesia. If the fracture is unstable after reduction, crossed pins may be placed to stabilize the fracture. A long leg cast is applied and can be bivalved if there are concerns for swelling or compartment syndrome.

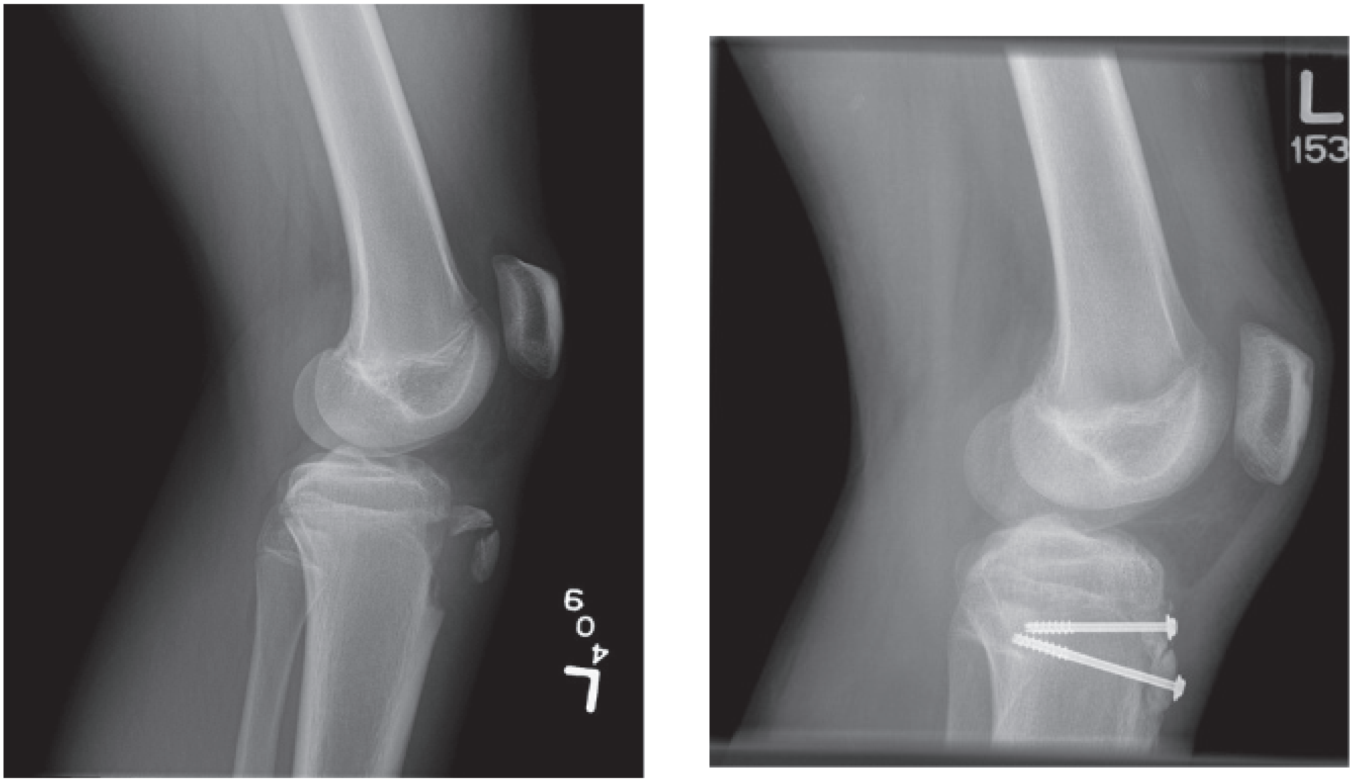
Tibial shaft fractures

There is a wide spectrum of tibial shaft fractures encountered in children. The "toddler's fracture" occurs most frequently in children under 3 years old during a relatively benign twisting mechanism that often is not witnessed by parents and leaves



(a) (b) (c) (d)

Figure 20.3.36 **(a)** and **(b)** Radiographs of an 8-year-old female with a type 3 tibial spine fracture. **(c)** and **(d)** The fracture was treated with arthroscopic suture and screw fixation within the epiphysis to avoid injury to the proximal tibial physis. Radiographs show advanced healing at 4 months postoperatively.



(a) (b)

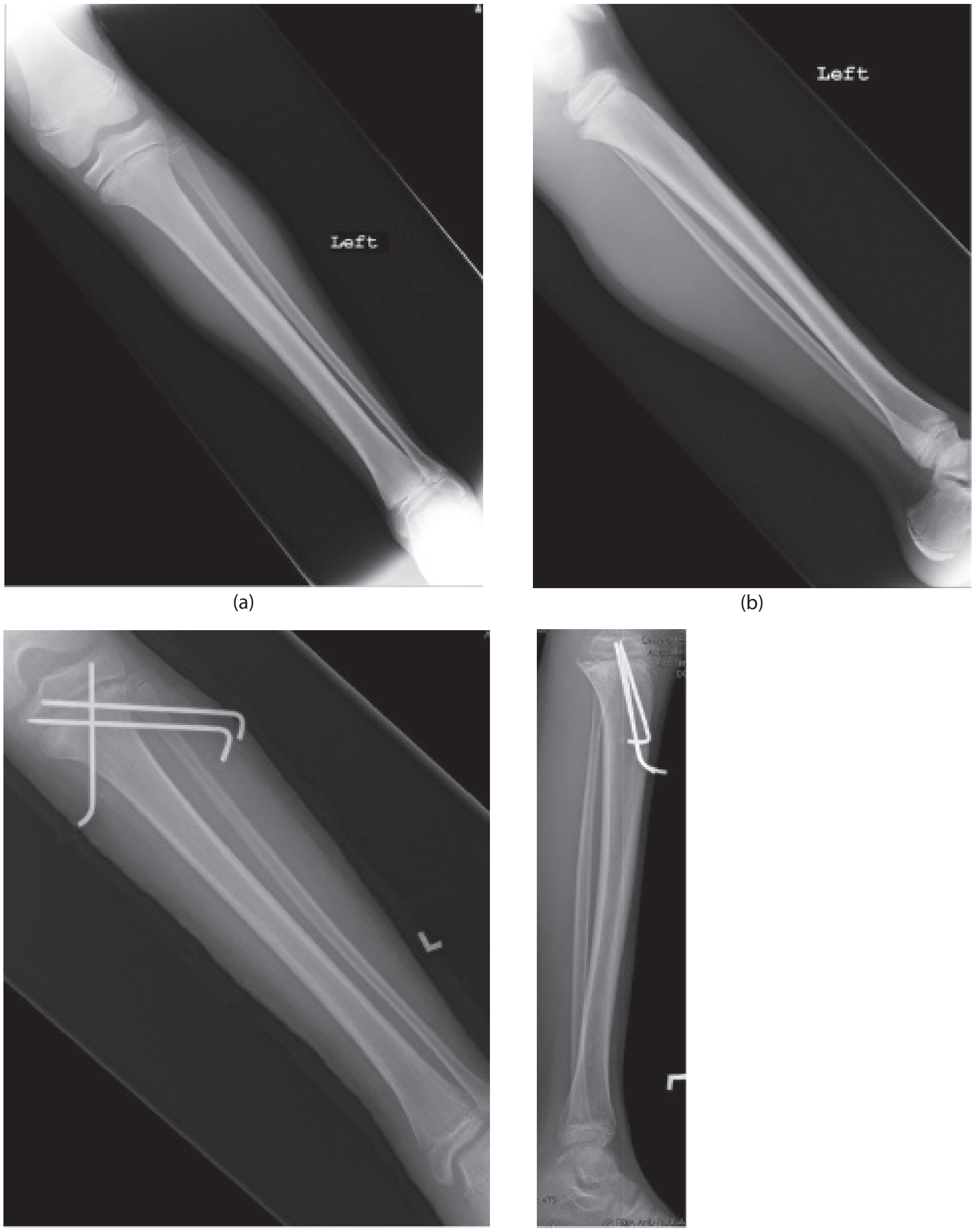
Figure 20.3.37 **(a)** and **(b)** Radiographs of a 14-year-old male who sustained a displaced, comminuted tibial tuberosity fracture resulting in patella alta while playing basketball. His fracture was treated with open reduction and screw fixation.

the child limping. X-rays may initially be normal or may show a nondisplaced spiral fracture of the distal tibial metaphysis [76]. These are stable injuries and are treated with immobilization in a weight-bearing cast or walking boot for 3–4 weeks.

Tibial shaft fractures in the older adolescent are more often associated with high-energy trauma. Due to the subcutaneous nature of the anterior tibia, these fractures are often open. Depending on the severity of the injury, examination may show significant deformity and swelling. Risk for compartment syndrome is high [77], so careful attention to the degree of swelling and neurovascular status of the leg and foot is necessary. X-rays are usually adequate to diagnose this injury and plan management (Figure 20.3.39). If the fracture line extends distally, a CT may be ordered to assess the distal tibial articular surface. If the fracture is open, antibiotics should be started immediately and a tetanus booster should be given if immunization status is not known or is not up-to-date. Cultures are not indicated [78–81]. The wound should be irrigated in the emergency department and the fracture immobilized in a splint. If the fracture is closed, it may be reduced and splinted in the emergency department. Patients are usually admitted for observation due to the risk of compartment syndrome [77]. Treatment may be continued in a cast if the fracture is stable [82,83]. Surgical treatment is indicated if the fracture is open, unstable, or malaligned. Surgical treatment varies with the age of the child. In older adolescents and adults, treatment of tibial shaft fractures is usually with a rigid intramedullary nail. Since this requires an entry point through the proximal tibia, use of a rigid nail should be avoided in children with open physes. Flexible nails with entry points at the medial and lateral proximal tibial metaphysis distal to the physis may be used to stabilize tibial shaft fractures in children with growth remaining [83–87]. Stabilization of tibial fractures with external fixation is usually reserved for skeletally immature patients with comminuted fractures and patients with significant soft tissue injury, such as from an open fracture.

Ankle fractures

Ankle fractures are very common fractures in the pediatric and adolescent population. Physical examination is very important in evaluation of these injuries in growing children, as many occur through the physis and have benign appearing x-rays. In general, if a patient with open physes has tenderness over the distal tibial or distal fibular physis, he should be treated for a fracture with immobilization and restricted weight bearing. Follow-up x-rays in 10–14 days can usually confirm the presence of a fracture with evidence of periosteal reaction. If the patient's pain is greatest in the region of the lateral ankle ligaments or the deltoid ligament, he may be treated for an ankle



(a) (b)

(c) (d)

Figure 20.3.38 **(a)** and **(b)** Radiographs of a 13-year-old male who was injured when he was struck in the left leg while playing football and developed compartment syndrome. There is a subtle irregularity at the proximal tibial physis best seen on the lateral image, representing a Salter-Harris I fracture. **(c)** and **(d)** The patient underwent fasciotomies for treatment of his compartment syndrome and percutaneous pinning of his proximal tibial physeal fracture.

sprain with early range of motion and weight bearing as tolerated.

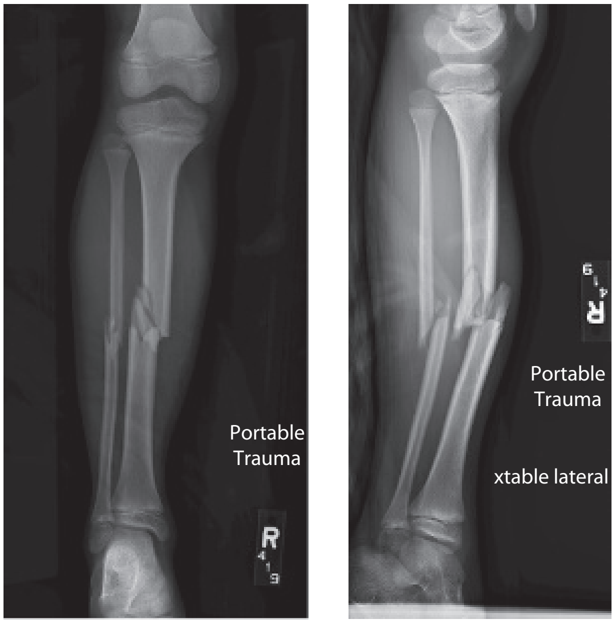
Ankle fractures associated with an ankle dislocation should be reduced and splinted immediately. Postreduction x-rays are important to assess the reduction, particularly if nonoperative or delayed operative treatment is planned. Particularly in young children, closed reduction and casting may be appropriate treatment. In older children with adult-type fracture patterns, operative treatment is often recommended.

Fractures of the distal tibial physis are common. Salter-Harris II fractures occur in younger patients. The epiphysis and its Thurston Holland fragment is often displaced posteriorly allowing the metaphyseal spike of the proximal fragment to impinge on the anterior soft tissues. This can cause compression or increase pressure in the space under the extensor retinaculum, resulting in "extensor retinaculum syndrome" [88]. The extensor hallucis longus (EHL) muscle, the tendons of the anterior compartment muscles, and the deep peroneal nerve lie under the extensor retinaculum at the level of the fracture. Consequently, extensor retinaculum syndrome disproportionately affects the EHL and the deep peroneal nerve, resulting in weakness of the EHL, pain with passive stretch of the great toe, and decreased sensation in the first webspace [89]. Treatment consists of fracture reduction and, if symptoms persist, opening of the extensor retinaculum and internal fixation of the fracture.

Triplane and Tillaux fractures are intra-articular distal tibial physeal fractures occurring in adolescents when their distal tibial physes are closing. The distal tibial physis has a predictable pattern of closure, progressively closing centrally, then medially, and finally laterally. Tillaux fractures are Salter-Harris III fractures of the anterolateral distal tibia that occur through the region of the physis that is still open in adolescent patients with an external rotation mechanism [90]. The fracture should be reduced with internal rotation and splinted [90]. A CT is obtained to determine the degree of displacement and step-off at the articular surface after reduction. If >2 mm of articular step-off or displacement remains after reduction, surgical treatment is usually recommended. Triplane fractures occur in the same age group and with a similar mechanism as Tillaux fractures. Unlike Tillaux fractures, triplane fractures may be two-, three-, or four-part fractures and involve the articular surface and extend into the distal tibial metaphysis as is typical in Salter-Harris IV fractures (Figure 20.3.40). A CT is recommended to assess the displacement and the fracture pattern at the articular surface for surgical planning. Displaced Tillaux and triplane fractures are usually treated operatively with closed or open reduction and internal fixation with screws.

Foot fractures

Talus fractures are rare in children and may occur through both high- and low-energy mechanisms [91,92]. They often occur during a fall from a significant height that dorsiflexes the ankle, allowing the talar neck to impinge against the anterior aspect of the distal tibia. Care must be taken to look for other injuries due to the severe trauma required to cause this fracture. Severe swelling may be present, so compartment syndrome of the foot should be considered. Standard AP, lateral, and oblique x-rays of the foot should be obtained. A CT and/or MRI should be obtained to better assess the fracture pattern and displacement. An MRI may be especially helpful in young children since much of their talus is still cartilage. Treatment of talus fractures depends on the age of the child, the fracture pattern, and its displacement. Younger children have the potential to remodel, so anatomic reduction and stabilization of the fracture may not be required. talar fractures in adolescents are more commonly treated surgically with recommendations similar to those for treatment of adult fractures. Avascular necrosis of the talar body and posttraumatic arthritis are the most significant complications of talar fractures [91,92].



(a) (b)

Figure 20.3.39 (a) and (b) Radiographs of an 8-year-old male who sustained a comminuted tibial shaft fracture when he was struck by a car while riding his bicycle.

Lisfranc injuries are injuries to the tarsometatarsal (TMT) joint that occur most commonly with motor vehicle accidents and falls [93–95]. Sports account for more of the lower-energy Lisfranc injuries, such as when another player lands on a football lineman's heel when the ankle is plantarflexed and the toes are dorsiflexed or when an equestrian gets his foot caught in the stirrup [96]. The Lisfranc ligament runs from the base of the 2nd metatarsal to the medial cunieform. Lisfranc injuries can be a partial or complete tear of the Lisfranc ligament or an injury that avulses the ligament with a piece of bone, usually from its attachment to the base of the 2nd metatarsal. On examination, significant swelling and bruising on the plantar surface of the foot should raise concern for a Lisfranc injury [97]. X-rays may be normal if it is a ligamentous injury. Standing x-rays should be obtained if non-weight-bearing x-rays are normal and a Lisfranc injury is suspected. Widening of more than 2 mm between the 1st and 2nd metatarsal bases is suggestive of a Lisfranc injury (Figures 20.3.41 and 20.3.42). Standing x-rays of the uninjured foot should also be obtained for comparison [96]. CT and/or MRI may also be helpful in evaluating this injury. CT may show a small avulsion fracture of the Lisfranc ligament from the 2nd metatarsal. MRI may show disruption of the ligament itself [98]. Sprains are generally treated with immobilization and restricted weight bearing for at least 6 weeks. Displaced fractures or ligamentous injuries are typically treated with closed or open reduction and stabilization with either k-wires or screws [96].

(a) (b) (c) (d) (e) (f) (g)

Figure 20.3.40 **(a)** and **(b)** Radiographs of a 9-year-old female who sustained a triplane fracture of her left ankle while skating. **(c)–(e)** CT images of her ankle were obtained to determine the pattern and displacement of her fracture. Figure 15a is an axial view through the epiphysis. Figure 15b is an axial view through the metaphysis. Figure 15c is a coronal image showing the displacement of the fracture in the epiphysis. **(f)** and **(g)** The fracture was treated with open reduction and screw fixation.

(a)

(b)

(c)

Figure 20.3.41 **(a)–(c)** Radiographs of a normal foot showing the normal relationship of the medial border of the second metatarsal aligning with the medial border of the middle cuneiform on the AP view and the medial border of the fourth metatarsal aligning with the medial border of the cuboid on the oblique view.

(a) (b) (c)

(d) (e) (f)

Figure 20.3.42 **(a)–(c)** Radiographs of a 13-year-old female who sustained a Lisfranc injury when she fell from a zip line. In addition to the fracture at the base of her second metatarsal, notice that the medial border of the second metatarsal does not line up with the medial border of the middle cuneiform on the AP view, indicating a Lisfranc injury. The medial border of the fourth metatarsal does line up with the medial border of the cuboid on the oblique view. **(d)–(f)** The fracture was treated with screw fixation of the Lisfranc joint (medial cuneiform-base of the second metatarsal) and of the first metatarsal–medial cuneiform joint. Radiographs obtained 6 months postoperatively show healing of her fractures.

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21

Pediatric hand trauma

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Introduction

Pediatric hand trauma remains somewhat of a black box even to the most experienced traumatologist. In the multisystem trauma, life-threatening injuries must be addressed first. However, for best long-term results hand injuries must be recognized early, and the hand surgeon should be involved as soon as possible. This is especially true for open, vascular, or potential nerve injuries. Keep in mind that, due to the peripheral location of the hand, the hand surgeon can usually perform at least temporizing procedures while the trauma surgeon or neurosurgeon operates on the trunk or head.

History

Publications depicting the anatomy and function of the hand as a clinical entity first appeared in the nineteenth century with major contributions from Sir Charles Bell's treatise "The Hand—Its Mechanism and Vital Endowments as Envincing Design" in 1834 and Duchenne's "Physiology of Motion" in 1867. However, it was not until the pre-World War II era that small groups of general surgeons in America recognized the consequences of hand disability and strove to cultivate the field of hand trauma. Through pioneering efforts across the country—from Kanavel and Koch of Chicago; Bunnell of San Francisco; Blair and Barret Brown of St. Louis; and Webster, Auchincloss, and Cutler of New York—the specialty of hand surgery began to evolve. With Cutler's 1942 publication "The Hand. Its Diseases and Disabilities" and Bunnell's "Surgery of the Hand" in 1944, hand surgery was firmly established as a true and distinct surgical specialty [1].

Literature

Excellent basic overviews can be found in both the emergency medicine and the pediatric literature. Though published in 1998, Ablove, Moy, and Peimer's "Pediatric Surgery for the Primary Care Pediatrician, Part II" in *Pediatric Clinics of North America* remains a useful tool for the basic evaluation and treatment of a variety of hand injuries in children [2]. They also include recommendations on what studies to perform and when to consult a specialist. Additionally, Harrison and Hilliard in "Emergency Department Evaluation and Treatment of Hand Injuries" in *Emergency Medicine Clinics of North America*, November 1999, provide further detail in the appraisal of specific injuries [3]. Although both papers are the reviews rather than actual studies, they provide a quick reference of the generally accepted standard of care for most acute hand injuries. For greater detail on how to perform common emergency room procedures of the hand, Henretig and King's second edition of *Textbook of Pediatric Emergency Procedures*, published in 2008, provides thorough step-by-step instructions with illustrations [4].

It is important to note that when compared to adults, children demonstrate an exceptional regenerative ability that allows for great ingenuity in both surgical and nonsurgical treatment. Because of this, new treatment techniques are constantly pioneered, and close attention to the evolving literature on hand trauma will help make one aware of new treatment options and recommendations.

Diagnosis of hand injuries

Clinical assessment

After initial stabilization of the patient following Advanced Trauma Life Support (ATLS) guidelines, a complete history and physical focusing on the entire upper extremity must be performed.

History should include basic information such as the child's age, dominant hand, and any prior injury to that extremity. Specific information relating to the accident including when and where it happened, the mechanism of injury, the position of the hand at the time of injury, and treatment received thus far is invaluable in formulating further treatment plans. A general medical and surgical history including tetanus immunization, current medications, and allergies should be obtained as well.

A focused physical exam follows. Expose the entire upper extremity including the shoulder and neck. Note the color of the hand as well as any swelling or edema and whether it is generalized or localized to specific areas. Observe the position of the upper extremity and determine any abnormality in its positioning. Both active and passive motion of the hand, fingers, and wrist should be checked and documented, as should sensation and vascularity.

To perform an accurate and detailed physical exam specific to the hand requires an exhaustive knowledge of hand anatomy and kinetics. Knowing the location and function of each component will help direct the physician's thinking during clinical assessment. A review of anatomy including muscles, tendons, nerves, and vascular supply is appropriate at this point.

Extrinsic muscle flexors

The bellies of the extrinsic muscles are located in the forearm with the flexors residing on its volar surface. The flexor pollicis longus (FPL) attaches to the distal phalanx of the thumb and bends both the metacarpophalangeal (MP) and interphalangeal (IP) joints of the thumb. The flexor digitorum profundus (FDP) attaches to the distal phalanx of each finger and bends all joints. It has a common muscle belly for the small, ring, and long fingers and usually an independent muscle for the index finger. The flexor digitorum superficialis or sublimus (FDS) attaches to the middle phalanx of the finger and bends the MP and the proximal interphalangeal (PIP) joints of the fingers. The FDS has independent muscle bellies for each finger; however, the muscle tendon unit to the little finger may be small or even absent. These anatomic differences allow for specific testing of each muscle on physical exam. The FDP can be tested by asking the patient to bend the finger at the distal interphalangeal (DIP) joint while the PIP joint is stabilized in extension by the examiner. Conversely, asking the patient to bend the finger at the PIP joint while the other joints are stabilized in extension can test the FDS.

In a young or unconscious child who cannot cooperate with an examination, the flexors can be indirectly evaluated by observing the digital cascade and the tenodesis effect. When the hand is in a resting position, the digits have a cascade of progressively increasing flexion from the index through the little finger (Figure 21.1). The tenodesis effect can be observed by passively flexing and extending the wrist. As the wrist moves from flexion to extension, intact flexors are placed under tension, causing the fingers to flex into their normal cascade. One may also squeeze the forearm, causing flexion of the digits with intact flexor tendons.

Injuries may occur anywhere along the course of the tendon, which has been divided into zones that differ in tendon phenotype, underlying anatomy, and approach as well as response to treatment (Figure 21.2) [5]. Zone I extends from the fingertip to the middle phalanx just distal to the insertion of the FDS. Zone II then begins and extends to the distal palmar crease. This zone notoriously contains an essential pulley system that prevents bowstringing of the tendons upon flexion. Injuries in this zone have the worst prognosis due to adhesion formation and failure of the tendon to glide within the pulley system. Zone III lies between the distal and proximal palmer creases, while well as Zone IV contains the carpal tunnel, extending from the proximal palmar crease to the distal wrist crease. Zone V extends proximally from the distal wrist crease.

Extrinsic muscle extensors

The extrinsic extensor tendons are arranged in six discrete compartments over the dorsum of the wrist that are separated by retinacular attachments to the radius and ulna bones (Figure 21.3a). The first dorsal compartment contains the abductor pollicis longus (APL) and extensor pollicis brevis (EPB). The muscles of this compartment contribute to abduction of the thumb. The second dorsal compartment contains the extensor carpi radialis longus (ECRL) and the extensor carpi radialis brevis. Both extend the wrist while the ECRL also causes radial deviation. The third dorsal compartment contains the extensor pollicis longus (EPL). The EPL lifts the thumb vertically with the palm flat down on a surface. The fourth dorsal compartment contains the extensor digitorum communis (EDC) and the extensor indicis proprius (EIP). The EDC is a common muscle belly that extends all four fingers while the EIP extends only the index finger. The fifth compartment contains the extensor digiti minimi (EDM) which extends the little finger, and the sixth dorsal compartment, containing the extensor carpi ulnaris (ECU), contributes to wrist extension and ulnar deviation.

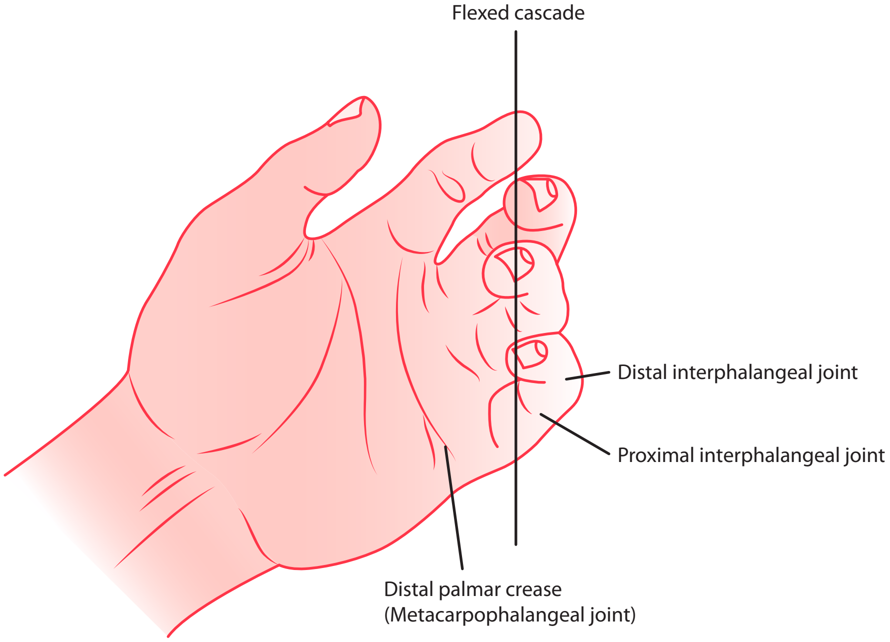

Figure 21.1 A normal cascade with increasing flexion from the index through small fingers.

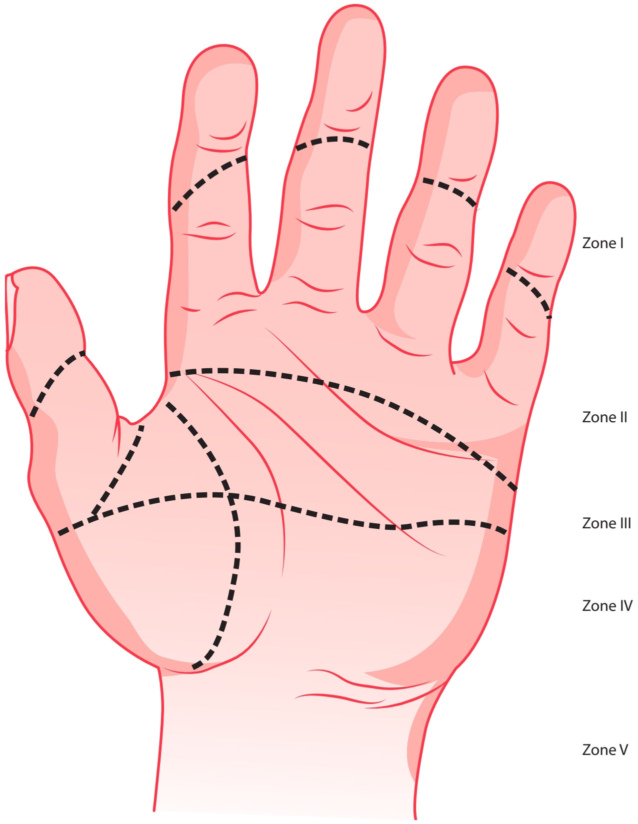

Figure 21.2 The flexor tendon zones of the hand.

Just as the flexor tendons may be divided into longitudinal zones, so too are the extensor tendons (Figure 21.3b). This classification, described by Kleinert and Verdan, illustrates eight zones of injury relative to underlying structures and joints that help guide treatment [6].

Neurological evaluation

Neurological evaluation of the pediatric hand varies depending upon the age, willingness to cooperate, and state of consciousness of the child. Ideally, both motor and sensory exams can be thoroughly completed. Full consideration must include three major nerves that innervate the hand, namely, the median, ulnar, and radial nerves.

The median nerve originates from the medial and lateral cords of the brachial plexus. It enters the forearm through the pronator teres muscle and innervates the flexor carpi radialis (FCR), palmaris longus (PL), the FDS to all fingers, the FDP to the index and long fingers, the FPL, and both forearm pronators. It enters the hand through the carpal tunnel and innervates the thenar muscles including the abductor pollicis brevis, the radial half of the flexor pollicis brevis (variable), the opponens pollicis, and the lumbricals to the index and long fingers. Test motor function by having the patient pinch the thumb and index finger while palpating the contraction of the thenar muscles.

The ulnar nerve originates from the medial cord of the brachial plexus and enters the forearm just posterior to the medial epicondyle between the two heads of flexor carpi ulnaris (FCU). It innervates the FCU and the FDP to the ring and little fingers. The ulnar nerve enters the hand through Guyon's canal and innervates the abductor digiti minimi, the hypothenar muscles (flexor digiti minimi, opponens digiti minimi, and abductor digiti minimi), the lumbricals to the ring and little fingers, all of the interossei, and the adductor pollicis. It may also innervate all or the ulnar half only of the flexor pollicis brevis. Test the ulnar nerve by having the patient either spread the fingers out against resistance or by crossing the fingers, both of which require proper functioning of the intrinsic muscles. This should be compared to the contralateral hand.

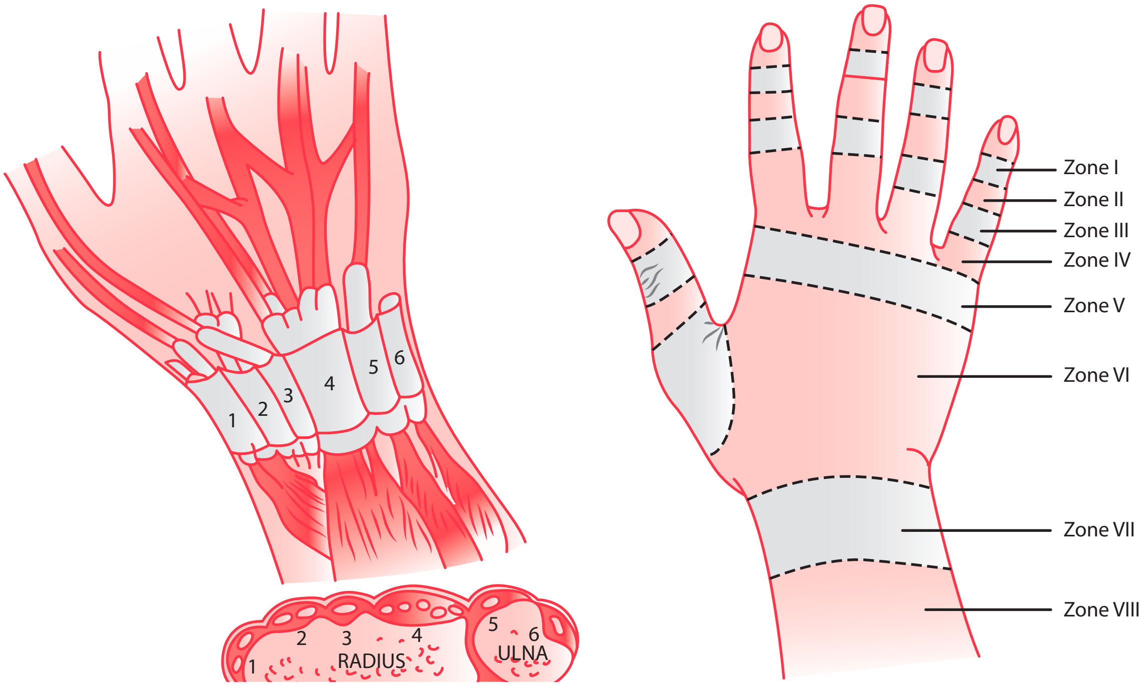

Figure 21.3 **(a)** The six extensor compartments of the wrist. **(b)** The extensor tendon zones of the hand. (Courtesy of Texas Children's Hospital, Houston, Texas.)

The radial nerve originates from the posterior cord of the brachial plexus and enters the forearm through the supinator muscle. It innervates the supinator, EDC, EDM, ECU, APL, EPL, EPB, and EIP. Test motor function by having the patient extend the wrist and fingers.

Furthermore, these nerves provide sensory information from well-defined distributions along the volar and dorsal surfaces of the hand (Figure 21.4). Assessing the appropriate distribution is important with injuries proximal to the wrist where the main trunks of these nerves may be severed. Sensation from the median nerve is best tested on the radial side of the index fingertip. The ulnar nerve should be assessed at the ulnar side of the little fingertip while the radial nerve is evaluated by touching the dorsum of the hand between the first and second metacarpals.

The digital nerves travel on the volar aspect on each side of the fingers. Sensation from these nerves is ideally tested using the two-point discrimination test. This is accomplished by bending a paper clip so its tips are about 5 mm apart, as normal two-point discrimination is less than or equal to 5 mm. On both the radial and ulnar side of each digit, touch the child's finger with just enough pressure to cause skin blanching with either one or two points. Inability to discriminate one point from two with repeated testing may indicate an injury. However, it should be emphasized that in children it is often difficult to obtain the degree of attention and cooperation necessary to perform this exam reliably. In these situations, when the location of the injury makes nerve transection likely, operative exploration is recommended.

Vascular examination

The radial and ulnar arteries supply the hand. A general vascular exam is accomplished by checking both pulses at the level of the wrist on the volar surface along with the color of the skin and the capillary refill at the nailbeds. Within the hand, these vessels usually anastomose to one another via a deep and superficial arch. Therefore, in an emergency situation, one of these arteries may usually be ligated without threat of hand ischemia. Ten to 15% of patients do not have an intact arch system and may require both vessels to perfuse the hand. This can be confirmed with the Allen test (Figure 21.5). The examiner compresses both vessels at the wrist, then the patient opens and closes the hand several times to fully exsanguinate it. One vessel is then released, and the hand is assessed for its vascularity with return of blood flow and color. This is then repeated with the other vessel. Failure of the hand to reestablish normal capillary refill (normal <3 s) with either the radial or ulnar artery indicates the likelihood of an incomplete vascular arch and dependence on both radial and ulnar arteries.

The deep palmar arch gives off the palmar metacarpal arteries. These, in turn, become the digital arteries that travel alongside corresponding digital nerves along the volar aspect of each side of the fingers. The ulnar artery supplies two additional named arteries that supply the thumb muscle and index finger, namely, the princeps pollicis artery and the radialis indicis artery, respectively. The princeps pollicis artery runs between the flexor pollicis brevis muscle and the tendon of the FPL while the radialis indicis artery

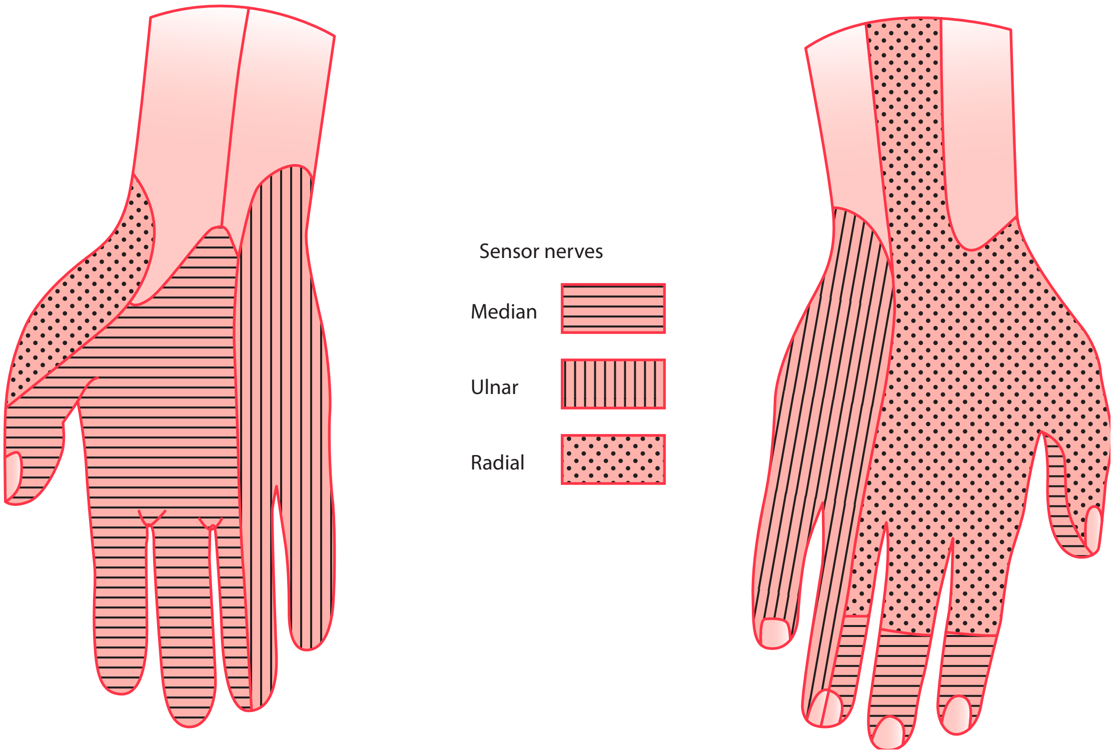

Figure 21.4 The sensory distribution of the hand.

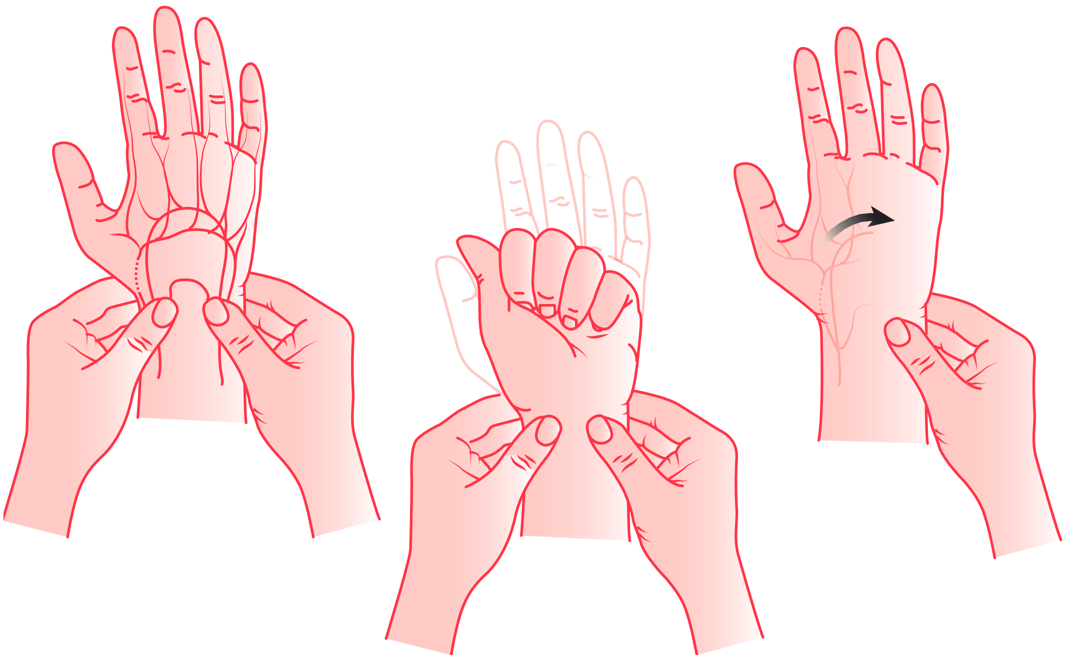

Figure 21.5 The Allen test. (Courtesy of Texas Children's Hospital, Houston, Texas.)

travels along the radial side of the index finger. Finally, tendons receive their blood supply in the digits from vincula, folds of mesotendon that contain small blood vessels and may additionally act as anchors to prevent proximal retraction of a severed tendon. When there is a question of injury, a Doppler should be used to test for a signal.

Other diagnostic tests

Very few diagnostic modalities add significantly to the astute clinical exam in the acute situation. However, in accordance with the American College of Radiology (ACR) Appropriateness Criteria® (last reviewed February 2015), plain three-view radiographs [posteroanterior (PA), lateral, and oblique] that include the joints immediately proximal and distal to the area of trauma can be helpful and are usually indicated. They are especially useful in penetrating trauma or when there is a question of a fracture or foreign body. X-rays should be ordered specifically of the area in which an injury is suspect, as simply ordering "hand x-rays" often results in inadequate visualization of the area of trauma. In the child it may also be helpful to obtain an x-ray of the contralateral uninjured hand. Due to the differences in the rate of growth and ossification, confusion may arise regarding normal versus abnormal anatomy. Comparing x-rays from both hands may clarify this.

In general, the ACR does not recommend CT imaging for the initial assessment of hand trauma. CT without contrast is recommended only for surgical planning or when clinical suspicion of a fracture remains high despite equivocal x-ray findings. Low-field MRI is less sensitive than radiographs for hand and finger fractures, and its role is limited to cases where specific soft-tissue abnormalities of tendons, ligaments, and the pulley system are expected [7].

Angiograms are rarely indicated in hand trauma. Even in cases with significant bleeding, the situation can usually be managed with direct pressure and operative exploration under tourniquet control. Information obtained from an angiogram rarely changes management, particularly as embolization is almost never performed in the upper extremity due to the risk of distal ischemia. An angiogram may be helpful in proximal penetrating wounds with a suspicion of vascular injury. Knowledge of the severity and location of the injury may facilitate proximal exposure, which can be difficult.

Treatment of hand injuries

Anesthesia

In the emergency room setting, local anesthesia can be used in a variety of ways. The most common are digital blocks, wrist blocks, and hematoma blocks. Local anesthesia can also be combined with conscious sedation. In this case, the child's respiration and oxygen saturation must be monitored carefully, and equipment and skilled personnel must be available to control the airway throughout the procedure.

Historically, local anesthetic with 1% or 2% of plain lidocaine without epinephrine was considered the most appropriate method. The traditional custom of withholding epinephrine stems from the theoretical risk of epinephrine-induced digital necrosis. There are 21 reported cases, most within the first half of the twentieth century, of digital necrosis after local injection with procaine and epinephrine [8]. However, recent comprehensive reviews of literature from around the world have revealed not a single report of finger necrosis after the use of lidocaine with epinephrine [8,9]. In their 2012 publication entitled "Epinephrine and Hand Surgery," Tobias Mann and Warren C. Hammert summarize the wealth of retrospective, prospective, and randomized double-blind studies that have recently supported its safety [10]. Moreover, the authors suggest benefits of using epinephrine in local anesthetic that include improved hemostasis during procedures, a decreased need for tourniquet use and sedation, and an increased duration of the analgesic effect in the postoperative period. Avoiding sedation theoretically allows the physician to intraoperatively assess active range of motion. However, literature is lacking as to whether or not epinephrine improves outcomes in hand trauma patients. Until clinical trials are performed to measure differences in cost, complication rate, and patient satisfaction, no official recommendations on the use of lidocaine with or without epinephrine exist.

Digital blocks, the most common nerve block used by ED physicians for minor wounds, can be carried out by either the volar or dorsal approach. The dorsal approach, described here, is the preferred method, as injection through the thicker palmar skin typically elicits much more pain (Figure 21.6). A 25- or 27-gauge needle is inserted at the dorsal base of the web space just distal to the metacarpal–phalangeal joint. A skin wheal is made with 1–2 mL of anesthetic in this area to block the dorsal sensation supplied by the dorsal digital nerve. The needle is then advanced toward the palm until its tip is palpable beneath the volar skin just distal to the web space. Another 1–2 mL is injected to block the palmar digital nerve. This procedure is repeated on the opposite side of the digit to ensure anesthesia of all four digital nerves.

Wrist blocks provide coverage of the median, ulnar, and radial nerves all together to provide a broad anesthetic useful for hand procedures. Physical exam checking for perfusion, sensation, and motor nerve function should be performed prior to injection of the anesthetic, and the surface of the wrist and palm should be disinfected. The specific domains anesthetized by blocking each nerve were previously illustrated in Figure 21.4. The anatomy of these nerves and the approach to blocking each one are described separately below.

The median nerve enters the palm through the carpal tunnel at a location deep to the PL tendon and between the tendons of the FDS and FCR. One can identify the protruding tendon of the PL by having the patient oppose the thumb and little finger while flexing the wrist against resistance. Insert the needle just radial to the PL tendon at the level of the proximal flexor wrist crease and directed distally at an angle 30° from perpendicular (Figure 21.7). In individuals who lack the PL tendon, the injection is made 5 mm medial to tendon of the FCR. A "click" may be felt as the flexor retinaculum is penetrated by the needle. If a paresthesia is elicited (while blocking any nerve), retract the needle slightly before injected 2–3 mL of anesthetic.

As the ulnar nerve runs through the middle forearm, it travels between the muscle bellies of the FDP and FCU muscles. Just proximal to the wrist it gives off both a palmar and dorsal cutaneous branch. As the ulnar nerve enters the wrist, it passes between the tendon of the FCU and the ulnar artery at a location deep to the artery. The ulnar nerve is anesthetized by inserting the needle at the proximal wrist

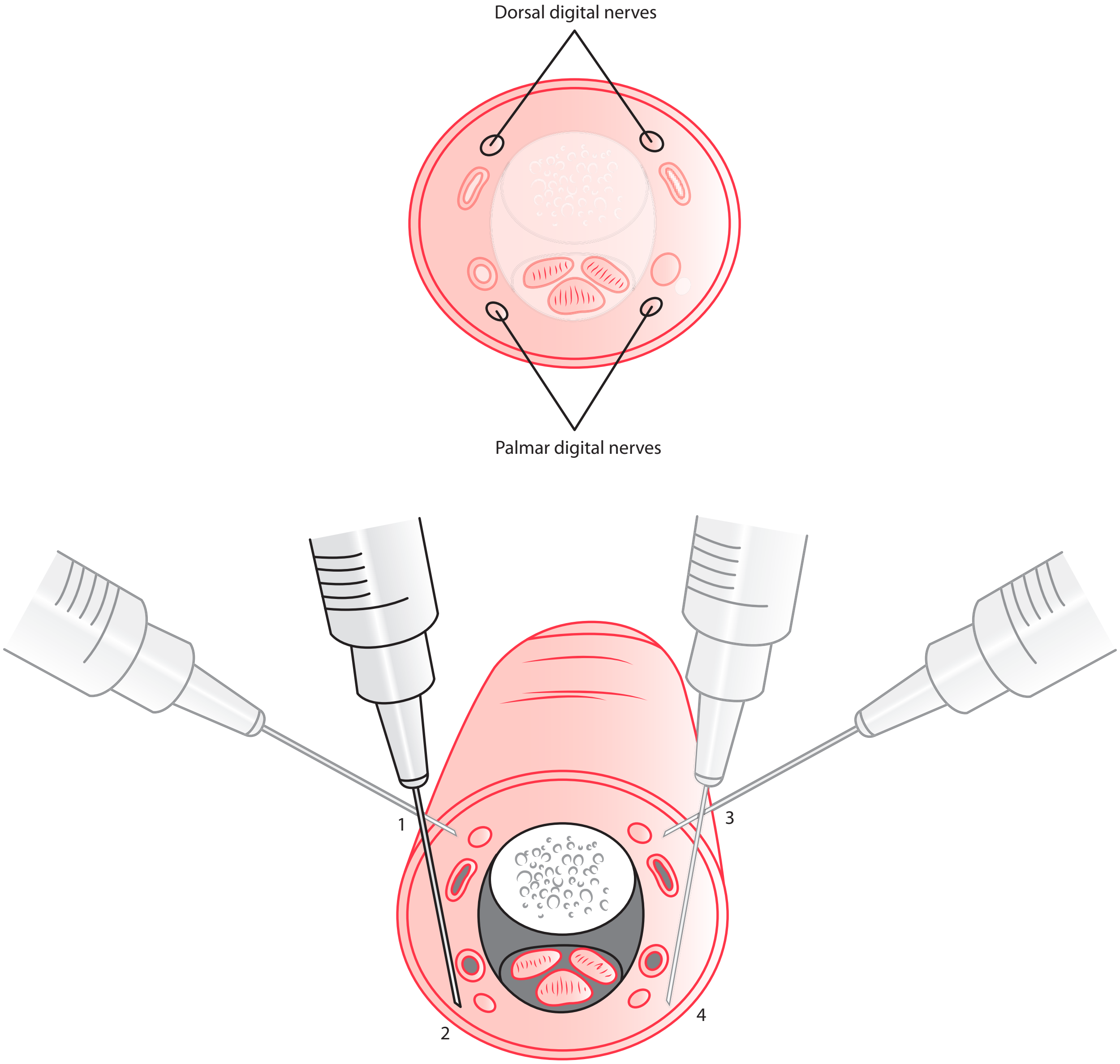

Figure 21.6 The dorsal approach to digital blocks. (Courtesy of Texas Children's Hospital, Houston, Texas.)

crease just medial and dorsal to the tendon of the FCU in an orientation parallel to the wrist crease (Figure 21.7). Dorsal sensory branches are field blocked by subcutaneous infiltration along the entire dorsum of the wrist.

The radial nerve approaches the wrist along the ventral and radial forearm. However, as it continues more distally, the radial nerve develops less predictable anatomy and gives off many smaller cutaneous branches in the wrist. The radial nerve block is essentially a field block with subcutaneous infiltration along a cuff-like distribution, from a location just proximal to the radial styloid to the dorsal midline of the wrist (Figure 21.7).

Hematoma blocks involve directly infiltrating local anesthetic into the hematoma of a fracture site and are most often used when performing closed reduction of a fracture. They may be used in conjunction with digital or wrist blocks.

Tourniquets

A tourniquet should almost always be used during the repair of hand injuries to control bleeding. It may be deflated or released at various times during the procedure to assess vascular perfusion after anastomosis or to assess hemostasis prior to closure. The tourniquet used most frequently is the upper arm tourniquet. Several layers of soft cast padding are wrapped around the upper arm and a standard pneumatic tourniquet placed over it. Traditionally, guidelines state that the width of the cuff should equal the diameter of the arm, but studies by Crenshaw et al. and Hargens et al. suggest wider cuffs allow a lower pressure to be used with the same effect [11,12]. Disposable blood pressure cuffs are appropriately sized for infants and children.

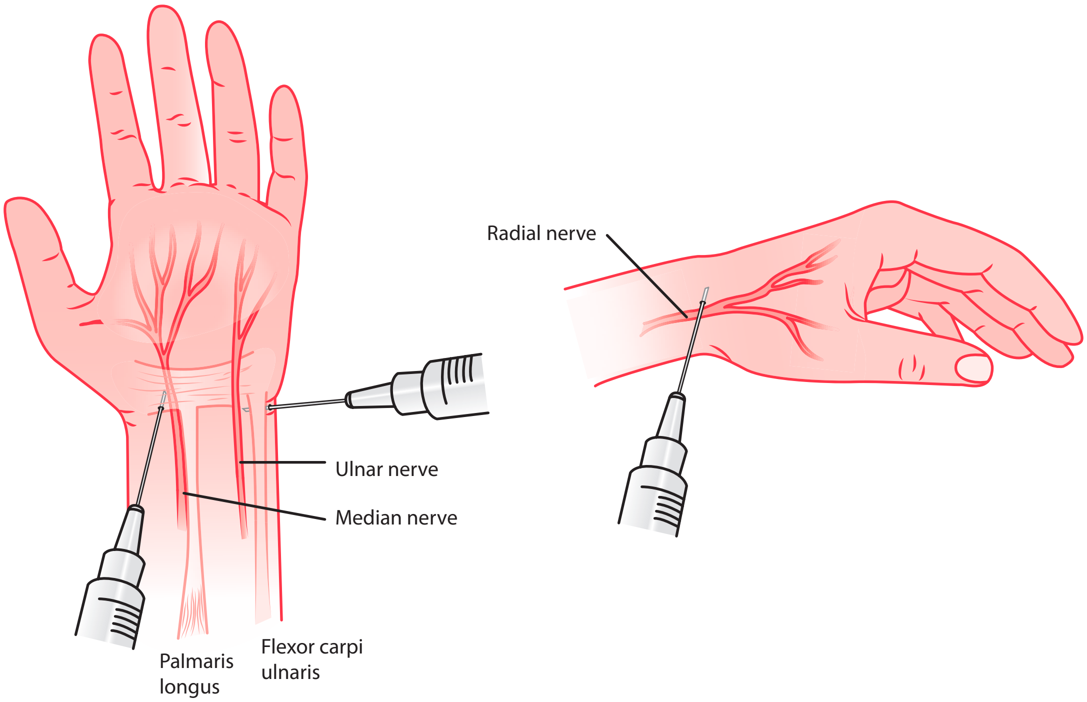

Figure 21.7 Wrist block showing approaches to the median, ulnar, and radial nerves. (Courtesy of Texas Children's Hospital, Houston, Texas.)

Typical pressures needed in children range from 150 to 260 mmHg, with 200 mmHg being the most common. Most hand surgeons will allot a maximum of 120 min of tourniquet time. After this, a period of reperfusion of 15–20 min with the tourniquet deflated is needed for the body to readjust pH in response to the ischemia. As a rule, 5–10 min of reperfusion are needed for every 1 h of tourniquet time.

Finger tourniquets are typically used in the emergency room setting for digital procedures. After the instillation of local anesthesia, a 0.25-in Penrose drain is wrapped around the finger distally to proximally to exsanguinate it, then clamped to itself at the base of the finger to achieve a tourniquet (Figure 21.8). Salem has described cutting the finger from a sterile rubber glove, stretching it over the operative digit, and rolling it proximally once the tip has been cut off to form a ring at the base of the finger [13]. In practice, it is usually easier to place the entire glove on the hand, then cut the tip of the finger off the glove and roll this proximally. Keep in mind that excessive pressure can easily be generated using these finger tourniquets. They should only be used for very short procedures.

Tendon injuries

Assessment of tendon injuries often relies heavily on the physical exam, as children tend to be less communicative about the events of the injury. After an initial survey looking for lacerations, deformities, or signs of bleeding, the child should be coached into active movement of each tendon suspected to be involved in the injury. Alternatively, observation of tenodesis and the digital cascade described previously can often reveal injured tendons. Flexor tendon injuries are commonly associated with neurovascular injury while extensor tendon injuries may involve intra-articular injury [14]. Complete work-up must consider these entities as well.

Extensor injuries are more common given their superficial location in the hand. Suspected injuries should be explored and repaired under tourniquet control in the operating room. There is no indication for wound exploration in the emergency room. The type of surgical repair performed depends largely on the zone in which the injury occurred and whether or not it was an open or closed injury [15,16]. Closed injuries to the distal zones (over the phalanges) may be treated with wound care and extension splinting. Open injuries and injuries of the proximal zones over the hand usually require primary surgical repair followed by splinting. Of note, suspected tendon injuries need not be operated on immediately. It is acceptable to consult a hand surgeon and simply suture the skin and splint the patient. The hand and wrist are placed in a dorsal splint with the wrist at 30° of extension, the MP joints in 70° of flexion, and the IP joints extended. Repairs should generally be performed within 1 week of the injury. Prolonged delay results in retraction of the proximal tendon and may result in the need to perform tendon grafting. Occasionally, given the superficial location of extensor anatomy, extensor tendons may be seen in the wound. Repair can be accomplished in the emergency room. However, consultation with a hand surgeon is still imperative.

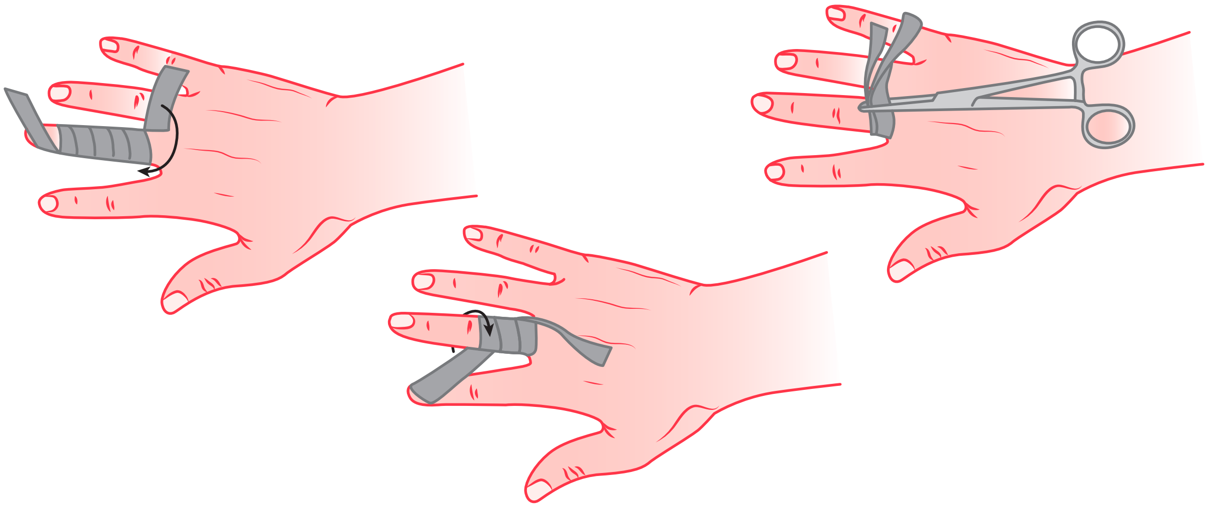

Figure 21.8 Penrose drain tourniquet technique. (Courtesy of Texas Children's Hospital, Houston, Texas.)

Flexor tendon injuries are most commonly open and caused by lacerations. Closed injuries, most often Zone I injuries, usually result from forced extension of the finger while actively flexed. Flexor tendon injuries are treated surgically.

Unlike the adult population, early range of motion exercises are not as frequently employed postoperatively in very young children (less than 4 years old) due to issues with compliance. Flexor and extensor tendon repairs in young children may be splinted for approximately 4 weeks to decrease the risk of rupture of the repair [17,18]. At this point, controlled mobilization is begun.

Nerve injuries

In the event of a suspected nerve injury, a hand surgeon should be consulted. Much like the treatment of tendon injuries, immediate repair is generally not necessary. The skin can be closed and the patient splinted as described previously. Nerve repair within the first 2–3 weeks is acceptable. Too long a delay, however, can lead to retraction of nerve ends necessitating grafting.

Vascular injuries

If a vascular injury is suspected, the examiner should apply direct digital pressure to the bleeding wound. Blind clamping of structures is never indicated. A hand surgeon should be consulted immediately. If the injury is at or near the axilla, a trauma or vascular surgeon should also be informed because proximal control may require exposure of the vessel in the chest.

Nail bed injuries

Nail bed injuries are commonly seen in children with crush injuries to the fingers, typically from catching the finger in a door. They are often associated with fractures of the distal phalanx. The problem with such injuries is the subsequent nail deformity that may develop. Knowledge of the anatomy of the nail bed and surrounding tissues fosters an understanding of the consequences of nail bed injuries and the treatment that follows.

The sterile matrix begins where the lunula ends and extends distally to the hyponychium (the junction between the nail bed and fingertip skin that contains neutrophils and lymphocytes essential to fighting off infection). The sterile matrix is closely adherent to the dorsal periosteum of the distal phalanx and is essential for adhesion between the nail and the nail bed. Damage to the distal nail and underlying sterile matrix can result in scar tissue if not properly repaired. This scar tissue may consequently result in a permanent ridge, split, or nonadherent nail. In these injuries, the nail plate must be removed to expose the nail bed. After proper analgesia, the nail is gently separated from the underlying adherent nail bed with the end of a fine-tipped scissors. The tip is slowly inserted between the nail and the nail bed with a slightly dorsal angle and constant pressure along the underside of the nail. The nail is freed from the eponychium and lateral folds by inserting the scissor tip between each. Attempts should be made to salvage nail bed tissue for proper reimplantation. Once the nail is removed, irrigation with sterile saline follows. The nail bed is best repaired with interrupted 6–0 plain gut suture under digital block and tourniquet. Following repair, the eponychial fold must be stented to prevent the germinal matrix from adhering to itself. This can be done by replacing the nail plate or inserting nonadherent gauze into the fold.

The germinal matrix comprises the proximal nail bed and extends proximal to the lunula. The lunula is the light semicircular area extending just distal to the eponychium, the fold of skin that covers the proximal nail. The germinal matrix produces roughly 90% of the nail volume and covers an area of the ventral floor from the proximal volar nail fold to the lunula. Damage to the proximal nail, i.e., the germinal matrix, may adversely affect future nail growth. More proximal lacerations that extend beneath the eponychium necessitate its reflection for repair of the underlying germinal matrix. The eponychium is reflected by making several millimeter cuts perpendicular to its edge in the area where it begins to curve distally.

A subungual hematoma in the face of an intact nail plate often presents with severe pain due to pressure beneath the nail. Treatment is aimed toward decompression of the hematoma and is most successful within the first 36 h of injury while the hematoma remains liquefied. These can be drained sterilely by making one or several holes through the disinfected nail plate with a needle or portable cautery. Provided the puncture does not reach the nail bed itself, anesthesia is unnecessary. The finger can then be placed in warm water or hydrogen peroxide to help evacuate the hematoma. However, in the face of a large subungual hematoma, the likelihood of a significant nail bed injury is generally high enough to warrant removal of the nail plate and repair of the bed. Along the same lines, subungual hematomas that are accompanied by disturbance of the nail or its margins require removal of the nail and evaluation of the nail bed .

It should be mentioned that the distal phalangeal fractures so often associated with nail bed injuries rarely if ever need treatment. Generally, addressing the soft tissue injury alone is sufficient. A finger splint may be helpful to provide comfort while the fracture is healing.

Fractures

Fractures should be suspected after trauma to the hand resulting in significant pain, tenderness, swelling, or deformity. X-rays should be obtained; comparison views of the unaffected hand may be helpful. Fractures with overlying lacerations or soft tissue loss should be considered open fractures and require irrigation prior to skin closure and reduction.

Essentially, all closed fractures in children with a normal neurovascular exam can be splinted and referred to a hand surgeon. The "safe" position to splint the hand is with the wrist in 30° of extension, the MP joints in 60–70° of flexion, and the IP joints in neutral (Figure 21.9) [19]. In very small children, it is difficult to actually splint the hand in this position due to the size of the hand and fingers. The priority should be given to simply preventing the child from moving or using the injured hand. As such, a bulky "boxing glove" dressing should be applied, completely covering the hand and fingers. It should be carried above the elbow with the elbow kept flexed at 90° to prevent the child from removing the splint. Care must be taken when splinting to avoid a tight bandage as the dressing must account for subsequent swelling.

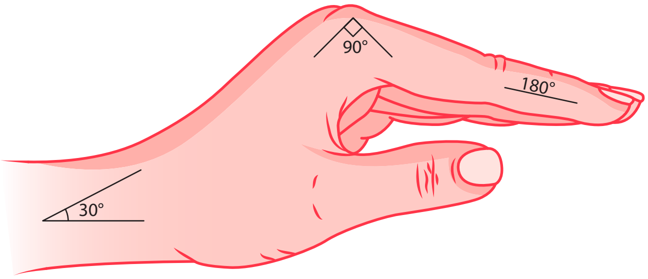

Figure 21.9 Safe position for postfracture splinting. (Courtesy of Texas Children's Hospital.)

For displaced fractures, closed reduction is sometimes possible. However, reduction and surgical stabilization may be necessary. A hand surgery consultation should be obtained in the emergency room or scheduled within the next 1–2 days.

Injection injuries

Penetration of the hand by fluids under pressure (paints, lubricants, abrasives, solvents, etc.) is unusual in children. However, when present these injuries require wide surgical opening of the hand, thorough irrigation, and mechanical debridement. Injection injuries often appear deceptively minor, as there may be only a very small puncture wound at the site of entry. However, there is potential for widespread contamination and necrosis. Rapidly increasing pain and edema are the hallmark of severe deep tissue damage. These injuries can easily develop into compartment syndromes and necessitate emergent referral for surgical debridement and fasciotomy.

Amputations

Indications for replantation in children are broader than for any other group [20]. Any amputated part should be wrapped in a saline-soaked gauze and placed in a plastic bag. This plastic bag should then be placed in another bag filled with water and crushed ice. The amputated part should never be placed directly onto ice. X-rays of the part and the remaining stump must be taken. The decision to replant is based on the type of injury, the condition of the hand and amputated part, and the overall condition of the patient [21]. Contraindications for replantation include associated major life-threatening injuries, major medical conditions precluding prolonged surgery, severe avulsion or crush injury prolonged ischemic time (more than 12 h warm ischemia for a digit or more than 6 h warm ischemia for a proximal limb amputation), multiple levels of injury, extreme contamination of the part, and psychiatric instability of the patient. Reimplantation should be considered for nearly all amputated parts in children, provided these contraindications do not exist.

The results of replantation depend a great deal on the level at which the amputation occurs. The most problematic level for replantation is in volar Zone II of the finger, within the flexor tendon sheath. This is also one of the most common sites of amputation. Just as with isolated flexor tendon injuries in this area, subsequent adhesions frequently result in stiffness that inhibits function. Although children tend to do better than adults, it is still a problem that must be considered.

Another common level for amputation in children is the fingertip. In very distal injuries, with only a very small portion of the fingertip amputated, replacement of the part on the finger as a composite, nonvascularized graft may be indicated. This works best in very young children with a clean amputation. For all other amputations of the fingertip (Zone I), a microsurgical fingertip replantation should be considered. Sebastin and Chung from the University of Michigan Health System propose categorizing Zone I into subzones that reflect the technical amenity of arteries, veins, and nerves to microsurgical repair [22]. However, most recent data suggest that microvascular anastomosis of only the artery, the least technically challenging component of microvascular replantation, provides satisfactory patient outcomes at up to 2-year follow-up [23,24].

In amputations proximal to the nail bed, the blood vessels are generally large enough to repair under the microscope. Replantations do well from a functional standpoint at this level, but the operation tends to be technically difficult due to the small size of the arteries and the relative paucity of veins in this zone.

Bites

Human or animal bites pose a significant threat of infection. *Staphylococcus aureus* and *Streptococcus* are the most common organisms, but *Eikenella corrodens* (Gram negative) can be found in one-third of human bite wounds. *Pasteurella multocida* is present in most cat and dog bites.

If no tendon or joint involvement is suspected, and there are no other abnormalities on physical exam, these wounds can be treated with copious irrigation and prophylactic antibiotics, then left open to heal by secondary intention [25]. The antibiotic of choice for treatment of bite wounds is ampicillin with a β-lactamase inhibitor such as Augmentin (amoxicillin/clavulanate) or Unasyn (ampicillin/sulbactam) if intravenous administration is necessary.

Bite wounds in the region of the MP joints should be expected to involve the joint and consideration given for joint exploration, irrigation, and intravenous antibiotics. Failure to diagnose and treat an intra-articular bite may result in a serious infection. Very large wounds can be closed in a delayed primary fashion at 4–5 days provided the wound has not become infected [26].

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PART IV

Outcomes

22

Rehabilitation of the child with injuries

CHRISTIAN M. NIEDZWECKI

Why should I read this chapter?

- Most traumatic spinal cord injuries (TSCIs) in children are associated with long-term deficits [1–3]
- Most moderate to severe traumatic brain injuries (TBIs) in children are associated with long-term deficits [4,5]
- 17%–33% of mild TBIs are associated with neurocognitive deficits at 1 year [6,7]
- Most TBI patients have unrecognized or unmet needs [8,9]

Rehabilitation professionals specialize in addressing these deficits and needs along the continuum of care from acute care through the postdischarge setting.

Introduction

Trauma is the major cause of morbidity and mortality in children and adults (Table 22.1), and central nervous system trauma is the major determinant of the severity of injury [10–14]. Improvements in trauma systems have increased the number of children surviving with severe injuries, though many will live a lifetime with acquired disabilities [11,13–17]. The long-term financial impact of these disabilities is substantial and has been shown for two subsets of children who have sustained traumatic injury: TBI and TSCI. In pediatric TBI, direct costs are on the order of a billion dollars per year in total hospital charges [17] with continued increases in health care costs in years following injury [18]. The longitudinal costs per individual with a high tetraplegic spinal cord injury (SCI) sustained at the age of 25 are estimated to be $4.7 million [1].

Rehabilitation systems have been developed to address these acquired disabilities along the continuum of care of the child with injuries from the intensive care unit (ICU) setting, to the inpatient ward, to acute inpatient rehabilitation, and through the outpatient setting. They are built to complement trauma systems and their advances with a look toward longitudinal care (i.e., what happens after the acute care hospitalization). They have been shown to improve functional outcomes [19], improve discharge disposition [20,21], and in some instances decrease acute lengths of stay [22]. In fact, the American College of Surgeons has recognized the need and benefits of rehabilitation services to the point that a Level I Pediatric Trauma Center is required to be "providing total care for every aspect of injury—from prevention through rehabilitation" [23].

Rehabilitation in the acute care setting

Rehabilitation begins in the intensive care setting. It includes addressing TBI- and SCI-specific needs to help each injured child meet his/her potential in terms of medical, physical, social, emotional, recreational, vocational, and functional recovery [24]. Rehabilitation services should consist of a multidisciplinary team of rehabilitation professionals that includes physical therapists, occupational therapists, speech and language pathologists, therapeutic recreational specialists, child life specialists, music therapy specialists, dedicated social workers, dedicated care managers, rehabilitation certified nurses, and pediatric rehabilitation certified physiatrists.

Table 22.1 Pediatric trauma incidence

	Adult	Pediatric
ER visits in US/year	30.8 M[a]	8.4 M[a]
Admits in US/year	2.3 M[a]	838 K[a]
Deaths in US/year	200 K[a]	12.5 K[a]
TBI—ER visits in US/year	1.7 M[b]	474 K[b]
TBI—Admits in US/year	275 K[b]	37 K[b]
TBI—Deaths in US/year	52 K[b]	2685[b]
TBI—Top cause	Falls (35.2%) Struck by/against (16.5%) MVC (17.3%)[b]	Falls (50.2%) Struck by/against (24.8%) MVC (6.8)[b]
SCI—ER visits in US/year	12,939[d]	1308[c]
SCI—Admits in US/year	11,412[d]	816[c]
SCI—Deaths in US/year	738[d]	8[c]
SCI—Top cause	Falls, MVC, and other[d]	RTAs, falls, and struck by others/ objects[c]

ER, emergency room; MVC, motor vehicle accident; RTA, road traffic accident, SCI, spinal cord injury; TBI, traumatic brain injury.

Sources: Data compiled from multiple sources as indicated by superscripts a–d, identified below.

[a] Centers for Disease Control and Prevention. *Web-based injury statistics query and reporting system (Wisqars): Injury prevention and control: Data and statistics, 2014.*

[b] Faul, M. et al., *Traumatic Brain Injury in the United States: Emergency Department Visits, Hospitalizations, and Deaths*, Atlanta, GA: Centers for Disease Control and Prevention, National Center for Injury Prevention and Control, 2010.

[c] Selvarajah, S. et al., *Journal of Neurotrauma*, 3, 1548–1560, 2014.

[d] Selvarajah, S. et al., *Journal of Neurotrauma*, 31, 228–238, 2014.

It has been shown that a delay in starting rehabilitation can impair functional outcomes and increase costs to the system [25–27]. Unfortunately, despite this evidence, there is significant variability in the initiation of rehabilitation services after TBI to the child [28].

Rehabilitation of pediatric TBI in the acute care setting

The medical and social concerns in the acute care setting are quite complex; however, there are four primary areas that rehabilitation professionals can assist in the care of children who have sustained a TBI.

The first and most obvious is in providing *individualized, age-appropriate, medically appropriate therapies focusing on preventing stasis* which includes range of motion, appropriate positioning, isometric strengthening, early mobilization, and appropriate recommendations for limb bracing and equipment.

The second area centers on communication of information to the primary trauma/medical team of *how acute factors can affect longitudinal TBI outcomes*. In the critical care setting, the common goal of the treatment teams is preservation of life, as it should be. The addition of rehabilitation professionals can serve to extend this goal to include a feedback loop of functional outcomes after the patient's critical care stay is over and correlate medical management parameters to functional outcome. In 1992, Michaud et al., and more recently in 2008, Scivoletto et al., published versions of these correlations [25,29]. Their work, among others, have served to permit the paradigm shift from morbidity to function after severe TBI in children. Their work has shown that elevations or depressions of intracranial pressure, unstable blood pressure, unstable oxygenation, delayed nutrition, and the presence of seizures decrease intelligence quotient (IQ) at 12 months after injury [30].

The third area in the acute care setting that rehabilitation professionals may assist in is the *identification and treatment of paroxysmal sympathetic hyperactivity (PSH)*. While the pathophysiology of TBI is beyond the scope of this chapter, the metabolic cascade of events after TBI has been documented to the extent of our current understanding by Giza and Hovda and Maxwell [31,32]. It is likely that this metabolic cascade is closely associated with the poorly understood consequence of TBI most recently known as PSH. In 2014, Baguley et al., using the Delphi method, published a consensus statement on defining the PSH syndrome, diagnostic criteria, and a proposed tool for future research (Figure 22.1) [33].

There are over 30 eponyms for this term (dysautonomia, autonomic storms, paroxysmal autonomic instability with dystonia, etc.); however, it is defined as "a syndrome, recognized in a subgroup of survivors of severe acquired brain injury, of simultaneous, paroxysmal transient increases in sympathetic (elevated heart rate, blood pressure, respiratory rate, temperature, sweating), and motor (posturing) activity." The syndrome usually begins 5–7 days after injury, episodes typically occur 1–3 times a day, episodes usually last less than 1–10 hours, and last from 1 to 2 weeks to several months [33]. This is an important topic as it is generally a diagnosis of

Clinical feature scale (CFS)

	0	**1**	**2**	**3**	Score
Heart rate	<100	100–119	120–139	≥140	
Respiratory rate	<18	18–23	24–29	≥30	
Systolic blood pressure	<140	140–159	160–179	≥180	
Temperature	<37	37–37.9	38–38.9	≥39.0	
Sweating	Nil	Mild	Moderate	Severe	
Posturing during episodes	Nil	Mild	Moderate	Severe	
			CFS subtotal		

Severity of clinical features	Nil	0	
	Mild	1–6	
	Moderate	7–12	
	Severe	≥13	

Diagnosis likelihood tool (DLT)

Clinical features occur simultaneously	
Episodes are paroxysmal in nature	
Sympathetic over-reactivity to normally nonpainful stimuli	
Features persist ≥3 consecutive days	
Features persist ≥2 weeks post–brain injury	
Features persist despite treatment of alternative differential diagnoses	
Medication administered to decrease sympathetic features	
≥2 episodes daily	
Absence of parasympathetic features during episodes	
Absence of other presumed caused of features	
Antecedent acquired brain injury	
(Score 1 point for each feature present) DLT subtotal	

Combined total (CFS + DLT)	

PSH diagnostic likelihood	Unlikely	<8	
	Possible	8–16	
	Probable	>17	

PSH, paroxysmal sympathetic hyperactivity.

Figure 22.1 Paroxysmal sympathetic hyperactivity—Assessment measure that includes the diagnosis likelihood tool (DLT) and the clinical features scale (CFS). (From Selvarajah, S. et al., *Journal of Neurotrauma*, 31, 1548–1560, 2014.)

exclusion, but occurs in 8%–33% of children with TBI and 6%–29% of children with acquired non-TBI, and has been shown to be associated with increased morbidity, increased health care utilization, poorer outcomes, and need for prolonged hospitalization and rehabilitation [33–35].

For the adult population, acute medical management guidelines for treatment of PSH exist, with morphine sulfate and β-blockers being first-line therapy in the acute setting [36,37]. While these are appropriate choices in the critical care setting for addressing complex vital signs, they may not necessarily address the dystonic motor signs component of this syndrome. Typically for these concerns, dopamine agonists, benzodiazepines, and/or gamma-aminobutyric acid (GABA) ergic agents are important to mediate symptoms. In tandem with pharmacological management, care needs to be taken to provide a low stimulation environment to address the patient who is hyperreactive to the external stimuli of light and noise. While recent studies in children with TBI and PSH have demonstrated prolonged hospital and rehabilitation stays, an optimal strategy for addressing this syndrome has yet to be developed and thoroughly tested [34,35].

Finally, the fourth area, and the one that affects rehabilitation professionals the most throughout their involvement with the child with a TBI, is communication with the medical team and the patient and family regarding the *severity of injury*. In 1974, the sentinel article by Teasdale and Jennett described the Glasgow Coma Scale (GCS) as a clinical scale to assess “the depth and duration of impaired consciousness and coma.” It is utilized as a primary marker for intervention in brain-injured patients and as a prognostic indicator for morbidity and mortality after TBI [38]. Adaptations to the GCS were developed and published for the pediatric brain injury population in 1984 [39]. Holmes et al. documented that the pediatric GCS in preverbal children had a favorable comparison to standard GCS in older children with blunt head trauma [40].

While the GCS has been well studied and is well integrated into our medical system and paradigms of acute care, it has shown some limitations both in the acute setting [41] and in specificity in prediction of specific longitudinal neurocognitive outcomes [29]. Due to these limitations, alternative indices for severity have been evaluated for prognostication after TBI. These include duration of loss of consciousness, GCS motor score at 3 days postinjury, days to reach GCS score of 15, days to reach GCS motor score of 6, and duration of posttraumatic amnesia (PTA). All of these have shown predictive value at 3 months and 1 year in neurobehavioral and functional outcomes, though the two most predictive measures have been shown to be days to reach GCS score of 15 and duration of PTA [29,42]. PTA is the time period during which the patient is unable to store and recall novel events. In children with TBI, it is typically measured by days to reach an age normative value on the children's orientation and amnesia test. This tool has been utilized to show how increased durations of PTA are associated with decreased IQ scores at 6 and 12 months (Figure 22.2 [43], Table 22.2, [42,44]).

Recently, PTA has been separated into the components of time to follow commands (TFC) and duration of PTA. The results of this separation have shown that while TFC and PTA predicted functional outcomes at discharge from acute inpatient rehabilitation better than GCS, TFC was the best predictor [44].

Rehabilitation of pediatric TSCI in the acute care setting

In the SCI population, rehabilitation professionals add the unique perspectives of longitudinal care to the patient's care team. These include, but are not limited to, expertise in individual mobility plans, spinal shock with implications, autonomic dysreflexia (AD), neurogenic bladder, neurogenic bowel, and functional prognostication.

While the pathophysiology of TSCI in children is beyond the scope of this chapter, our current understanding is well described by Witiw and Fehlings and Rowland et al.. An important aspect based on this knowledge that may affect medical therapy selection is the concept of spinal shock [45,46]. This phenomenon is not a component of other forms of shock (cardiogenic, hypovolemic, septic, etc.) and has a time course that may extend years. Specifically, spinal shock is the loss of reflex neurological activity and all spinal reflexes, while neurogenic shock is the loss of adequate tissue perfusion associated with hypotension from neurological insult. In light of this, rehabilitation professionals can facilitate care by advocating for use of abdominal binder, lower limb compression, and oral vasopressors [47].

The sentinel work of Ditunno et al. describes four phases of spinal shock and their time courses (Table 22.3) [48]. This work has significant implications for bowel and bladder management. Rehabilitation professionals can serve as guides for the initiation of bowel and bladder management programs. For example, despite the mounting evidence that indwelling Foley catheters are associated with increased urinary tract infections, in a patient in spinal shock receiving large volumes of intravenous crystalloid, their bladder will likely not be able to empty, leading to a recommendation that judicious use of Foley catheters are appropriate and an intermittent catheterization program should be postponed until the amount of intravenous volumes are decreased.

In children, most of the functional prognostication after SCI is based on the information obtained from the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) Examination (Figure 22.3) [49]. A full description of the use and intricacies of this examination are beyond the scope of this chapter, though there are some useful terms that are important in prognostication after SCI [50]:

- Neurological level of injury (NLI): The NLI refers to the most caudal segment of the spinal cord with normal sensory and antigravity motor function on both sides of the body, provided that there is normal (intact) sensory and motor function rostrally. The segments at which normal function is found often differ by side of the body and in terms of sensory and motor testing. Thus, up to four different segments may be identified in determining the neurological level, that is, R(ight)-sensory, L(eft)-sensory, R-motor, and L-motor. The single NLI is the most rostral of these levels.
- Skeletal level: This term has been used to denote the level at which, by radiographic examination, the greatest vertebral damage is found. The skeletal level is not part of the current ISNCSCI because not all cases of SCI have a bony injury, bony injuries do not consistently correlate with the neurological injury to the spinal cord, and this term cannot be revised to document neurological improvement or deterioration.
- Incomplete injury: This term is used when there is preservation of any sensory and/or motor function below the neurological level that includes the lowest sacral segments S4–S5 (i.e., presence of "sacral sparing"). Sensory sacral sparing includes sensation preservation (intact or impaired) at the anal mucocutaneous junction (S4–S5 dermatome) on one or both sides for light touch or pin prick, or deep anal pressure. Motor sacral sparing includes the presence of voluntary contraction of the external anal sphincter upon digital rectal examination.
- Complete injury: This term is used when there is an absence of sensory and motor function in the lowest sacral segments (S4–S5) (i.e., no sacral sparing).
- Zone of partial preservation (ZPP): This term, used only with complete injuries, refers to those dermatomes and

CHILDREN’S ORIENTATION AND AMNESIA TEST (COAT)

General Orientation:

1. What is your name? First (2) ______________ (5) ______________
   Last (3) ______________
2. How old are you? (3) ______________ When is your birthday?
   Month (1) ______________ Day (1) ______________ (5) ______________
3. Where do you live? City (3) ______________
   State (2) ______________ (5) ______________
4. What is your father’s name? (5) ______________
   What is your mother’s name? (5) ______________ (5) ______________
5. What school do you go to? (3) ______________
   What grade are you in? (2) ______________ (5) ______________
6. Where are you now? (5) ______________ (5) ______________
   (May rephrase question: Are you at home now? Are you in the hospital?
   If rephrased, child must correctly answer both questions to receive credit.)
7. Is it daytime or night time? (5) ______________ (5) ______________

General Orientation Total ______________

Temporal Orientation: (Administer If Age 8–15)

8. What time is it now? (5) ______________ (5) ______________
   (correct = 5; < hr. off = 4; 1 hr. off = 3; >1 hr. off = 2; 2 hrs. off = 1)
9. What day of the week is it? (5) ______________ (5) ______________
   (correct = 5; 1 off = 4; 2 off = 3; 3 off = 2; 4 off = 1)
10. What day of the month is it? (5) ______________ (5) ______________
    (correct = 5; 1 off = 4; 2 off = 3; 3 off = 2; 4 off = 1)
11. What is the month? (10) ______________ (10) ______________
    (correct = 10; 1 off = 7; 2 off = 4; 3 off = 1)
12. What is the year? (15)______________ (15) ______________
    (correct = 15; 1 off = 10; 2 off = 5; 3 off = 1)

Temporal Orientation Total ______________

Memory:

13. Say these numbers after me in the same order. (Discontinue when the child fails both series of digits at any length. Score 2 points if both digit series are correctly repeated; score 1 point if only 1 is correct.)

3	5 ______________	35296	81493 ___________	
58	42 ______________	539418	724856 ___________	
643	926 ______________	8129365	4739128 ___________	(14) ______________
7216	3279 ______________			

14. How many fingers am I holding up? Two fingers (2) ______________
    Three fingers (3) ______________ 10 fingers (5) ______________ (10) ______________
15. Who is on Sesame Street? (10) ______________
    (can substitute other major television show) (10) ______________
16. What is my name? (10) ______________ (10) ______________

Memory Total ______________

OVERALL TOTAL ______________

Figure 22.2 The children’s orientation and amnesia test. (From Ewing-Cobbs, L. et al., *Neurosurgery*, 27, 683, 1990.)

Table 22.2 TBI severity in children

TBI severity	Glasgow Coma Scale	Loss of consciousness	Posttraumatic amnesia (hour)	Radiology and physical examination
Mild	13–15	<15–30 min	<1	HCT: NL Neuro exam: NL
Moderate	9–12	15 min–24 h	1–24	HCT: Abnormal Neuro exam: NL/combative/lethargic
Severe	3–8	1–90 days	>24	HCT: Abnormal Neuro exam: Coma

GCS, Glasgow Coma Scale; HCT, hematocrit; LOC, loss of consciousness; NL, normal; PTA, posttraumatic amnesia.

Sources: McDonald, C.M. et al., *Archives of Physical Medicine and Rehabilitation*, 75, 328, 1994; Suskauer, S.J. et al., *Journal of Pediatric Rehabilitation Medicine*, 2, 297, 2009.

Table 22.3 Four phases of spinal shock

Phase	Time	Reflex	Pathophysiology
1	0–1 day	Areflexia/hyporeflexia	Loss of descending facilitation
2	1–3 days	Initial reflex return	Denervation supersensitivity
3	1–4 weeks	Initial hyperreflexia	Axon-supported synapse growth
4	1–12 months	Final hyperreflexia	Soma-supported synapse growth

Source: Ditunno, J.F. et al., *Spinal Cord*, 42, 383–395, 2004.

myotomes caudal to the sensory and motor levels that remain partially innervated. The most caudal segment with some sensory and/or motor function defines the extent of the sensory and motor ZPP, respectively.

Using these determinants, rehabilitation professions work with patients and families on the functional implications of these terms. A complete functional prognosis by neurological level is detailed in Table 22.4; some key levels to be aware of are as follows:

- C5 → Self-feeding
- C7 → Wheelchair (w/c) transfer
- C7 → Manual w/c propulsion
- C7 → Self-cath
- T2 → Grasp w/o orthosis
- L2-3 → Community ambulation

The motor and sensory components of the ISNCSCI examination has been shown to be reliable and valid in children with SCIs over the age of 4 years old, though the examination is more difficult to complete in children under 10 years of age. This is developmentally appropriate in children of these ages [51]. The anorectal component of the ISNCSCI examination has been shown to be more reliable in children over 5 years of age. This also is developmentally appropriate [52].

These unique aspects to the child with a SCI are important to note and correlate with their unique injury characteristics which are different from adults. In the United States, in children with SCIs under 17 years old, 90.3% of injuries are classified as incomplete, 40.5% of injuries are in the cervical region, and 14.3% of injuries had concurrent TBI [14,53].

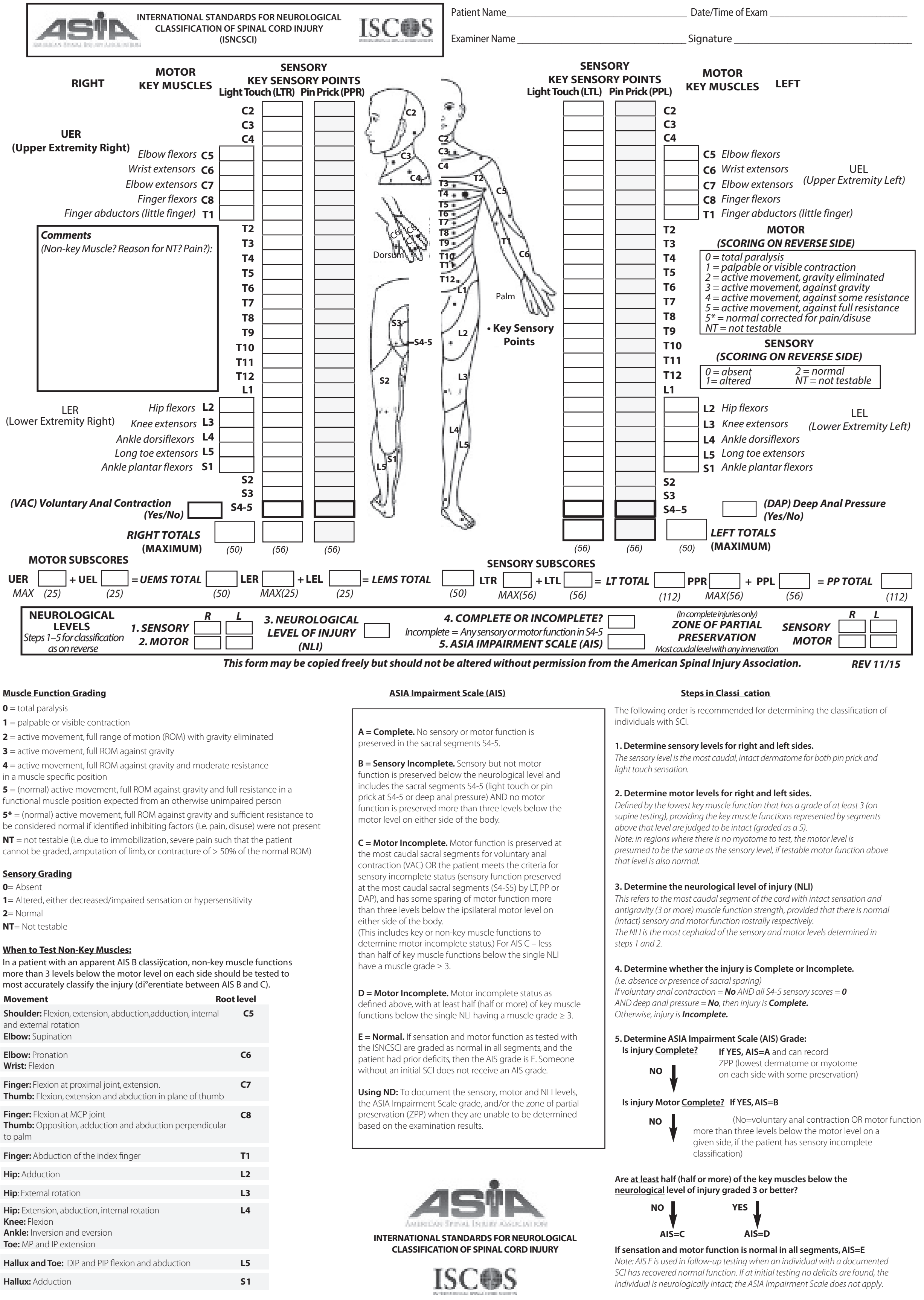
Other areas that rehabilitation professionals can assist in the care of the child with acute SCI are in appropriate, individualized programs for range of motion, strengthening and early mobilization, gastric/duodenal stress ulcer prevention, pressure ulcer prevention (regular skin checks, rotation schedule), thermoregulation (impaired heat and cold regulation with adjustment to ambient temperatures), anticoagulation recommendations for prolonged immobilization, and dysphagia identification/treatment (associated with surgeries, intubations, and respiratory paralysis) [54,55].

Rehabilitation in the acute inpatient rehabilitation setting

Acute inpatient rehabilitation is another part of the spectrum of rehabilitation for the child with injuries. These programs are based on functional recovery, its measurement, and reintegration of the child and family into the home and community settings. They focus on educating children with injuries and their families/caregivers on how to manage their new deficits while maximizing their functional recovery. Ideally, the Acute Inpatient Rehabilitation Program that serves children with injuries has a cadre of individuals dedicated to the pediatric population. This includes physical therapists, occupational therapists, speech and language pathologists, therapeutic recreational specialists, child life specialists, music therapy specialists, dedicated social workers, dedicated care managers, rehabilitation certified nurses, and pediatric rehabilitation certified physiatrists. Each program should have developed its own admission and discharge criteria which will be defined uniquely based on the program's setting and infrastructure. For example, some programs may accept children on ventilators, while others may not have the specific training or respiratory therapy support to do so. In general, though, children must be medically stable, be able to tolerate and participate in at least 3 hours of therapy 5–6 days a week, have family or caregivers to be trained, and have a firm discharge disposition. The disposition is very important as much of the therapy, training, and education in the Acute Inpatient Rehabilitation Program will be aimed at successfully reintegrating into the home setting. A successful reintegration should decrease emergency room visits and unnecessary imaging and/or testing.

The gold standard of guidelines for an Acute Pediatric Inpatient Rehabilitation Program has been put forth by the Commission on Accreditation of Rehabilitation Facilities (CARF). Its Medical Rehabilitation Standards Manual, which is updated yearly, clearly outlines the services and programs that are required for facility accreditation and provides an excellent framework for quality rehabilitation care of the child with injuries. It has specific guidelines for children with TBI and SCI [56].

Acute Pediatric Inpatient Rehabilitation Programs typically use standardized functional outcome measures to determine their progress and effectiveness during the



INTERNATIONAL STANDARDS FOR NEUROLOGICAL CLASSIFICATION OF SPINAL CORD INJURY (ISNCSCI)

Patient Name______________________ Date/Time of Exam ______________________

Examiner Name ______________________ Signature ______________________

RIGHT

	MOTOR KEY MUSCLES		SENSORY KEY SENSORY POINTS Light Touch (LTR)	Pin Prick (PPR)
		C2		
		C3		
		C4		
UER (Upper Extremity Right)	Elbow flexors	C5		
	Wrist extensors	C6		
	Elbow extensors	C7		
	Finger flexors	C8		
	Finger abductors (little finger)	T1		
		T2		
		T3		
		T4		
		T5		
		T6		
		T7		
		T8		
		T9		
		T10		
		T11		
		T12		
		L1		
LER (Lower Extremity Right)	Hip flexors	L2		
	Knee extensors	L3		
	Ankle dorsiflexors	L4		
	Long toe extensors	L5		
	Ankle plantar flexors	S1		
		S2		
		S3		
(VAC) Voluntary Anal Contraction (Yes/No)		S4-5		
RIGHT TOTALS (MAXIMUM)	(50)		(56)	(56)

Comments
(Non-key Muscle? Reason for NT? Pain?):

LEFT

SENSORY KEY SENSORY POINTS Light Touch (LTL)	Pin Prick (PPL)		MOTOR KEY MUSCLES	
		C2		
		C3		
		C4		
		C5	Elbow flexors	UEL (Upper Extremity Left)
		C6	Wrist extensors	
		C7	Elbow extensors	
		C8	Finger flexors	
		T1	Finger abductors (little finger)	
		T2		
		T3		
		T4		
		T5		
		T6		
		T7		
		T8		
		T9		
		T10		
		T11		
		T12		
		L1		
		L2	Hip flexors	LEL (Lower Extremity Left)
		L3	Knee extensors	
		L4	Ankle dorsiflexors	
		L5	Long toe extensors	
		S1	Ankle plantar flexors	
		S2		
		S3		
		S4–5		(DAP) Deep Anal Pressure (Yes/No)
(56)	(56)		(50)	LEFT TOTALS (MAXIMUM)

MOTOR
(SCORING ON REVERSE SIDE)

0 = total paralysis
1 = palpable or visible contraction
2 = active movement, gravity eliminated
3 = active movement, against gravity
4 = active movement, against some resistance
5 = active movement, against full resistance
5 = normal corrected for pain/disuse*
NT = not testable

SENSORY
(SCORING ON REVERSE SIDE)

0 = absent	2 = normal
1= altered	NT = not testable

MOTOR SUBSCORES

UER ☐ + UEL ☐ = *UEMS TOTAL* ☐ LER ☐ + LEL ☐ = *LEMS TOTAL* ☐
MAX (25) (25) (50) MAX(25) (25) (50)

SENSORY SUBSCORES

LTR ☐ + LTL ☐ = *LT TOTAL* ☐ PPR ☐ + PPL ☐ = *PP TOTAL* ☐
MAX(56) (56) (112) MAX(56) (56) (112)

NEUROLOGICAL LEVELS
Steps 1–5 for classification as on reverse

	R	L
1. SENSORY	☐	☐
2. MOTOR	☐	☐

3. NEUROLOGICAL LEVEL OF INJURY (NLI) ☐

4. COMPLETE OR INCOMPLETE? ☐
Incomplete = Any sensory or motor function in S4-5
5. ASIA IMPAIRMENT SCALE (AIS) ☐

(In complete injuries only)
ZONE OF PARTIAL PRESERVATION
Most caudal level with any innervation

	R	L
SENSORY	☐	☐
MOTOR	☐	☐

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Muscle Function Grading

0 = total paralysis

1 = palpable or visible contraction

2 = active movement, full range of motion (ROM) with gravity eliminated

3 = active movement, full ROM against gravity

4 = active movement, full ROM against gravity and moderate resistance in a muscle specific position

5 = (normal) active movement, full ROM against gravity and full resistance in a functional muscle position expected from an otherwise unimpaired person

5* = (normal) active movement, full ROM against gravity and sufficient resistance to be considered normal if identified inhibiting factors (i.e. pain, disuse) were not present

NT = not testable (i.e. due to immobilization, severe pain such that the patient cannot be graded, amputation of limb, or contracture of > 50% of the normal ROM)

Sensory Grading

0= Absent

1= Altered, either decreased/impaired sensation or hypersensitivity

2= Normal

NT= Not testable

When to Test Non-Key Muscles:

In a patient with an apparent AIS B classification, non-key muscle functions more than 3 levels below the motor level on each side should be tested to most accurately classify the injury (differentiate between AIS B and C).

Movement	Root level
Shoulder: Flexion, extension, abduction,adduction, internal and external rotation **Elbow:** Supination	C5
Elbow: Pronation **Wrist:** Flexion	C6
Finger: Flexion at proximal joint, extension. **Thumb:** Flexion, extension and abduction in plane of thumb	C7
Finger: Flexion at MCP joint **Thumb:** Opposition, adduction and abduction perpendicular to palm	C8
Finger: Abduction of the index finger	T1
Hip: Adduction	L2
Hip: External rotation	L3
Hip: Extension, abduction, internal rotation **Knee:** Flexion **Ankle:** Inversion and eversion **Toe:** MP and IP extension	L4
Hallux and Toe: DIP and PIP flexion and abduction	L5
Hallux: Adduction	S1

ASIA Impairment Scale (AIS)

A = Complete. No sensory or motor function is preserved in the sacral segments S4-5.

B = Sensory Incomplete. Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-5 (light touch or pin prick at S4-5 or deep anal pressure) AND no motor function is preserved more than three levels below the motor level on either side of the body.

C = Motor Incomplete. Motor function is preserved at the most caudal sacral segments for voluntary anal contraction (VAC) OR the patient meets the criteria for sensory incomplete status (sensory function preserved at the most caudal sacral segments (S4-S5) by LT, PP or DAP), and has some sparing of motor function more than three levels below the ipsilateral motor level on either side of the body.
(This includes key or non-key muscle functions to determine motor incomplete status.) For AIS C – less than half of key muscle functions below the single NLI have a muscle grade ≥ 3.

D = Motor Incomplete. Motor incomplete status as defined above, with at least half (half or more) of key muscle functions below the single NLI having a muscle grade ≥ 3.

E = Normal. If sensation and motor function as tested with the ISNCSCI are graded as normal in all segments, and the patient had prior deficits, then the AIS grade is E. Someone without an initial SCI does not receive an AIS grade.

Using ND: To document the sensory, motor and NLI levels, the ASIA Impairment Scale grade, and/or the zone of partial preservation (ZPP) when they are unable to be determined based on the examination results.

INTERNATIONAL STANDARDS FOR NEUROLOGICAL CLASSIFICATION OF SPINAL CORD INJURY

Steps in Classification

The following order is recommended for determining the classification of individuals with SCI.

1. Determine sensory levels for right and left sides.
The sensory level is the most caudal, intact dermatome for both pin prick and light touch sensation.

2. Determine motor levels for right and left sides.
Defined by the lowest key muscle function that has a grade of at least 3 (on supine testing), providing the key muscle functions represented by segments above that level are judged to be intact (graded as a 5).
Note: in regions where there is no myotome to test, the motor level is presumed to be the same as the sensory level, if testable motor function above that level is also normal.

3. Determine the neurological level of injury (NLI)
This refers to the most caudal segment of the cord with intact sensation and antigravity (3 or more) muscle function strength, provided that there is normal (intact) sensory and motor function rostrally respectively.
The NLI is the most cephalad of the sensory and motor levels determined in steps 1 and 2.

4. Determine whether the injury is Complete or Incomplete.
(i.e. absence or presence of sacral sparing)
If voluntary anal contraction = ***No*** *AND all S4-5 sensory scores =* ***0***
AND deep anal pressure = ***No****, then injury is* ***Complete.***
Otherwise, injury is ***Incomplete.***

5. Determine ASIA Impairment Scale (AIS) Grade:

Is injury Complete? **If YES, AIS=A** and can record ZPP (lowest dermatome or myotome on each side with some preservation)

NO ↓

Is injury Motor Complete? If YES, AIS=B

NO ↓ (No=voluntary anal contraction OR motor function more than three levels below the motor level on a given side, if the patient has sensory incomplete classification)

Are at least half (half or more) of the key muscles below the neurological level of injury graded 3 or better?

NO ↓ **AIS=C**
YES ↓ **AIS=D**

If sensation and motor function is normal in all segments, AIS=E
Note: AIS E is used in follow-up testing when an individual with a documented SCI has recovered normal function. If at initial testing no deficits are found, the individual is neurologically intact; the ASIA Impairment Scale does not apply.

Figure 22.3 The International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) examination worksheet. (From the American Spinal Injury Association: International Standards for Neurological Classification of Spinal Cord Injury, 2013; Atlanta, Georgia.)

Table 22.4 Functional outcomes in spinal cord injury by neurological level of injury

Measure	C1–C4	C5	C6	C7	C8–T1
Feeding	Dependent	Independent with adaptive equipment after setup	Independent with or without adaptive equipment	Independent	Independent
Grooming	Dependent	Minimal assistance with equipment after setup	Some assistance to independent with adaptive equipment	Independent with adaptive equipment	Independent
UE dressing	Dependent	Requires assistance	Independent	Independent	Independent
LE dressing	Dependent	Dependent	Require assistance	Some assistance to independent with adaptive equipment	Usually independent
Bathing	Dependent	Dependent	Some assistance to independent with equipment	Some assistance to independent with equipment	Independent with equipment
Bed mobility	Dependent	Requires assistance	Requires assistance	Independent to some assistance	Independent
Weight shifts	Independent in power chair with power tilt or recline mechanism	Requires assistance unless in power chair	Independent	Independent	Independent
Transfers	Dependent	Requires maximum assistance	Some assistance to independent on level surfaces	Independent with or without board for level surfaces	Independent
Wheelchair propulsion	Independent with power chair; dependent in manual wheelchair	Independent with power chair; independent to some assistance in manual wheelchair with adaptations on level surfaces	Independent with manual wheelchair with coated rims on level surfaces	Independent, except for curbs and uneven terrain	Independent
Driving	Unable	Independent with adaptations	Independent with adaptations	Independent in car with hand controls or adapted van	Independent in car hand controls or adapted van

LE, lower extremity; UE, upper extremity.
Source: Adapted from Kirshblum, S.C. et al., *Journal of Spinal Cord Medicine*, 34, 535–546, 2011. With permission.

acute inpatient rehabilitation stay. There are many outcome measurement tools that are used for this including the Pediatric Evaluation of Disability Inventory (PEDI) [57], the Functional Independence Measure for Children (WeeFIM™) [58], and the more recent Pediatric Evaluation of Disability Inventory Computer Adaptive Test (PEDI CAT) [59]. These tests are to translate functional progress on numerous items into a standardized score that can be compared to age normative values.

While the most evident aspect of Acute Pediatric Inpatient Rehabilitation Programs is in addressing the physical needs of a child with injury, it is just as important that they have means to address the social and emotional aspects of new onset impairments. These aspects impose as many, if not more, stressors on the child and the family. Acute Pediatric Inpatient Rehabilitation Programs should have dedicated resources including psychology, social work, and counselors to address this with the child and family members.

Rehabilitation of pediatric TBI in the acute inpatient rehabilitation setting

In an effort to improve the standardization of acute inpatient rehabilitation care for children with TBI, quality indicators for care components [60], and structure and organization [61] of rehabilitation programs based on a Delphi technique have been published.

To gain a conceptual framework of how TBI recovery in children naturally progresses, it is helpful to understand the Rancho Level of Cognitive Functioning Scale (LCFS). This scale is widely accepted as describing the process of cognitive recovery from coma to near normal recovery [62]. Understanding the expected steps in TBI recovery allows for anticipation of concerns that will arise as the child progresses including impaired arousal, agitation, and cognitive impairments (Table 22.5).

In the acute inpatient rehabilitation setting, the initial step in addressing any of these concerns is environmental modification. This includes providing environments with appropriate levels of stimulation, voice and reaction modulation, and regular redirection from inappropriate responses or activities before utilizing medications for behavioral modulation [63]. A complete discussion of medication management in the child with TBI is beyond the scope of this chapter; however, Pangilinan et al. provide an extensive review of pharmaceutical intervention in the child with TBI [64].

In LCFS levels I–III, impaired arousal is a major concern. The broader category of impaired arousal is disorders of consciousness. In clinical practice, dopaminergic agents

Table 22.5 Rancho Level of Cognitive Functioning Scale (LCFS)

____ (1)	Level I—No response Patient does not respond to external stimuli and appears asleep.
____ (2)	Level II—Generalized response Patient reacts to external stimuli in nonspecific, inconsistent, and nonpurposeful manner with stereotypic and limited responses.
____ (3)	Level III—Localized response Patient responds specifically and inconsistently with delays to stimuli, but may follow simple commands for motor action.
____ (4)	Level IV—Confused, agitated response Patient exhibits bizarre, nonpurposeful, incoherent, or inappropriate behaviors, has no short-term recall, attention is short and nonselective.
____ (5)	Level V—Confused, inappropriate, nonagitated response Patient gives random, fragmented, and nonpurposeful responses to complex or unstructured stimuli—simple commands are followed consistently, memory and selective attention are impaired, and new information is not retained.
____ (6)	Level VI—Confused, appropriate response Patient gives context-appropriate, goal-directed responses, dependent upon external input for direction. There is carry-over for relearned, but not for new tasks, and recent memory problems persist.
____ (7)	Level VII—Automatic, appropriate response Patient behaves appropriately in familiar settings, performs daily routines automatically, and shows carry-over for new learning at lower than normal rates. Patient initiates social interactions, but judgment remains impaired.
____ (8)	Level VIII—Purposeful, appropriate response Patient oriented and responds to the environment but abstract reasoning abilities are decreased relative to premorbid levels.

Source: Hagen, C. et al., *Levels of Cognitive Functioning*, Rancho Los Amigos Hospital, Downey, CA, 1972.

(amantadine and methylphenidate) are the primary medications utilized to improve arousal. Use of these medications is based primarily on extrapolations from adult TBI literature, as there is a dearth of pediatric literature specifically related to the use of these medications in the child with a TBI [65,66].

In LCFS level IV, the main concern turns to agitation. This can manifest as physical aggression that requires specialized training to recognize escalations and techniques to deescalate behaviors. Efforts have been undertaken to solidify the symptoms specifically associated with the term agitation following TBI. The consensus definition published is "posttraumatic amnesia plus an excess of behavior such as aggression, disinhibition, and/or emotional lability" [67]. As with arousal, most medication management is derived from the literature in adult TBI populations. The two aspects that need addressing at this stage are sleep/wake cycles and behaviors while awake. Normalizing the sleep/wake cycles of an agitated child can be quite difficult, though providing a structured, predictable routine is paramount to success. In addition, medications such as melatonin for sleep cycle architecture regulation and trazodone for sleep initiation can be very useful. Addressing agitated behavior while awake requires a multidisciplinary team approach, structured environments, and often, medication management. Clinically, the options include benzodiazepine drugs, β-blockers, anticonvulsant agents, antidepressant medications, and antipsychotic agents [63,64,66].

Once the child has progressed through LCFS level 4, then the primary concern becomes the many varied cognitive deficits associated with TBI which will affect all learning and education goals during and beyond the child's stay in the Acute Pediatric Inpatient Rehabilitation Program. This is why it is important to have caregiver involvement and training. The primary deficits include, but are not limited to, attention, memory, processing speed, and executive functions [4,16]. Identification of patterns associated with these deficits and education on treatments and accommodations become the responsibility of the acute inpatient rehabilitation team.

The most visible aspect of acute inpatient rehabilitation is in the realm of mobility. In most instances, physical recovery occurs before cognitive recovery, and much training and education during inpatient rehabilitation is focused on safety with mobility and activities of daily living (ADLs), the cognitive aspects of mobility and ADLs. However, for those children who do have physical deficits (in both TBI and TSCI) with mobility and/or ADLs, one of the primary determinants of mobility and self-care is the development of movement disorders that include hypertonia [68], negative motor signs [69], and hyperkinetic movements [70]. The management strategies in the child with injury begin with stretching, bracing, and therapies, move to systemic management with oral medications [71,72], progress to focal chemical denervation with injections of botulinum toxin and/or phenol [73], and finally move to orthopedic and/or neurosurgical interventions such as intrathecal baclofen [74] and deep brain stimulation (Table 22.6) [75].

Rehabilitation of pediatric TSCI in the acute inpatient rehabilitation setting

In the acute inpatient rehabilitation setting, medical management and education in a child with a TSCI can be predominantly divided into two areas: those dependent on the level of injury (AD and respiratory compromise) and those independent of level of injury (neurogenic bladder, neurogenic bowel, pressure ulcers, and spasticity).

A child whose spinal cord is injured at the T6 level or above is at risk of developing AD. "AD is a symptom complex that arises from a noxious or intense stimulus below the level of injury that leads to an unopposed discharge of the sympathetic nervous system. This sympathetic discharge is unable to be modulated from higher cerebral centers and often results in hypertension" [24]. It represents a life-threatening situation and requires intact spinal reflexes (i.e., patient cannot be in stage 1 of spinal shock). AD is seen with greater frequency in complete injuries, tetraplegia, and in children over 5 years old. The most common causes are urologic (75%) and bowel impaction (18%). The most common symptoms/complaints are facial flushing (43%), headaches (24%—uncommon in <5 years), sweating (15%), and piloerection (14%—uncommon in <5 years). The most common signs are blood pressure elevations (93%), tachycardia (50%), and bradycardia (12.5%) [76]. Due to average blood pressures in children varying by age, the Consortium for Spinal Cord Medicine published suggested guidelines for determining significant hypertension in AD—children: 15 mmHg above baseline; adolescents: 15–20 mmHg above baseline [77].

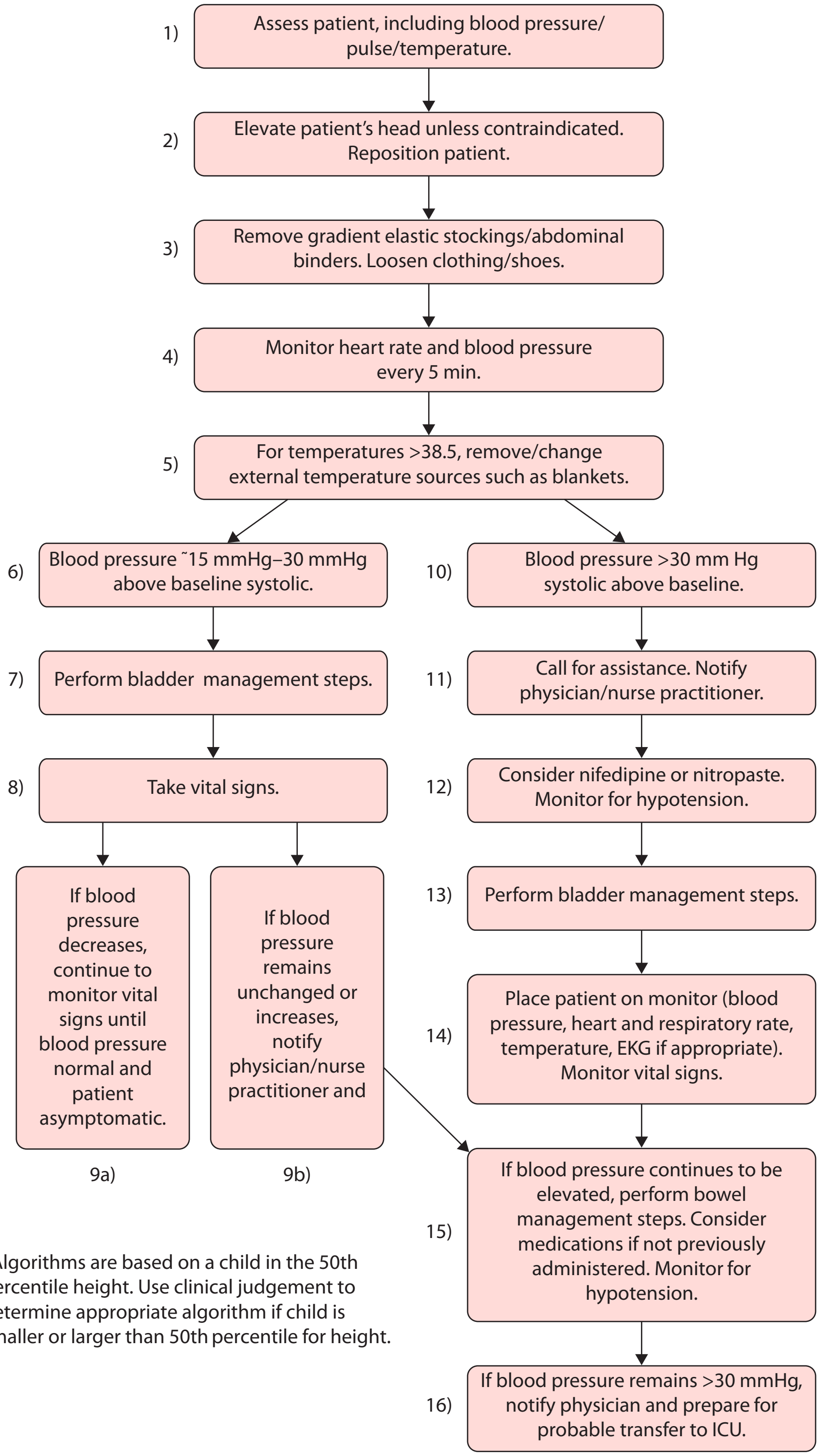
AD treatment algorithms have been developed specifically for children <13 years, and >13 years [78]; however, in general, the patient should be placed in a seated/semireclined position with head elevated and the inciting problem needs to be found. If a child's blood pressure should elevate above the age recommendations, use of medications such as sublingual Nifedipine or Nitroglycerine paste applied to the chest wall above the level of injury may be used (Figure 22.4).

In children with injuries at C5 or above, respiratory compromise is of great concern in the acute inpatient rehabilitation setting. The anatomic structures of import are the phrenic nerves (origin C3–5) that innervate the main muscle of respiration, the diaphragm; the intercostal nerves that innervate the secondary muscles of respiration, the internal and external intercostal muscles; and the abdominal muscles that serve to increase cough effectiveness. When affecting this musculature, forced vital capacity drops and the efficacy of coughing/clearing mucus from the respiratory system is severely compromised. This can lead to a higher predisposition to pneumonia, chronic atelectasis, mucus plugging, nocturnal hypoventilation, hypoxemia, hypercapnia, and obstructive sleep apnea. Primary management of respiratory compromise due to SCI includes the use of abdominal binders, incentive inspirometry, chest percussion, and postural drainage. This is followed by the use of Flutter valves, Acapella devices, and continuous positive airway pressure (CPAP)/bilevel positive airway pressure

Table 22.6 Medications used to treat spasticity in children

Drug	Mechanism of action	Side effects and precautions	Pharmacology and dosing
Baclofen	Binds to receptors (GABA) in the spinal cord to inhibit reticular formation and spinal cord to inhibit reflexes that lead to increased tone	Sedation, confusion, nausea, dizziness, muscle weakness, hypotonia, ataxia, and paresthesias	Rapidly absorbed after oral dosing, mean half-life of 3.5 h
	Also binds to receptors in the brain leading to sedation	Can cause loss of seizure control	Excreted mainly through the kidney
		Withdrawal can produce seizures, rebound hypertonia, fever, and death	Dosing: in children start 2.5–5 mg/d, increase to 30 mg/d (in children 2–7 years of age) or 60 mg/d (in children 8 years of age and older)
Diazepam	Facilitates postsynaptic binding of a neurotransmitter (GABA) in the brain stem, reticular formation and spinal cord to inhibit reflexes that lead to increased tone	Central nervous system depression causing sedation, decreased motor coordination, impaired attention and memory	Well absorbed after oral dosing, mean half-life 20–80 h
		Overdoses and withdrawal both occur	Metabolized mainly in the liver
		The sedative effect generally limits use to severely involved children	In children, does range from 0.12–0.8 mg/kg/d in divided doses
Clonidine	Alpha 2-agonish; acts in both the brain and spinal cord to enhance presynaptic inhibition of reflexes that lead to increased tone	Bradycardia, hypotension, dry mouth, drowsiness, dizziness, constipation, and depression	Well absorbed after oral dosing, mean half-life is 5–19 h
		These side effects are common and cause half of patients to discontinue the medication	Half is metabolized in liver and half is excreted by kidney
			Start with 0.05 mg bid, titrate up until side effects limit tolerance
			May use patch
Tizanidine	Alpha 2-agonist	Dry mouth, sedation, dizziness, visual hallucinations, elevated liver enzymes, insomnia, and muscle weakness	Well absorbed after oral dosing, half-life 2.5 hours
			Extensive first pass metabolism in liver
			Start with 2 mg at bedtime and increase until side effects limit tolerance, maximum 36 mg/d
Dantrolene sodium	Works directly on the muscle to decrease muscle force produced during contraction	Most important side effect is hepatotoxicity (2%), which may be severe	Oral dose is approximately 70% absorbed in small intestine, half-life is 15 hours
	Little effect on smooth and cardiac muscles	Liver function tests must be monitored monthly, initially, and then several times per year	Mostly metabolized in the liver
		Other side effects are mild sedation, dizziness, diarrhea, and paresthesias	Pediatric dose range from 0.5 mg/kg, bid, up to a maximum of 3 mg/kg, qid

Source: Green, L.B. and Hurvitz, E.A., *Physical Medicine & Rehabilitation Clinics of North America*, 18, 859–882, 2007.



*Algorithms are based on a child in the 50th percentile height. Use clinical judgement to determine appropriate algorithm if child is smaller or larger than 50th percentile for height.

Figure 22.4 Autonomic dysreflexia (AD) treatment algorithm for <13 year. (From McGinnis, K.B. et al., *Journal of Spinal Cord Medicine*, 27, S61, 2004.)

(BIPAP) that provide noninvasive positive pressure ventilation [79]. At times, diaphragmatic pacing can be considered [80]. While the literature suggests that the diaphragm may recover at least partially in the first year after injury [81], two essential techniques that must be learned by children with SCIs are glossopharyngeal (GP) breathing [82] and the assisted cough or "quad cough" [83]. In GP breathing, the "muscles of the mouth and pharynx are used to propel small volumes of air through the larynx into the lower airways. The glottis is used to trap the air into the lungs while the next gulp of air is being processed. The process is repeated until a satisfactory breath is obtained" (Figure 22.5).

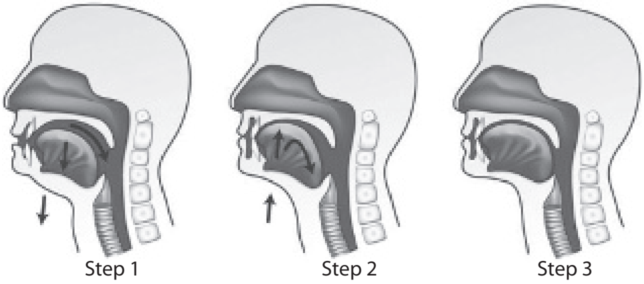


Figure 22.5 Glossopharyngeal (GP) breathing. (From Maltais, F., *American Journal of Respiratory and Critical Care Medicine*, 184, 381, 2011.)

The assisted cough or "quad cough" is a maneuver in which a care provider performs an abdominal thrust and/or squeeze over the chest wall that is coordinated with either the patient's spontaneous breath or with an assisted breath. Contraindications to quad coughing are as follows: unstable spine in traction, internal abdominal complications, chest trauma such as fractured ribs, and a recently placed vena cava filter [83].

In addition to managing the aforementioned injury level dependent sequelae, an acute inpatient rehabilitation program must address all bowel and bladder programs with the context of age-appropriate development. For the bladder, this includes preschool: participation; school age: should have been taught clean intermittent catheterization and should be close to independent, depending on hand function [84]. Similarly for the bowel, this includes toddler: gather supplies, use potty chair, cooperate; preschooler: bear down, clean up, cooperate; and school age: gradual transfer of responsibility [85].

The goals of managing a neurogenic bladder are the prevention of life-threatening complications (i.e., AD, urosepsis, etc.), preservation of renal function, and social continence. These are traditionally attained through an intermittent catheterization program, an external collection system, reflex/pressure voiding, and/or indwelling catheters. More invasive options include functional electrical stimulation (FES), neuromodulation and FES, procedures for increased outlet resistance, bladder augmentation, and surgical urinary diversion. Three common medications used to assist in meeting these goals are anticholinergics, imipramine, and pseudoephedrine. One of the most common problems with managing a neurogenic bladder is urinary tract infections; however, while symptomatic infections are treated with antibiotics, bladders will be colonized with bacteria and can lead to bacturia that is asymptomatic. This is typically followed and not treated [53,84].

The goals of managing neurogenic bowel are to control constipation via daily and complete elimination at a socially convenient time and allowance for age-appropriate independence. The first of the traditional approaches to meeting these goals includes an appropriate diet that has adequate fiber (5 g + 1 g for each year of age), adequate hydration (a 10 kg-child required 1 L a day, a 25–kg child requires 1.6 L a day, a teenager requires 2 L per day), and exercise and activity. Habit training is an important approach which entails placing the child on the toilet 15 min after a meal, allowing him to "push," but not having him there for longer than 10–15 min. Success will likely be improved with the utilization of digital stimulation, suppositories, and small-volume enemas, and at times, large-volume enemas. If problems persist, options that can be discussed at the outpatient setting are a bowel management tube (with an inflatable bulb) and cone irrigation system, antegrade continence enema, and biofeedback with therapeutic electrical stimulation [84].

One additional area of sentinel importance to the child with a TSCI and rehabilitation professionals is pressure ulcer prevention and management. Pressure ulcers have an incidence of 25%–66% in the SCI population and costs in the United States alone top $11 billion annually for treatment [86]. The primary prevention methods include pressure reliefs, daily full body skin checks, and appropriate urinary/bowel management.

The challenges of educating a child with injury and the child's caregivers are compounded when the child also has a concomitant TBI. One of the few studies that have looked into this topic found that in a single center, 39 out of 103 cervical TSCI also had closed head injuries, and that 90% of children who died with a TSCI had concurrent closed head injuries [87].

Additional complications seen in the inpatient rehabilitation setting are spasticity (see section "Rehabilitation of Pediatric TBI in the Acute Inpatient Rehabilitation Setting"), immobilization hypercalcemia, heterotopic ossification (HO), psychological adjustment, depression, and anxiety [50].

Rehabilitation in the outpatient rehabilitation setting

Once a child with the injury is discharged from an inpatient rehabilitation program, the rehabilitation process continues. This may be in an outpatient program where therapies are provided 1–3 times a week, or in a day rehabilitation program where the child attends daily, but sleeps in the home setting.

Outpatient follow-up for TBI will include further evaluations of neurocognitive deficits and their effect on reintegration into the home and school setting. It will continue to address topics of sleep/wake cycle disturbances, behavior and mood disturbances, and the application of these topics to the child's life as he/she grows into a contributing member of society.

Outpatient TSCI follow-up will initially focus on prevention of readmissions [88], and then move toward the following—(1) overuse injuries: rotator cuff tears and carpal tunnel syndrome [89]; (2) pain and development of chronic pain: nociceptive, neuropathic [90]; (3) psychological adjustment: depression, anxiety, suicide [89]; (4) paralytic scoliosis [91]; and (5) sexuality: marriage, divorce, sexual dysfunction, reproduction, abuse, and parenting [92].

SUMMARY

Rehabilitation in the child with injuries is a complex, continuous process that spans the rest of that child's life. Rehabilitation professionals can contribute at every point along the initial hospitalization, through acute inpatient rehabilitation, and beyond. It is paramount that the child with injuries return to home, school, and society.

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Communication with families

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Introduction

The ability to communicate effectively with patients and their families is one of the most valuable skills that a physician should possess. It is the vehicle through which physicians and other members of the multidisciplinary team engage in patient- and family-centered care and signals to family members that they are part of the care team [1]. Effective communication is the bridge to a relationship of trust between the physician and the child and family. This skill becomes even more important when a physician must communicate distressing information, when a child's condition deteriorates, or if death occurs. How such information is conveyed during catastrophic events has a profound impact on the coping and grieving process of families [2]. It is vital that a physician be educated in and adhere to principles of compassionate communication that are outlined by the Institute for Medicine and the American Academy of Pediatrics [3,4]. The informant's behavior and preparedness during these times of crisis will have a lasting effect on the family.

The three primary components of successful communication are compassion, clarity, and a proper environment [5,6]. Much useful information is available from retrospective reviews of family members' experiences during times of change or sudden death [1,7–9].

Compassionate delivery of information is one of the most important factors in acute event notification [10]. While a caring manner is often naturally displayed by physicians who have been directly involved in a patient's care, there are certain circumstances that complicate this interaction. One situation involves the initial care of an unstable trauma victim, in which a prior relationship has not been established with family members. Whether a trauma victim is hemodynamically normal or abnormal, the simple fact that their child has been injured will qualify as bad news to parents.

It is important for the family to know that helping their loved one is of paramount importance. This is conveyed by the use of phrases such as "We are doing (or we did in the case of death) everything we can (could) to help your child" and explaining the steps in the medical intervention [11]. Using the child's name during conversations about care is a simple action that immediately brings the interview to a more personal level. It is equally important to use correct pronunciation and appropriate gender references as defined by the young person. One can no longer assume a child's gender by their appearance. A simple way to understand gender identity of a patient is to ask what pronoun the patient uses [1]. Most transgender people use pronouns we are most familiar with like "he" and "she," and usually dress and groom in alignment with our culture's gender expectations. However, there are exceptions. Some people are not able or do not want to align with binary gender stereotypes and prefer the subjective pronoun.

Basic public speaking skills such as eye contact and timing are important adjuncts to use when speaking with families. Looking at all persons gathered together while talking, in order to acknowledge the individuals present, including any siblings, makes a conversation more meaningful [1,12]. Speaking in a calm, quiet manner that conveys feelings of empathy about the child's condition and the impact that this news is having on family members is also part of compassionate communication. It is equally important to pause during the conversation, allowing adequate time for input and questions. Asking parents for information that might help treatment or lead to different courses of action is vital. Actually asking, "Are there any questions?" often prompts parents to seek answers they otherwise would have been afraid to ask. It also provides confirmation that their thoughts and questions are valid, and reinforces that the child and the family are equally important to the physician [13,14]. Ultimately, the message and the messenger are inseparable [15].

After compassionate delivery, clarity of the message is the most important factor in communication. During an acute crisis, it is not uncommon for family members to unconsciously repress intolerable facts. Even if they do hear what the physician has said, comprehension may be delayed. For this reason, the physician must be clear, honest, and give simple explanations. Repetition and patience are often required. The physician must set aside an ample amount of time to spend with a given family [13]. This is time well spent, as it paves the way for future interactions.

It is vital that the health care provider should be aware of the facts related to the medical situation before the interview begins [13,16]. Possessing accurate knowledge allows a physician to be more confident and in control and conveys a sense that the family member has received care from an informed, prepared provider.

Often, it is not possible to relay all of the facts at one setting. This is when *pacing* becomes important. This means that the family is given time to process a fundamental but finite amount of information. After a period of time, the physician can return and add more information to this frame of reference. This facilitates understanding and more effective decision-making, if required [17,18]. In addition, it dampens the initial dismay when families are told of a concerning change in their loved one's condition. It is helpful to provide a summary of findings as each interview is completed, including a discussion about when the next meeting is likely to occur. Although the above concepts are pertinent to most encounters, it is important to adapt communication style to the given situation, as parental responses will be dependent on individual circumstances.

The conditions of the information session include the physical environment and the timing of the interaction. The best time to talk with families, particularly about acute change, is as soon as possible after the change occurs. This can be especially difficult in the emergency department, as the focus of the physicians' attention is on assessing and treating the child. A compounding factor is that the family may not arrive at the hospital until the child has been there for some time. The child may already have been taken to the critical care unit or operating room, resulting in a necessary delay before the physician can speak with family members. In this circumstance, one member of the trauma team may be asked to leave and communicate with the child's family.

The physical environment is extremely important for effective communication. Privacy is vital. Even in an acute setting such as the emergency department, a quiet area away from other people should be set aside, where the physician can sit down with the family and speak freely and openly. Ideally, the person who speaks with a family should be the health care provider who has had the most interaction with them, and with whom the family has formed a relationship of trust. Since this is not feasible in the acute trauma setting, it is helpful to allow such interactions to take place in the presence of the family's support system and a member of the hospital's family support team. Family members want to be advised of distressing information expeditiously and in the company of their loved ones [15,19].

The manner in which families are told of their child's status should be tailored to the individual situation. If you are interacting with family members who came to the United States as immigrants or refugees, they may not be able to speak or understand English (limited in English proficiency [LEP]), especially medical jargon. Thus, it is critical to alert the hospital so that a translator can be dispatched immediately to help with the communication effort or to use a trained translator by phone. Often younger members of the family speak and understand the English language better than parents or grandparents do, but it is preferable to have a professional adult translator rather than a minor, related child convey bad news to their elders. Family members, friends, and untrained bilingual hospital staff who provide ad hoc interpretation frequently commit errors of interpretation. In fact, false fluency errors by untrained hospital interpreters can be almost as common as by ad hoc interpreters because of a lack of skills training. The approach will also be dependent upon whether or not the child is likely to recover. Family responses will vary depending on the circumstances and their culture [20], and the physician should be prepared for this.

Fortunately, the most common scenario an individual physician will encounter when speaking with a family is one in which a child is likely to recover. In some circumstances, the child will recover and be normal, but in others the child will more likely recover with impairments. In either situation, the key to an effective interaction is clarity and honesty. The informant must be informed and forthright about every aspect of the patient's care and prognosis. Family members will understandably have questions. The medical care provider who is able to adequately address the questions will quickly and deservedly earn a family's trust, whether or not the answers to the questions are apparent when the conversation occurs [21].

When a child dies

Delivery of the news of a child's death has an impact that will last a lifetime [2]. In the case of sudden death, preparation is not possible. While the principles of communication already discussed apply, it is often difficult during times of acute crisis for families to remember what is told to them [22]. It is beneficial for a third party, often the chaplain or another member of the family support team, to remain with the family for a time or meet with them again to ensure that there are no unresolved issues or unanswered questions. This is helpful in preventing some aspects of pathologic grief that can stem from a lack of complete understanding on the part of the family [2,23].

Families of children who are chronically ill or have a more protracted course prior to death have a unique set of needs [24]. The physician and family have often had time to establish a relationship of trust and understanding. This scenario allows the health care provider to more adequately prepare the family for the death or for the possibility of death [25]. However, there are situations where parents are not open to discussions about the eventuality of death. They naturally do not want to feel that they have given up on their child. Although more challenging, it is still the physician's responsibility to provide continual support and honest information during the child's illness and at the time of death. Follow-up after the death of a child is also critical for a sense of closure, to aid in family coping during the bereavement period, and to prevent feelings of abandonment by the medical team that cared for the child [26]. Specific recommendations for bereavement care include (1) reminding the family that "everything was done" for their child can help prevent complicated mourning; (2) attending visitations, funeral, or memorial services shows the family that members of the medical team cared for the child as an individual; (3) providing follow-up contact a few days after the death ensures family members they have the support they need; (4) scheduling a postdeath conference with the family a few weeks or months after the death will allow review of the sequence of events that led to the child's death and reassurance that bereavement support can reduce distress; (5) ensuring that family have access to ongoing support from social workers, therapists, or chaplains who are part of the multidisciplinary team will establish continuity of bereavement care; (6) referring family to other bereavement specialists in the community such as hospice, grief support agencies, Compassionate Friends, or other parent support groups will extend their support structure outside of the hospital family; (7) offering psychoeducation about the potentially prolonged nature of grief will allow them to better embrace and understand the normal grieving process; and (8) sending notes or calling on the anniversary will reinforce the memory of their loved one and let them know you have not forgotten them [1].

Family presence during resuscitation

A concept that is receiving more attention but remains somewhat contentious in the setting of acute trauma is family presence during cardiopulmonary resuscitation (CPR) [14,27]. Interestingly, most family members have a desire to be present during the resuscitation of their child. They want the reassurance through the observation that medical personnel are vigorously trying to save their child's life. It is also conceivable that this will be the last time that their child is "alive" and parents want to be there at the time of death. In interviews with family members who have been present during end-of-life procedures, there is a common theme of overwhelming gratitude for having been given the opportunity to be present. This seems to be constant, regardless of the outcome of the medical efforts. For the surviving family members, it removes doubt about what occurred and helps them understand that everything possible was done to save their loved one. This allows for a more healthy grieving process [27–30]. A recent systematic review of studies on family presence during pediatric resuscitations indicates that parents who were present during the resuscitation of their child would choose to be present again if faced with that option and would recommend the same to others. These parents had better coping and less distress related to their child's death than parents who were not allowed to be present for the resuscitation [31].

There also seems to be a strong desire on the part of family members, particularly parents, to be present during invasive procedures. The ability to stay with the child decreases the anxiety level of the parents and child. There is no consistent evidence that family presence distracts from the provision of optimal medical care. In fact, one study showed that only a few providers felt as though there was an impact on technical performance, therapeutic decision-making, or teaching [32].

Understanding brain death

While there are clear-cut medical criteria for brain death, this information is often very difficult to communicate to families [33]. Further, a misunderstanding of what brain death represents can be a source of parental guilt if volitional withdrawal of care occurs. Such grief can later stem from misconceptions that the family was an instrument in the child's death or gave up on the child too soon. The lay press and other media venues can be particularly misleading about recovery from "deep coma" [2,34]. One way to provide comfort to patient families is to clearly explain that waiting longer would not have helped. There are books available to help with communication efforts. Some families may wish to view test results or witness the apnea test.

Each state has criteria for brain death. An example of a legal definition for the determination of brain death is as follows. The occurrence of human death shall be determined in accordance with the usual and customary standard of medical practice, provided that death shall not be determined to have occurred unless the following minimal conditions have been met:

1. When respiration and circulation are not artificially maintained, there is an irreversible cessation of spontaneous respiration and circulation or
2. When respiration and circulation are artificially maintained, there is total and irreversible cessation of all brain function, including the brainstem.

Individual state criteria may require verification of brain death by more than one licensed physician, and verification more than once at some later time interval. If pharmacologic agents have been used that preclude doing an apnea test, a brain blood flow study may be needed.

An example of the clinical criteria for the diagnosis of brain death is as follows:

1. Determine and document the probable cause of death.
2. The patient must be normothermic (temperature >36°C).
3. The absence of narcotics, sedatives, and hypnotics.
4. Exclude high cervical spine fracture.
5. Glasgow Coma Scale of 3 (i.e., no motor or verbal response to pain and no eye opening).
6. Absent brain stem reflexes, including the pupillary light reflex, corneal reflex, gag reflex, cough reflex, oculocephalic (doll's eye) reflex, and the oculovestibular (cold water caloric) test.
7. Valid apnea test
    a. Monitor cardiac rhythm and arterial blood pressure. Stop test if moderate to severe hypotension or dysrhythmia occurs.
    b. Preoxygenate with an FiO_2 of 100%.
    c. Start test with a $PaCO_2$ of 40 mmHg.
    d. Obtain an arterial blood gas (ABG) prior to disconnecting the patient from the ventilator.
    e. Disconnect the patient from the ventilator. Supply 6–7 L/min of 100% oxygen through tubing inserted into the endotracheal (ET) tube.
    f. Watch the patient for any evidence of spontaneous respiratory effort.
    g. Approximately 10 minutes after disconnecting the patient from the ventilator, obtain an ABG.
    h. Connect the patient to the ventilator and adjust to pretest settings.
    i. $PaCO_2$ must be 60 mmHg or greater or 20 mmHg above the patient's baseline on the posttest ABG for the test to be valid.

Organ donation issues

In seeking consent for organ donation, effective communication is essential and should take place in a comfortable, private area and not at the patient's bedside [13]. This interaction should occur after the family has been notified of brain death and has had time to comprehend this information, and in the presence of a limited number of persons who have been chosen by the parents. The process of temporally separating brain death determination and potential organ donation is called *decoupling*. Decoupling gives the family time to grieve their loved one's death.

Once families have had time to process the death of their loved one, a discussion should be held regarding organ donation. The Centers for Medicare and Medicaid's Federal Conditions of Participation (COP) requires that all families be given the opportunity for organ and tissue donation. Numerous studies have shown that the organ donation rate is greatly dependent on this initial interaction. The COP requires that the discussion of potential organ donation be led by someone with specific training in this area, typically an organ procurement organization (OPO) representative. Physicians are also allowed to lead this discussion if they have had formal training approved by their local OPO. These discussions work best when they take place in a private area, and when the physicians and OPO representatives work together. Physicians are not prohibited from discussing organ donation if the family brings up the topic [35].

If organ donation is not chosen, it is an optimal time to begin explaining and discussing the process for discontinuing ventilator support. In either case, the goal of the physician is to lead surviving family members to a decision that is personal, thoughtful, and comfortable for them.

Bereavement

Losses are inevitable, but there is no greater acute stress for a family than the sudden loss of a child due to injury through an accident, natural disaster, suicide, or violent attack from domestic or neighborhood violence or war [36]. There are predictable windows for building resilience in the midst of an emotionally charged environment, for both providers and the patient's family.

The family: Coping with unpredictability

Nothing in a parents' experience prepares them for the emotional chaos and lack of predictability that is characteristic of pediatric trauma. By the time their child arrives at the emergency room, the accompanying adults are understandably overwhelmed by feelings of shock, confusion, and fear for their child's safety. They literally place their child and their faith in the competent hands of the trauma team. The trauma team's first response is to the medical/surgical assessment and treatment of the pediatric patient. However, the focus of this section is to describe the accompanying psychosocial issues for the family that inform our handling of their needs.

The family's acute grief reaction

What do families need as they enter the emergency department? They look to the trauma team to assure them that their child will be all right. All parents want two characteristics in a physician during a crisis: expertise and experience. They want their surgeon (and hospital) to have the ultimate expertise and level of skill *and* they want their surgeon to be performing this skill on their child not for the fourth time but for the four thousandth time.

Expertise and experience: The perfect answer to the unpredictable event that has put their precious child at risk.

In the midst of trauma, therefore, the family must receive assurance about the team’s expertise and experience.

- Who should communicate with the family?
- What can be expected as an understandable and predictable response to their acute grief reaction?
- What is “best practice” or protocol in this psychosocial arena, which anticipates family needs?

The term “protocol” suggests a prescribed procedure that responds in kind to the acute grief reaction from the family members as well as the child if he or she is conscious. Often a lack of time compromises the ability to foster a completely satisfactory communication. The family needs to know: (1) the status of their child, (2) what is being done, (3) what is the expertise and experience of those treating her, and (4) will she be okay? In some hospitals, written pamphlets or photos that introduce the various members of the trauma team are on display. In any event, a designated first person who acknowledges the adult accompanying the child soon after arrival can provide the needed reassurance by a simple direct statement, “Your child, (use the child’s name as you learn it) is in the very best place. Our team is ready and equipped to help her. What is unique to you is all too familiar to us.” There is no need for more explanation as more is not necessarily better. This simple sentence provides much needed reassurance.

This designated first person may be a chaplain or a member of the family support services team and can also ask the family about past medical history and provide important information to the trauma team resuscitating the child. This individual acts as a liaison between trauma team and family.

The grieving parent’s defense mechanisms

The three defense mechanisms employed by grieving parents are denial, projection, and detachment. Medical providers most often see these defense mechanisms as barriers between parents and providers.

Denial: “I’m sure Anthony will be fine. He is a real fighter.”—parent
“Mrs. Terry is in such denial. I need to get her to accept that her child is not responding.”—nurse
Projection: “Doctor, why didn’t you tell me he was not going to live?”—angry parent
“I only want that nice nurse to be with my child; I like the way she looks at him.”—parent
Detachment (not typical in acute grief reactions):
“I can’t get to the PICU more than every few days to see my toddler; I have too much else going on in my life.”—parent

When the death occurs, some important steps need to be taken to help family members overcome these defense mechanisms. First, family members need to see the deceased child [37] and have time to say goodbye with some level of privacy. Second, just as the members of the medical team explained the steps in treatment and details of the interventions along the way, upon the news of the death, family members need to revisit the sequence of events leading to the death. This will both help them understand why the child died under these circumstances and how vigorously the medical team worked to try to save the child’s life. This is also a time for members of the medical team to answer questions about the child’s condition and treatment. Both pieces of information help the family make sense of the loss, which helps with long-term coping. Finally, members of the team can recommend that family members visit the site of an accident or natural disaster to better comprehend the severity of the incident, enhance feelings of closeness to the deceased and what they might have experienced, and come to terms with their loved one’s death [36]. When a child has died as a result of a suicide, or there is suspicion of child maltreatment, or when the child has died via homicide by a nonfamily member, the criminal justice system becomes involved. Thus, the final family goodbye with the deceased child may need to be supervised.

Next steps: Surgery or “the impossible outcome”

One of the most difficult aspects of caring for a family during trauma is the lack of time to create a trusting relationship. Following stabilization, some children will be sent immediately to surgery. The multidisciplinary trauma team has done its job and has transferred the patient to the next set of capable hands. An expectant family still needs information and support as they identify a new set of providers in whom they entrust their child’s care. If a child dies in the emergency department, the family has little or no time to understand what has happened, or how it is possible that their child could have been fine 1 minute and dead in a matter of minutes or hours.

If a child dies in the emergency department, the relationship that was initiated between the team and the family will serve the bereaved family for years to come. Anecdotal responses from bereaved parents suggest best outcomes when the pediatric trauma team demonstrated empathy and provided them with timely answers and understanding of their child’s unique medical situation. A nurse who used their child’s name or rubbed a mother’s tense neck, a surgeon whose eyes filled up with tears as he described efforts made to save the youngster’s life, a chaplain’s sensitive tone of voice or presence throughout an impossible wait, all reassure parents and family members that their child was cared for in a personal way [7].

Long-term bereavement

When a child dies, particularly as a result of trauma, parents may suffer from major depressive disorder, posttraumatic stress disorder (PTSD), or prolonged grief disorder (PGD) [36,38]. In addition to making sense of how their precious child was healthy and alive one moment and dead the next, they need to revise two assumptions about their world:

- That their child will outlive them
- That they could protect their child

These basic assumptions about their world have been shattered, and normal mourning must work through these shattered assumptions. It is highly recommended that professional counseling be considered within the first 3 months following a child's death. No death is more isolating than parental loss of a child, as extended family and friends often feel inadequate to comfort and provide solace.

As is often the case with childhood trauma, understanding the precipitating events and processing and resolving the guilt that parents or caregivers experience is an additional stressor that deserves a professional's assistance. Professionally facilitated grief support groups, specifically for parents who have lost children, are often useful.

Within the first year of bereavement, grieving parents often find themselves ready to understand the medical details surrounding their child's death. A compassionate surgeon who treated their child, and is willing to interpret the autopsy report with the parents, can help parents accomplish the powerful and significant task of understanding their child's death. This is a necessary requirement of their grief resolution. In fact, studies have shown that the majority of parents would like to meet with the physician who was caring for their child at the time of death to discuss the events leading up to and following the death, as well as provide feedback on their experience [39]. This and other follow-up behaviors noted in the previous section *Grieving Parent's Defense Mechanisms* have been found to lessen the blow of the death and prevent prolonged grieving.

Coping skills: Personal, professional

Patient families

Parents

The bereavement response by parents to the death of their child varies greatly and is influenced by their sense of culpability, whether they have surviving children, their own coping skills, and perceived support from extended family and friends [2]. Parents who report a strong religious belief often draw upon that strength during difficult times in the bereavement process. Grieving parents must be made aware of the fact that coping with a death is a very personal process that can be influenced by many factors such as personality, gender, culture, resilience, and one's own trauma history [40]. Thus, each parent is likely to grieve differently. This understanding may help mitigate problems down the road when, for example, a mother becomes upset that her husband copes by working harder and holding in his emotions so that she can feel that he is strong and reliable. If parents are encouraged to communicate frequently about how they are dealing with the child's death even in the presence of a marriage and family therapist, this may keep them from breaking apart, which often occurs after a child dies [41].

Surviving siblings

Surviving siblings often experience the loss of their brother or sister as a dual loss, as they also have lost their parents as they know them. Family life will never be the same. The task of creating a "new normal" is painful at best and is realized by each family member at his or her own pace.

Following the death of a sibling, children often suffer from anxiety, irritibility, and loneliness. Without additional support or counseling, long-term anxiety may be up to four times higher in siblings. This may be compounded by feelings of marginalization during the acute illness of the deceased sibling. Surviving siblings may benefit from open and honest communication that is appropriate for their developmental age, as well as family counseling following the death [42]. All of the follow-up activities noted above should include siblings to acknowledge their loss as well as help them cope with an overwhelming and emotional event in their young lives.

Children's understanding of death

For adults, death creates a sense of disequilibrium or a disruption in their usual "steady state." For children, however, death represents a "developmental interference that results in a suspension of their ongoing growth." The goal of a clinical intervention with children is to get them "unstuck" and to help them get through, over, under, or around a temporary barrier to their normal and healthy forward movement [3,23,40,43]. The clinician should view the child's ability to cope with a significant loss or death in relation to three factors:

- The child's ability to make sense of the death developmentally
- The child's history of loss and death
- The child's normal ability to cope with change

Although Piaget did not specifically address a child's ability to understand death, much of the current thinking about how children perceive death comes from his theories about cognitive development. This framework is very

Table 23.1 Developmental stages in children's understanding of death

Developmental stage	Perception of death	Reaction to death	Anticipatory guidance
Infant (0–2 years)	No cognitive understanding of death, perceived as separation or abandonment	Distress, frustration, regression	Identify a surrogate caregiver, learn caregiver's routine, provide nurturing and dependable environment
Preschooler (3–5 years)	View death as temporary or reversible, or possibly as punishment	Associated with magical thinking that wishes can come true	Respond to questions with concrete, simple explanations. Avoid euphemisms such as "lost, sleeping, gone to heaven, with the angels"
Latency age (6–8 years)	Understand death to be final, irreversible but not universal	Children this age do not think that they themselves will die; find death difficult to understand	Reassure that life will still be safe. Have a need to discuss details of the death. Need direct, simple answers regarding what will be the same and what will be different due to this death (i.e., predictability)
Preadolescent (9–12 years)	Views death as final, irreversible and universal (adult understanding)	Intellectualize death, often unemotional, may be sarcastic or seemingly insensitive	Be authentic. Verbalize that in spite of your grief, you are still able to care for your children
Adolescent (13–18 years)	Have an adult understanding of death, but behave as if they are immortal	Interested in exploring society's attitudes about life and death. Often reject traditional adult rituals surrounding death and create their own using abstract and philosophical reasoning	Need adults to help sort out often colliding feelings of sadness, anger, disbelief, and isolation

helpful in assessing a child's reaction to the death of a loved one and the clinician's role in providing anticipatory guidance to the adults in the child's life (Table 23.1). As useful as this framework is, children regress under stress and the boundaries are meant as developmental markers only. A child's history with loss or death, personal temperament, and prior ability to cope with change all inform us of an individual child's reaction to death.

Medical providers: Nurses and physicians

The pediatric trauma team confronts the stressful possibility of a death every time a patient arrives for medical treatment. When the outcome is death, everyone involved in the child's care understandably grieves. Even the most seasoned physician may frame the death in terms of his own perceived failure. Every nurse understands the profound grief that the family now faces. Routine debriefing of the treating team is seldom the norm in hospital emergency departments or even in neonatal and pediatric intensive care units. Medical providers are often understandably reluctant to become vulnerable and participate in the unfolding of the psychosocial aspects of treating the pediatric patient, particularly in the real-time context of treating other trauma patients. They are purposely "defended" and that defense needs to be respected.

Several major medical centers across the United States have begun to develop comprehensive programs to assist their health care workers process their grief. At Johns Hopkins Children's Center, a part of this comprehensive program includes routine bereavement debriefing sessions. These sessions are offered after all patient deaths with invitations extended to all health care providers caring for the deceased patient. The sessions are facilitated by a bereavement coordinator and focus on the details of the incident, disruptions the traumatic event can cause both physically and emotionally, as well as the emotional response of the health care professionals. Time is spent focusing on the relationship to the deceased patient and his or her family members as well, not just on the death event. These sessions are typically scheduled approximately 1 week later, to allow the individuals some time to process their thoughts and feelings first. These sessions are almost universally found to be helpful, informative, and meaningful by the participants [44].

Secondary trauma and PTSD

It is not uncommon for health care workers such as physicians, nurses, aides, social workers, and Emergency Medical

Technician (EMT) professionals to suffer from secondary traumatic stress (STS) after being exposed to a single patient who is injured or who dies from any number of traumatic events such as suicide, homicide, child maltreatment, accident, war, or natural disaster [45]. This may also be repetitive, which is particularly true when a health care provider works in an emergency department or pediatric intensive care unit and faces numerous instances of death and traumatic injury due to violence or other causes. An individual with STS has been exposed to an extreme traumatic event or stressor or multiple traumatic events to which he or she responds with fear, helplessness, or horror [43,46–48]. Given time, most people will recover from the psychological effects of a traumatic event or secondary traumatic exposure. However, research has shown that repeated exposure to traumatic events takes an emotional toll on health providers and can lead to burnout and PTSD [45,49,50]. PTSD represents a failure to recover from trauma exposure and is characterized by intrusive thoughts including distressing memories or nightmares related to the event, numbing or attempts to avoid reminders of the event, and symptoms of hyperarousal. STS can be prevented or addressed through individual and group engagement in self-care activities (e.g., engaging in exercise, taking mental health days, receiving massages, celebrating birthdays and work successes within departments), attentive supervision, provision of social support by supervisors and colleagues, and active engagement of staff in hospital policy development. Treatment for PTSD involves educating the person about the nature of the disorder, providing a safe and supportive environment for discussion, and relieving the distress associated with memories and reminders of the event through such evidence-based interventions as trauma-focused cognitive behavioral therapy (TF-CBT) or eye movement and desensitization and reprocessing (EMDR). The judicious use of medications can also benefit traumatized patients and professionals with high levels of STS by alleviating the symptoms of stress and PTSD and improving ability to function. Both secondary trauma and PTSD can be diagnosed and treated by primary care physicians, psychiatrists, and clinical psychologists. Debriefing programs for health care workers have sometimes been found to be useful in helping individuals cope with traumatic events sufficiently enough to alleviate the symptoms or signs of secondary trauma and prevent PTSD.

SUMMARY

It is important to remember that families do not “get over” their loss. Rather, they change their lives to accommodate the loss.

It is estimated that 19% of the adult population has experienced the death of a child, including adult children. In studies of how the relationship of the family member to the deceased affects the level of grief, it is well known that parents surviving their child’s death have significantly higher intensities of grief than other studied groups.

Very few parents seek help from therapists or formal support groups. This underscores the importance of medical care providers and the health care system as a whole taking the initiative to offer support services to surviving parents and family members [51,52].

Three terms aid in understanding: denial, wish, and hope. Denial is the unconscious repression of intolerable facts. To wish is imagining a future despite the available facts. Hope is imagining a future in light of the available facts. The principal goal of the health care team is to provide the framework for families to begin again to hope. This involves helping them reach a point where they can understand what has happened to their loved one, recognize the long-term consequences, and work toward a realistic future under these conditions.

Many institutions, particularly children’s hospitals and trauma centers, have family support teams. The purpose of these individuals is to support families in crisis or newly bereaved and to provide comfort measures. The goal of the intervention is to positively impact the grieving process by supporting parents and other family members as they make the drastic transition into life without their deceased loved one.

Another adjunct that can be provided is a resource center that lists resources to address grief caused by the loss of a loved one, as well as other associated forms of loss such as bankruptcy, chronic illness, divorce, and loss of employment.

Allowing parents and other surviving family members to discuss their feelings about the deceased and relay memories of their loved one seems to have countless benefits. By allowing parents to secure the memory of their child in the people around them, it permits validation of the child’s life. Otherwise, parents may feel that they have lost the child’s presence *and* the memory of the child. Sadly, friends and family members that are potentially one of the greatest sources of support may avoid even mentioning the child for fear that it’s too painful to the parents. The family’s support network needs to know that recalling the past is one of the forms of therapy that parents need most.

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24

Long-term outcomes in injured children

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Pediatric trauma: Scope of the problem

As the leading cause of death and disability in children, pediatric trauma accounts for some 10 million hospitalizations, 80,000 permanent disabilities, and 12,000 childhood deaths every year in the United States. Despite a decrease in the overall rate of injury to children in recent years, led by marked decreases in the numbers of children injured in motor vehicle collisions, the incidence of pediatric trauma in the United States remains among the highest in the world, reflecting both the dangers of our highly mechanized society and the reality of urban violence, including that related to firearms [1]. In fact, the rate of fatal injury resulting from violence may actually be increasing [2,3]. While children more often survive significant polytrauma than adults, long-term morbidity is all too common. Four children are left with permanent disability for every trauma-related mortality [1]. This statistic highlights the need to assess long-term functional status and quality of life in this population.

Injuries in children leave a lasting physical, emotional, and financial impact. They account for over one-third of all emergency department (ED) visits, and pediatric trauma results in estimated annual costs of over $200 billion [4,5]. Additionally, it is estimated that there are 10 million injury-related primary care visits each year in the United States, accounting for a significant portion of health care expenditures, especially for children aged 5–14 [6]. While it is impossible to accurately quantify the indirect costs to families and to society in general, it is clear that they are staggering. Given this, pediatric trauma represents the greatest public health challenge to children in the United States. Efforts must be focused to better understand the ways in which we can both decrease the occurrence of pediatric injury and optimize the outcomes of those injured.

The challenge of assessing pediatric outcomes

While we have indeed made great strides in our ability to care for injured children, we have made much less progress in our ability to assess the broadly defined long-term outcomes of these injuries. Of the articles reviewed for this chapter, none truly met Class I criteria with regard to the degree of methodological rigor supporting the conclusions; retrospective reviews (Class III) predominated.

Admittedly, clinical research in the setting of pediatric trauma, including the assessment of pediatric health status and quality of life, has numerous intrinsic difficulties. First, any functional assessment in children must be performed in a developmental context. Key aspects of quality of life such as physical, emotional, and social function rapidly evolve as the child ages. Measures of health status for this population must allow for comparison to age-adjusted normative values. Second, many significant pediatric injuries are relatively rare. All but the busiest of pediatric trauma centers see only an occasional significant spine or pelvic fracture. Finally, given issues of growth and healing, long periods of follow-up are needed to document the "final" outcomes of affected children.

Despite these difficulties, rigorous patient-oriented clinical research focusing on issues germane to the injured child is a prerequisite for the timely evolution of clinical practice in this area. Fortunately, new clinical research methodologies present exciting opportunities to explore issues related to these outcomes.

Volume: Outcome relationships

In 2014, the American College of Surgeons (ACS) Committee on Trauma stated that pediatric patients "may have special needs that are optimally provided in the environment of a children's hospital with demonstrated expertise in, and commitment to, pediatric care and trauma care" [7]. Over the last several decades, numerous studies have documented a relationship between higher patient volumes for specific conditions and better outcomes for various cohorts of adult and pediatric patients. Sollano et al. demonstrated a significant inverse relationship between the volume of surgical repair of congenital heart defects at a given hospital and in-hospital mortality [8,9]. Potoka et al. demonstrated a significant inverse relationship between the risk-adjusted mortality and the volume of pediatric intensive care unit admissions [10].

In many areas of the United States, trauma care has been regionalized, with specialized centers designated for pediatric trauma. The ACS recommends minimum patient volumes for pediatric trauma centers. Currently, pediatric Level I centers must annually admit at least 200 injured children and Level II centers must admit at least 100 under 15 years of age [7]. Despite the increase in the number of pediatric trauma centers, Petrosyan et al. reported in 2009 only 10% of injured children were treated at pediatric trauma centers and 47% of children were seen at centers without any trauma credentialing [6]. Utilizing the KIDs' inpatient database (KID) of 2000, Densmore et al. compared mortality, length of stay, and hospital charges of injured children treated at children's hospitals, adult hospitals, and pediatric wards of adult hospitals. They found that, after adjusting for variance in injury severity scores (ISS), these outcome variables were significantly higher in adult hospitals compared to children's hospitals, and especially in pediatric units within adult hospitals [11]. Using data from the Pennsylvania trauma registry, Konvolinka et al. [12] concluded that mortality might increase when surgeons treat fewer than 35 seriously injured patients per year [13].

Several recent studies have examined the relationship between dedicated pediatric regional trauma centers and patient outcomes. In a comparison of survival rates of pediatric trauma, Cooper et al. found that children treated within a specialized pediatric trauma system had higher severity-adjusted survival rates [14]. Doolin et al. found a strong relationship between in-house specialized personnel and outcome [15]. Specifically, the presence of an in-house pediatric surgeon was associated with a lower rate of mortality among severely injured children. Pollack noted lower severity-adjusted mortality for children treated at tertiary care facilities [16]. Nakayama et al. showed that mortality was higher in rural nonpediatric centers (6.2%) in comparison with pediatric centers (4.1%) [17]. Patoka has shown that children treated at regional pediatric trauma centers have better functional outcomes at discharge in comparison with children treated at adult centers and nonspecialized centers for trauma [10]. More recently, Wang et al. compared the outcomes of severely injured pediatric patients in the state of California, and found improved outcomes among injured children treated at trauma centers compared to nontrauma centers, but was unable to demonstrate that subspecialty pediatric trauma centers conferred mortality benefit over adult trauma centers [18]. Interestingly, Miyata compared outcomes for injured children treated at Level I and Level II pediatric trauma centers, and after controlling for age, injury, and severity with matched case-control methodology, found no differences in mortality between Level I and Level II pediatric trauma centers, even when patients required laparotomies, thoracotomies, or cardiopulmonary resuscitation (CPR) in the initial 24 hours [19]. Despite several studies supporting the relationship between specialization, patient volumes, and outcomes in pediatric trauma, it is not clear that children unanimously have improved outcomes at pediatric trauma centers. It is unclear if this disparity is related to the overall low mortality rate in pediatric trauma, the relative scarcity of Level I pediatric trauma centers, the lack of reported trauma-related data from nondesignated centers, or the degree of specialization of providers at various trauma centers [19,20]

While it may be intuitive that we do best what we do most often, forces within our health care system sometimes discourage specialization. However, as will be obvious from the following review, we have much room to improve the outcomes of children who sustain significant trauma.

Functional status and quality-of-life assessment in a pediatric population

While children are more likely to survive traumatic injury, many endure significant long-term problems in physical function and overall health. Aitken et al. recently reviewed the experience of the National Pediatric Trauma Registry (NPTR) and found that, even when excluding head injuries, 14.5% children captured in this 6-year study of NPTR had persistent disabilities [1]. The ability to quantify deficits in functional status and health-related quality of life (HRQOL) is germane to the assessment of injured children.

Fortunately, measures to assess functional status and HRQOL in children have recently become widely available. These instruments are designed to assess the physical, psychological, and social dimensions of health, as outlined by the World Health Organization (WHO) [21]. There are several tools available for use, but two of the most commonly used include the Child Health Questionnaire (CHQ) and the Pediatric Quality of Life Inventory (PedsQL).

The CHQ is perhaps the best-validated measure for the assessment of general health status in children [22] and is similar to the Short Form-36 (SF-36), which has been widely used in the adult literature. The CHQ consists of a short questionnaire, which can be scored and generates multiple domains that span the spectrum of physical, psychosocial, and social health in injured children [23]. Age-adjusted normative values are available and play an important role for the comparison of health status in children after trauma, for which premorbid scores are not available.

The PedsQL 4.0 is the fourth and most recent version, and was designed to measure the WHO core health dimensions. The 23 items on this scale are designed to assess physical, emotional, social, and school functioning in children ages 2–18 years [24]. The PedsQL 4.0 is brief, easily understood, developmentally appropriate over a wide age range, and validated and, in addition, disease-specific modules can be included to afford both general and disease-specific quality-of-life measures [25].

The Pediatric Orthopedic Society of North America has also developed a health status questionnaire, which also exhibits good validity and reliability across a range of pediatric musculoskeletal conditions [13].

A large prospective epidemiological study of outcome after adult trauma utilized a similar adult quality-of-life measure, the Quality of Well-Being scale, and documented profound perturbations in quality of life at 12–18 months after major injury. The authors concluded that the magnitude of dysfunction has likely been underestimated by more traditional measures of patient outcome and that quality of life measures have an important role in the long-term assessment of patients who have sustained traumatic injury [26]. Research continues to incorporate these HRQOL measurement tools as a means to provide meaningful data to guide evidence-based decision making in the area of pediatric trauma and pediatric health.

Pediatric polytrauma: Outcomes

There has been a marked improvement in mortality rates of injured children over time. The mortality rate attributable to unintentional deaths in children has fallen by 50% between 1970 and 1990 [27]. Between 2000 and 2009, the unintentional death rate for children less than 19 years of age declined another 29%, and in 2013 was reported to be 9.3 per 100,000 children [28]. This is a result of both successful prevention strategies including recommended physician–parent injury prevention counseling, increased use of seat belts and child safety seats, improvements in vehicular design, reduced drunk driving, and improved trauma care [29,30].

Much less has been documented concerning the long-term outcomes of injured children. In a review of the literature in this area published in 1997, Van der Sluis et al. identified only seven studies that focused on the "long-term" (the maximum follow-up in this group was 2–4 years) outcome of injured children and concluded that there was a "dearth of outcome studies on severely injured children" [31]. The authors went on to collect information regarding functional status (as measured by the Functional Independence Measure [FIM]) and quality of life (as measured by the SF-36) at an average of 9 years after injury on a cohort of children who sustained significant polytrauma. Despite the fact that 42% of these patients had some degree of resultant cognitive impairments, SF-36 scores were generally satisfactory. On the other hand, Wesson et al. found that pediatric trauma had profound effects on the physical and psychological health of children and their families at 12-month follow-up [32]. Among children who experienced major trauma, 71% had persistent physical limitations, 41% had behavioral disturbances, and many children exhibited a decrease in academic performance. Another study by the same author showed that 88% of children surviving severe injuries had functional limitations at discharge with 54% still having limitations at the 6-month follow-up [33]. Valadka et al. published the results of a retrospective study, which assessed health status of children via a telephone interview at a minimum of 1 year after significant trauma [34]. Half of children who were a minimum of 6 years after injury were found to have long-term sequelae. Furthermore, in a prospective study by Winthrop et al., children who experienced moderate to severe trauma were assessed for quality of life and recovery of function at hospital discharge, 1, 6, and 12 months after injury. Children demonstrated rapid recovery between discharge and 6 months postinjury, however, at 6 months postinjury, physical function remained lower than age-matched norms [35]. Thus, the available literature suggests that a large percentage of children who sustain significant trauma have persistent functional limitations and disability, despite modern improvements in patient care.

Outcomes of traumatic brain injury

Traumatic brain injury (TBI) has, both by incidence and severity, the greatest influence on long-term outcome of any childhood injury. TBI is the leading cause of injury mortality over 1 year of age and long-term injury disability in children. In addition, many more of the children who are admitted to a hospital annually following a brain injury go on to have significant, life-long sequelae from their injury [36]. These children typically return to their communities and schools, where primary care physicians, educators, and families often poorly understand their problems. Many children make significant cognitive improvements, only to be plagued by ongoing behavioral, social, and psychological problems. Current work in this area revolves around the recognition of these long-term deficits and the development of techniques to maximize cognitive function and social reintegration.

Expected functional outcome following TBI varies with the initial severity of the brain injury. The Glasgow Coma Scale (GCS) is most often utilized to determine the degree of acute neurological dysfunction following traumatic brain. The GCS may be used to divide children with brain injuries into three groups: mild (GCS 13–15), moderate (GCS 9–12), and severe (GCS ≤8). Ultimate functional outcome has been demonstrated to correlate with the GCS on presentation in a study of over 500 adults and children in Finland [37]. In a study of 81 consecutive children with brain injuries, O'Flaherty found that fine motor skills, self-care, and academic performance correlated directly with the severity of initial injury, even at 2 years postinjury [38].

In a case-control series of 76 children with mild, moderate, or severe brain injuries, Yorkston found a significant correlation between the severity of brain injury and a range of cognitive measures [39]. Jaffe and coworkers found a relationship between the severity of brain injury and residual impairment at 1 year after injury in a case-control series of 94 brain-injured children [40].

Mild brain injury is associated with few changes in neurological function, which may not persist. Polissar, in a case-control study of 53 children with a mild TBI, used a broad battery of neuropsychological tools to disclose a mild association between brain injury and neurobehavioral variables initially and 1 year after injury [41]. In a case-control study of children with a mild TBI, a severe TBI, or an orthopedic injury, Max found that children with a mild TBI had abnormal teacher-rated adaptive function scores [42]. However, children with a mild brain injury have been found to be similar to controls in reading comprehension and spelling at 12 months after injury, and in memory skills and academic performance at 24 months after injury [38,43,44]. Other studies have found that a mild TBI had no effect upon behavioral problems, neurobehavioral functioning, or memory [43,45,46].

Severe TBI has the most profound effect upon functional outcome. In a series of 105 children who were survivors of severe TBI, only 44% were found to have a good functional outcome 5 years after injury [47]. Significant persistent deficits have been noted in memory, sustained attention, behavioral problems, and educational performance [43,48–50]. Certain factors may help predict which children will have a worse outcome. The threshold for neurophysiologic dysfunction is lower in children than adults, and a critical GCS score is considered to be ≤5 [51]. Children with severe TBI who have an initial GCS of 3–5 and a delay in return to GCS 15 of more than 1 month, have more profound, persistent deficits [52].

Among children with a severe TBI, approximately 3% persist in a vegetative state [47]. Kriel studied a group of 26 children who remained unconscious for more than 90 days after TBI and found that 20 regained some consciousness, 11 of whom were eventually able to communicate. They found that improved outcome could be predicted by the degree of atrophy on brain computerized tomography (CT) performed 2 months after injury [53]. Ricci found that the ratio of *N*-acetyl aspartate and choline noted on brain magnetic resonance spectroscopy was able to differentiate between eight patients who remained in a vegetative state and six patients who ultimately regained some consciousness [54]. Fulkerson et al. found that the abnormal pupillary responses most strongly correlated with survival and outcomes at 1 year [55].

The outcome of TBI varies with age, and children have been shown to have improved overall outcomes compared to adults [56]; however, significant TBI in the youngest children has been found to produce long-lasting deficits, which persist and adversely affect the child's development [57]. In a group of 97 children referred for rehabilitation following a severe brain injury, Kreil found worse cognitive and motor deficits, as well as more brain atrophy, among children under 6 years of age, compared to children 6 years of age or older [58]. Some hypothesize that these poorer outcomes may be related to the disruption in the acquisition of and the future development of skills that were not yet acquired at the time of injury [59].

Long-term outcomes of TBI

There is conflicting evidence in the literature about the prospect of functional improvement after severe brain injury. Carter, in a longitudinal study of over 100 children with severe brain injuries, found that 12–61 survivors had an improved functional outcome at 5 years after injury as compared to 1 year postinjury [47]. However, other series have failed to demonstrate an improvement in the functional outcome following the first month after injury. Ewing-Cobbs et al. found no improvement in educational scores between 6 and 24 months in a series of children followed prospectively [60]. Jaffe found significant improvement in cognitive function during the first year after TBI, but only negligible change over the next 2 years [61]. Kriel, Ricci, and Berger reported significant improvements in outcome after the first few months following TBI in children with devastating injuries [53,54,62]. In 2006, Chapman described the term "neurocognitive stall" to describe a paradox in the brain recovery of children with TBI. There appears to be a slowing or halting of cognition, social, and motor development in children that occurs both at the time of injury and then a subsequent "stall" which may occur years after TBI [63]. Although children may return close to their baseline after a TBI, subsequent learning may be affected due to deficits in memory, attention, processing speed, and executive function [59].

Various long-term cognitive problems have been reported in children following severe brain injury. Roman examined verbal learning and memory in a group of children following mild, moderate, or severe brain injury. The children with mild to moderate injuries scored similarly to control patients, while deficits were found in children with a severe brain injury [64]. Catroppa et al. also found a difference in sustained attention, reading comprehension, and arithmetic between children who had sustained a mild to moderate or a severe brain injury [65]. Attempts to address the attention difficulties through medication have met with mixed results. While Mahalick found that methylphenidate administration improved attention skills in 14 children following TBI, other authors, such as Williams, have found no effect [66,67].

The ability to actively participate in educational activities is one of the key duties of childhood. Children with a TBI have a variety of school-related difficulties. They suffer from cognitive deficits and behavioral and psychological problems that may adversely affect their ability to participate in social situations. Kinsella found a high rate of special educational needs among children following severe TBI [45].

Ewing-Cobbs found, in a prospective longitudinal analysis of 33 brain-injured adolescents, lower reading recognition, spelling, and arithmetic scores 6 months after brain injury. At 2 years after injury, despite the return of test scores to an average level, nearly 80% of the children had either failed a grade or required ongoing special education assistance [50]. Nybo found that the majority of toddlers who had suffered a severe TBI had cognitive and social problems that persisted into adulthood [68].

A portion of these persistent problems may be secondary to behavioral and personality disturbances. Max found an increased incidence of psychiatric problems in the second year after brain injury [69]. Emanuelson found that, despite a normal IQ and ambulation, none of 23 children treated in a regional rehabilitation center for a severe brain injury had been able to adjust to a normal life because of behavioral and personality disturbances [70]. In fact, Catellani et al. found that a group of adults who had suffered a severe TBI in childhood were poorly adjusted socially and still had problems related to behavioral and psychiatric disorders. These problems did not improve with age, despite an improved ability to conduct activities of daily living [71]. Investigators have also noted a difference in TBI outcomes that may be ascribed to other factors, such as the levels of parental stress and coping skills. In a group of 18 children with severe TBI, Rivara found a high level of strain in their families 3 years after injury that correlated with the child's outcome [72]. Max found that family dysfunction was associated with deficits in child adaptive functioning [73]. Kinsella found that parental coping skills had a significant impact on a child's behavioral sequelae after severe TBI [74].

Given the significance of long-term neurodevelopmental outcomes to the developing brain of a child, it is vitally important that rehabilitation specialists are involved in the care of children with TBI for long-term follow-up to help them reach their optimal functional status.

Outcomes of trauma to the extremity in children

Musculoskeletal injuries continue to constitute the predominant category of pediatric trauma. A recent retrospective review of 601 patients treated at a Level I regional pediatric trauma center found that half of all consultations to the emergency room were by the orthopedic service [75]. Moreover, treatment of musculoskeletal trauma is the most likely cause for admission and for surgical intervention among children sustaining pediatric trauma.

Improved methods of bone and soft tissue management have markedly improved the outcome of severe injury to the extremity. Femoral fractures, which are common among children with polytrauma, demand prompt treatment in order to reduce early complications and improve long-term outcomes. Intramedullary and external fixation are increasingly used even in young children in order to achieve prompt early stabilization and improve management of the injured child. Multiple studies have documented excellent long-term outcomes with regard to acceptable bony healing and return to function [1,76].

Open fractures of the extremity continue to pose a significant challenge, though improvements in early management and techniques of limb salvage including bone transport and myocutaneous free flap transfer have led to higher rates of limb salvage. As in adults, the Gustillo classification predicts complications and risk of limb loss, though rates of infection, including limb-threatening osteomyelitis are lower than those found in adults [77,78].

Borne et al. reviewed pediatric amputee patients utilizing the National Trauma Data Bank (NTDB) between 2007 and 2011. They found that trends in pediatric amputations have not significantly varied in the last decade. The most common mechanisms of injury included amputations to extremities caught between two objects (i.e., sliding doors), powered lawn mowers, motor vehicle collisions, gunshot wounds, and off-road transport, with a trend toward lower-energy amputations in younger children and high-energy mechanisms in adolescents [79]. Lawn mower injuries continue to account for many avoidable, significant injuries to children despite an increase in public awareness, with amputation resulting in about one-half of cases [80]. Mehlman recently reviewed cases of traumatic hip dislocation and noted a strong association with delay in reduction of >6 hours and an increased risk of avascular necrosis to the femoral head [81]. Although limb replantation continues to present a significant technical challenge, the rate of successful upper extremity replantation seems to be higher in children >9 years of age [82].

Outcomes of pediatric pelvic fractures

Pelvic fractures represent < 0.2% of all fractures in children, yet contribute to nearly 5% of all Level I pediatric trauma admissions [83]. Although significant pediatric pelvic trauma is much less common than other injuries, these injuries can have an immense effect on the health of affected children. Mortality is less common than in adults with one recent study reporting a 5% overall mortality rate for 722 pediatric pelvic fractures reported in the NPTR compared to a 17% mortality rate among similar injuries in an adult population [84]. A recent analysis by Marmor et al. utilizing the NTDB compared children with pelvic fractures (<13 years) to adolescents (13–17 years) and adults (18–54 years) and found a decreased mortality in adolescents (6.8%) but an increased mortality in children (10.2%) compared to adults (8.5%) [83]. Associated injuries, including abdominal, genitourinary, and head trauma, are commonplace in both adults and children [85,86].

Pelvic fractures in children differ significantly from those found in adults. The pediatric pelvis is plastic and deformable, and will absorb significant energy prior to failure. Thus, pelvic fracture in a child is indicative of a high-energy injury. Furthermore, injuries to the pediatric growth plate may result in progressive deformity, although the effect of growth disturbance on long-term outcome has not been adequately characterized. On the other hand, remodeling may occur during growth, leading many orthopedic surgeons to opt for nonoperative treatment of injuries which would require open reduction and internal fixation in an adult population [87,88].

An improved understanding of the issues related to the early management of these injuries has resulted in a marked improvement in short-term outcomes including mortality and early complications. Children are much less likely to have life-threatening exsanguinations as a result of pelvic fracture, and there has been an increased awareness that hemodynamic instability in this setting demands an aggressive search for other sources of bleeding [2]. Another study found that children who present with a pelvic fracture and additional bony fractures are much more likely to have head and abdominal injuries and have twice the risk of death as those presenting without concomitant skeletal injuries [89]. The pelvic fracture classification of Torode and Zieg (avulsion, iliac wing, simple ring, or ring disruption) has been shown to be an accurate predictor of blood loss, associated injuries, and expected outcomes [2,85,86,90,91]. Long-term morbidity is often more related to associated injuries, most notably head injury, rather than the bony injury [85,86].

Much less is understood about more broadly defined, important long-term outcomes including functional status and quality of life in children with pelvic fractures. In a review of 17 children under 12 years of age who sustained unstable pelvic ring fractures, Schwarz et al. found that bony asymmetry and malposition resulted in low back pain and functional impairment [92]. On the other hand, in a retrospective review of 54 children at a mean follow-up of 11 years, Rieger et al. found that long-term disability was rare and related to severe pelvic ring disruptions, acetabular fractures, or concomitant injuries [93]. Noting that little is known about functional outcome in pelvic fractures in children, Upperman et al. reviewed the FIM, which is part of many pediatric trauma registries, for a group of children who sustained pelvic fracture [94]. He found that a majority of children have significant limitations in locomotion and transfers at discharge.

The relative lack of data describing long-term outcomes in this area has led to significant controversy regarding the appropriate treatment of these uncommon but potentially devastating injuries. Some orthopedic surgeons have opted for a nonoperative approach, even to unstable injuries, citing the potential for remodeling inherent in the immature skeleton [87,88]. On the other hand, others have opted for surgical intervention [77,92,95,96]. Pelvic fractures can result in significant disability, pain, reduction in quality of life, sexual difficulties, and problems at work in adults. There is good evidence in the adult literature that the quality of anatomical reduction correlates with functional outcomes in this area [95,96]. No study to date has specifically examined the effect of nonanatomical reduction or bony malunion on arthritis, though this is a concern.

Further research is necessary to elucidate the intermediate and long-term outcomes of children with specific pelvic injuries and to help guide the appropriate indications for surgical intervention in this area.

Outcomes of spinal cord injuries

Spinal cord injuries (SCIs) in childhood are uncommon, but devastating. Out of 11,000 persons who suffer a SCI each year in the United States, approximately 1000 are aged 15 years or less [8]. Nearly one-half of these children suffer a complete SCI with little prospect for improvement. About 60% of children with an SCI suffer from tetraplegia, a higher percentage than in adults. Children surviving the first month after an SCI have an average life span of 60 years when paraplegic, and 52 years when tetraplegic (Table 24.1). The majority of children with SPIs complete high school, attend college, and are ultimately employed [97,98].

Functional outcome after SCI is dependent upon whether the injury is complete or incomplete and the level of injury. Outcome may also be affected by the development, or avoidance, of a variety of postinjury medical and psychological complications [99]. The International Standards for Neurological and Functional Classification of Spinal Cord Injury or American Spinal Injury Association (ASIA) scale is the most widely used method of codifying residual function below the level of SCI (Table 24.2) [100]. ASIA A injuries are sensory and motor complete. ASIA B injuries are sensory incomplete and motor complete. ASIA C injuries are motor incomplete with the majority of affected muscles having less than three-fifths strength. ASIA D patients are motor intact with the majority of affected muscles having greater than three-fifths strength. ASIA E patients have normal sensory and motor function.

Although motor function may improve over time after injury, the ASIA impairment scale measured 1 week

Table 24.1 Life expectancy of children with spinal cord injury (SCI) surviving at least 1 year postinjury

Current age	No SCI	Paraplegia	Tetraplegia	Ventilator dependent
5	71.6	59.5	52.6	39.4
10	66.6	54.6	47.6	34.9
15	61.7	49.8	43	30.4

Source: Vogel L, DeVivo M., *Top Spinal Cord Inj Rehabil.*, 1–8, 1997.

Table 24.2 American Spinal Injury Association classification and ambulation

ASIA level	Sensory	Motor	Ambulation (%)
A	Complete	Complete	<1
B	Incomplete	Complete	50
C	61.7	Incomplete, weak	75
D		Incomplete, antigravity	95
E	Normal	Normal	100

after injury may predict the prospects for ambulation. Of patients with a complete, or ASIA A injury, 80%–90% of injuries will remain complete and, of those who do become incomplete, only 4% will ambulate. Patients with incomplete injuries have a much better prognosis for subsequent ambulation. ASIA B patients at 1 week have a 50% chance of regaining adequate motor strength to walk. This may be positively predicted by the presence, or absence, of sacral sensory sparing. Those without sacral pin sensation have a much poorer prognosis for ambulation. ASIA C and D patients have a 75% and 95% chance of walking, respectively [101]. ASIA E patients have no discernable deficit and should return to their full preinjury level of function. Significant recovery of motor function may occur in many patients over the first 3 months after injury. Further motor recovery, at a slower pace, may be noted over the next 6 months, with smaller improvements in functional recovery documented up to 2 years after injury [102]. The recovery of motor function occurs more rapidly with incomplete SPIs and is more likely to occur in younger patients [103].

Despite this recovery, a motor examination performed 1 month following injury may be prognostic of ultimate recovery [104]. The presence of even one-fifth strength in a muscle group 1 month after injury is associated with a 97% chance of recovery of antigravity strength in that muscle group by 1 year after injury. In contrast, muscle groups with no strength on testing at 1 month have only a 10% chance of achieving antigravity strength by 1 year after injury [102].

A number of late effects of SCI, as well as a number of medical complications, may adversely affect ultimate functional outcome. Sadly, 64% of adults report ongoing significant musculoskeletal or neuropathic pain 6 months after their SCI [105], which is likely also the case in children. Scoliosis is common following SCI in children, and its severity is increased by younger age at onset, complete lesions versus incomplete, and paraplegia versus tetraplegia [106]. Kyphosis also commonly occurs, and has been associated with an increased risk of syringomyelia when angulation is greater than 15° [107]. Whether associated with kyphosis or not, posttraumatic syringomyelia may occur in 25% of paraplegic patients, and may lead to progressive neurological deterioration [107,108]. Progressive noncystic tethering of the spinal cord has also been reported, and may lead to similar neurological deterioration [108]. It is hoped that this late deterioration may be prevented with more aggressive spine stabilization.

Children with an SCI have been shown to return quickly to school following a rehabilitation program: mean of 10 days following discharge for paraplegic children and 62 days for tetraplegic children, according to one study [109]. Educational performance among children with an SCI is excellent. In Dudgeon's study, most patients graduated from high school and pursued higher education. Many schools modified their curricula to accommodate the needs of the children, most of whom had teacher aides [97]. Interestingly, age of injury may correlate with how well patients adjust to life with an SCI. The prevalence of depression in adults with adult-onset SPIs ranges from 18% to 37%, while in adults with pediatric-onset SPIs the incidence is reported to be much lower at 8% [110]. January et al. (2015) also found that patients with pediatric-onset SPIs reported greater psychological growth related to their traumatic injury, and coping mechanisms play an important role in this development.

The prognosis may seem bleak for children with a high cervical SCI who leave the hospital ventilator dependent. However, Oo found that of 107 adult patients who were ventilator dependent upon discharge, 21% subsequently recovered adequate diaphragmatic function to allow them to be weaned from the ventilator [111]. Many of these patients required more than a year to recover sufficient diaphragmatic strength not to require ventilator support. Similar data for children are not available.

Bowel problems are common following SCI. Goetz studied 88 children with SPIs and found that 68% reported that their bowel habits interfered with school and other activities and resulted in dissatisfaction [112]. Most patients require long-term use of oral and/or rectal medications for bowel control. Krogh reported that up to 75% of patients report at least a few episodes of fecal incontinence per month, and that nearly one-third felt that their bowel problems were more burdensome than their sexual or urologic dysfunction [113].

Issues such as these contribute to dissatisfaction with quality of life after SCI. Using the standardized measures of quality of life, Kannisto found that patients with SCI scored significantly lower than the population sample. Not surprisingly, patients with SCI placed greater significance upon the measures for mental functioning, communicating, and social participation [114]. Gorman examined the psychological health of 86 children who suffered an SCI prior to 16 years of age, and found that self-esteem, depression, and self-perception were lower than average, regardless of age or level of injury [115].

Given the long-term adverse consequences following SCI in children, this is another area where the involvement of rehabilitation specialists is of vital importance. Details on how these specialists can aid in recovery are available in Chapter 22.

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