Pediatric Trauma Care

A Practical Guide

Alfred P. Kennedy Jr
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Robert Ricca
Editors

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Preface

"Rejoice O young man in the youth"
Ecclesiastes 11:19

The naissance surrounding this text was conceived with a desire to present to the reader with a succinct and portable "handbook" for the most common clinical problems encountered by those of us who care for the injured child. It is not meant to be an exhaustive treatise. Each chapter is designed to present the reader with concise information surrounding the injury complex. Chapters are divided into Clinical Pearls, focused diagnosis and management, ending with take home points. It is with sincere gratitude that the majority of content is presented by authors who serve or have served in this nations' Defense. The debt of service shall never be paid.

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Independence Day 2021

Contents

Chapter 1
Introduction: (Unique Factors to Pediatric Trauma)

Robert Ricca

Abstract Trauma is the leading cause of death in children. The last several years have seen significant improvements in the care of the traumatically injured pediatric patient in part due to research efforts focused on pediatric trauma. These efforts are paramount as children differ from adults in many ways including size and proportion, as well as in their physiologic response to injury. The provider caring for a traumatically injured pediatric patient must be aware of these key differences such as: management of the pediatric airway, the risk for hypothermia, pliable rib cage and significant pulmonary contusion in the absence of rib fractures. Some critical points in adult management have significantly contributed to pediatric trauma management, including balanced resuscitation strategies, early use of blood products, prophylaxis of venous thromboembolism, and more recently, use of whole blood instead of component therapy. Similarly, some pediatric trauma strategies have changed the way adult patients are managed including non-operative management of solid organ injury. These issues have illustrated the need for trauma capabilities that are dedicated to the management of the injured child. This textbook strives to provide a clinically focused management strategy that is a rapid reference for those individuals who care for these injured children. This chapter will touch on research efforts and organizations that have improved quality outcomes for pediatric trauma patients not discussed elsewhere in this text.

Keywords Pediatric trauma · Trauma training · Trauma organizations · Epidemiology

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Key Concepts

- Care of traumatically injured children has fallen under the auspices of pediatric surgeons for the last century. Recently we have seen a resurgence of interest in pediatric surgical trauma care.
- Key differences exist in body composition, physiologic response to injury as well as underlying trauma mechanisms between the pediatric and adult that trauma patient.
- Multiple organizations exist that focus on collaborative research efforts, advocacy and clinical practice guidelines to improve outcomes for the treatment of traumatically injured children.
- There are several courses focused on the different phases of care that can add to the knowledge of professionals caring for traumatically injured patients. These range from pre-hospital care to advanced surgical exposures.

Introduction

William Ladd has long been identified as the founder of pediatric surgery in North America. His commitment to the surgical care of children began in 1910 when he joined the staff of the Children's Hospital in Boston. A mere 7 years later, Dr. Ladd was an integral part of one of the largest mass casualty efforts that affected children during the twentieth century. On December 6th, 1917, during the height of World War I, the SS Mont-Blanc, a French cargo ship, collided with a Norwegian vessel the SS Imo. The SS Mont-Blanc was carrying wartime munitions, and the result of the collision was a tremendous detonation that injured over 9000 individuals in some reports. Scores of children were amongst those injured, and it was Dr. Ladd, amongst many other healthcare professionals, who traveled from Boston to assist with the mass casualty event resulting from the explosion. These children suffered from both thermal injuries as well as other traumatic injuries from the blast and shock wave that destroyed countless houses and businesses in the area. Almost a century later, trauma remains the leading cause of death in children in North America. Legend holds that this event spurred the birth of pediatric surgery in North America. While this may be surgical lore, the understanding by Dr. Ladd and his counterparts that pediatric trauma victims during this event required unique management strategies is a key point that still holds true today [1].

Over the course of the last century we have seen a continued expansion of trauma capabilities throughout the world. Training in trauma and critical care is available following general surgery residency [2]. Many of these surgeons provide care for injured children, however, there has been a move recently to increase the involvement of pediatric surgeons in the care of traumatically injured children. The recognition of differences in physiology and subsequent management of traumatically injured children when compared to adults has led to the evolution of pediatric-specific trauma centers. The American College of Surgeons (ACS) now verifies centers as Level 1 or Level 2 pediatric trauma centers. The criteria for verification are well established by the ACS and have demonstrated decreased injury-related mortality and improvements in quality related metrics compared to non-ACS-verified centers. At the time of this publication, there are more than 60 Level 1 pediatric trauma centers in the United States and over 50 Level 2 pediatric trauma centers [3]. These centers serve as the experts in pediatric trauma care within the regional trauma system where they are located and interact routinely with all components of the trauma system to improve the care of the injured child.

Trauma affects children of all ages. Unintentional injury remains the leading cause of death in children of all ages. For children aged 10–14, intentional or self-inflicted harm is also the second leading cause of mortality. The most common mechanism, at the time of this writing, across all ages is motor vehicle collisions (MVCs). The breakdown of trauma mechanism is then broken down by age, with assaults, firearm injuries, sports-related injuries, falls and burns as the second leading cause of injury depending upon the age of the patient. Similar to prevention efforts in adults, recognizing the age at which traumatic injury is more likely to occur allows for educational efforts and injury prevention programs that serve to decrease the rate of injury as well as the extent of injuries [4, 5].

The understanding of the epidemiology of injuries is an important facet in the overall treatment of the pediatric trauma patient. It can be used to determine injury patterns as recognize potential injuries when children arrive in the trauma bay from the pre-hospital setting. Furthermore, the understanding of mechanisms can prompt injury and trauma prevention programs that can be used to decrease the frequency of traumatic events. Trauma is typically due to the application of a force to the human body with subsequent transfer of energy. As we will see in this manuscript, the understanding of how this force is applied can be important to not only injury prevention but also in determining what injuries would be expected from a specific mechanism. The recognition of motor vehicle collisions as a leading cause of morbidity and mortality has prompted the initiation of legislation that enforces the use of seatbelts for children [6]. The Center for Disease Control (CDC) notes that proper use of age and size-appropriate restraining devices reduces serious and fatal injuries in pediatric patients by nearly 80%. Similarly, children are at risk for non-accidental trauma [6]. The recognition of injury patterns and mechanisms of injury that are inconsistent with the age or developmental status of the patient should prompt a workup for child abuse. These efforts can prevent future injury and identify children who are at risk for future traumatic events.

Pediatric patients are managed in an algorithmic fashion similar to adult patients. The Advanced Trauma Life Support (ATLS) program teaches a systematic concise methodology to the approach of the trauma patient. All trauma patients, upon arrival to the hospital setting, should be managed according to the primary survey of Airway, Breathing, Circulation, Disability and Exposure/Environmental concern [7]. As we have noted, there are physiological differences in pediatric patients that providers must be aware of when caring for injured children. Recognition of difficult airways and understanding that hypoxia is a leading cause of cardiac arrest in children is vital in the initial management of the trauma patient [8]. Early blood transfusion using a balanced resuscitation of component therapy products has been introduced recently in the 10th edition of ATLS. These guidelines now call for only one 10 mL/kg bolus of crystalloid fluid before transitioning to packed red blood cells [8]. Assessing neurologic status may be made difficult by the child's developmental age. Glasgow Coma Scale assessment must be modified to address the child who may not be verbal due to age or underlying medical conditions [8]. Due to the proportionately greater surface area of skin seen in children, they are at greater risk for hypothermia when exposed to evaluate for all injuries during the secondary survey. Appropriate warming measures need to be instituted to ensure they maintain normothermia [8].

Trauma Organizations

Two of the best-known organizations who provide research efforts, guidelines, education and sharing of clinical experiences are the Eastern Association for the Society of Trauma (EAST) and the Western Trauma Association (WTA). These organizations have members who are both adult and pediatric trauma surgeons with a primary focus on improving outcomes of traumatically injured patients. They have robust websites located at: https://www.east.org and https://www.westerntrauma.org [9, 10]. Both sites have recommended practice management guidelines that focus on specific injury. These guidelines are rapidly accessible and can be quickly reviewed to determine appropriate management strategies. Both organizations have a wealth of knowledge for the individual caring for a traumatically injured patient. The Pediatric Trauma Society (PTS) is an organization for healthcare providers who care for traumatically injured children. Similar to EAST and WTA it also focuses on research, quality improvement, clinical practice guidelines and advocacy. These guidelines are available on their website and include rapid reference visual abstracts. The link to the guideline portion for the website is: https://pediatrictraumasociety.org/resources/guidelines/ [11].

The American Pediatric Surgical Association (APSA) also provides education and advocacy for trauma related issues. Advocacy issues that have been addressed or supported by APSA related to trauma include Gun Related Violence, Child Abuse and Drowning. Additionally, several committees focus either directly or indirectly on pediatric trauma initiatives [12]. APSA has a robust trauma committee and surgical critical care committee that directly influence the care of critically injured children. Likewise, the Education committee and Outcomes committee have, at times, focused on the management of pediatric trauma patients through systematic reviews and promulgation of current literature to the greater body of pediatric surgeons [13]. The American Academy of Pediatrics (AAP) is another national organization that provides advocacy for trauma related issues that affect pediatric patients and their families [14].

Improving outcomes for critically injured pediatric patients is a main focus of current research efforts. Similar to the National Surgical Quality Initiative Program (NSQIP), the American College of Surgeons Committee on Trauma (ACS COT) has also initiated a Trauma Quality Initiative Program (TQIP). Since 2016, the ACS

COT has offered a Pediatric TQIP that allows for data collection on traumatically injured children. Institutions who are either ACS verified Level 1 or Level 2 trauma centers or those who are "in-process" may join and participate. This quality program not only provides training in data collection and the use of data to improve trauma outcomes at a single institution, but it also allows for sharing of best practice guidelines and quality initiatives through regular conference calls and an annual meeting [15].

Research consortiums such as the ATOMAC+ group have enhanced the ability to provide treatment guidelines and recommendations by allowing for multi-center collaborative research networks. This consortium initially began with six institutions from Arkansas, Texas, Oklahoma, Memphis and Arkansas designated as the ATOMAC group. Since then, they have expanded with further institutions joining the research efforts causing a renaming to ATOMAC+. They have provided guidelines and research on a breadth of trauma topics including blunt cerebrovascular injury, solid organ injury, trauma resuscitation and transfusion [16]. Continued efforts through consortiums will only serve to improve the understanding of pediatric trauma mechanisms, allow for guidelines for both prevention and treatment and ultimately result in improved outcomes for critically injured children.

It would be remiss to complete this section without recognizing the significant impact that the military experience in recent conflicts has provided to the current management of pediatric trauma patients. The treatment of both military and civilian personnel, including children, and the collection of data through the Joint Theater Trauma Registry has provided yet another opportunity to critically assess management strategies. This has continued a trend started by surgeons who provided care during conflicts in Korea and Vietnam, returning to the United States with improved knowledge on the management of traumatically injured personnel. Multiple pediatric surgeons who actively care for pediatric trauma patients have spent time in a deployed setting caring for injured children in a theater of war or humanitarian setting. These experiences have only served to improve the care provided to children injured in a civilian setting. Additionally, research evaluating the use of whole blood therapy, balanced resuscitation, massive transfusion, use of tourniquets and tranexamic acid (TXA) for hemorrhage control amongst other items has been able to be translated to civilian practice [17]. The Joint Trauma System provides continuously updated clinical practice guidelines, available at https://jts.amedd.army.mil/index.cfm/pi_cpgs/cpgs with some focusing on austere surgical care that a pediatric surgeon on a humanitarian mission might encounter [18]. Continued partnership with military physicians will only serve to improve civilian care moving forward.

Training Opportunities

There are several courses offered to teach skills specifically related to the management of trauma patients. Perhaps the most well-known course is the Advanced Trauma Life Support (ATLS) Course that is offered through the American College of Surgeons. This course is dedicated to offering healthcare providers with a safe and effective methodology for the initial management of trauma patients. Over one million physicians in more than 80 countries have completed the course. It remains the scaffold upon which most trauma resuscitations are based [7]. Alongside ATLS, the Advanced Trauma Care for Nurses course is dedicated to providing registered nurses who care for trauma patients with a more in-depth understanding of the management of trauma patients. It runs concurrently with ATLS courses and shares the didactic portion [19]. Stop the Bleed is another course sponsored by the American College of Surgeons that provides education to the lay person on how to manage bleeding in a severely injured patient. These courses have even been offered to high school students with successful application of the skills to respond and provide life-saving care [20]. These efforts have been born from numerous mass casualty events where immediate care can be provided by a bystander while waiting for first responders to arrive upon the scene. Trauma Evaluation and Management (TEAM) is an introductory level course on the management of traumatically injured patients that is geared towards medical students. The content is derived from the ATLS course and can serve as a primer for medical students to increase their knowledge on trauma management [21].

Advanced courses for surgeons on surgical techniques and exposures are also offered. Advanced Trauma Operative Management (ATOM) is a course designed for senior residents, trauma fellows, military surgeons or general surgeons who may be called upon to manage trauma patients. It is designed to improve competence in the management of penetrating trauma to the chest and abdomen. The course is made up of lectures with a lab session with 1:1 supervision. The surgeon is taught how to identify and repair multiple injuries including repair to the bladder, diaphragm, spleen, liver, inferior vena cava and cardiac injuries [22]. Advanced Surgical Skills for Exposure in Trauma (ASSET) is another course that teaches operative exposure for traumatic injuries designed for senior residents, trauma fellows and general surgeons. This can be seen as a follow-on training to the ATOM course and provides training in surgical exposure to five anatomic areas: neck, chest, abdomen/pelvis, upper and lower extremities. This course uses cadaver training with hands on experience in operative exposure [23]. The Basic Endovascular Skills for Trauma (BEST) offers training in endovascular techniques such as the use of resuscitative endovascular balloon occlusion of the aorta (REBOA). These techniques have been used in adolescents in place of emergency thoracotomy to temporize life-threatening hemorrhage [24].

The Royal College of Physicians and Surgeons of Canada sponsors the Trauma Resuscitation in Kids (TRIK) course. This course is the only trauma course dedicated solely to the management of pediatric trauma. It is a 2-day simulation-based course focused on the roles of the team leader and team members [25]. For those healthcare providers who find themselves working in a remote or rural area that may be a critical access hospital, the Rural Trauma Team Development course is offered by the ACS emphasizes a team approach to the initial evaluation and resuscitation of the trauma patient at a rural facility. The course assists health care professionals working in a rural setting in determining the need to transfer the patient to a higher level of care. While many pediatric surgeons or trauma surgeons work in an urban center and will receive transfers from the rural site, knowledge of this course and the education provided can assist with smooth communication and transfer of patients to a higher echelon of care [26]. Continuing with training for trauma systems, the Disaster Management and Emergency Preparedness Course (DMEP) provides education on the planning, implementation and review of disaster plans for mass casualty scenarios. While it encourages attendance by healthcare providers who will be first responders in a mass casualty scenario, it also encourages attendance by healthcare administrators, public health professionals and emergency management experts who will be intimately involved in the planning and preparation phase for mass casualties and other disaster scenarios [27].

Conclusions

While it may be surgical lore that the birth of pediatric surgery started with Dr. Ladd traveling to Halifax, Nova Scotia the recognition by Dr. Ladd that these children required care by experts in the pediatric surgical field is a profound concept still applicable today. Understanding epidemiology, physiology and mechanisms of injury as well as injury patterns is paramount to not only providing outstanding care to the trauma patient but to also ensure appropriate preventive strategies are in place. Continued collaborative efforts amongst pediatric trauma centers through formalized programs such as the Pediatric Trauma Quality Initiative Program and regional centers such as ATOMAC+ will serve to enhance our understanding of trauma and provide guidelines that will continue to improve outcomes. Pediatric surgeons and healthcare professionals should remain aware of the multiple training opportunities available to enhance their knowledge of every aspect of trauma care.

Take Home Points

- Numerous courses are available to train the healthcare provider in the initial resuscitation, management and operative treatment of trauma patients.
- Trauma quality initiatives such as the Pediatric Trauma Quality Initiative Program as well as research consortiums such as ATOMAC+ serve to enhance our understanding of pediatric trauma, provide guidelines and improve outcomes.
- Numerous organizations exist to provide guidelines or advocacy for pediatric trauma patients. The practitioner caring for critically injured children should be aware of these organizations that provide clinical practice guidelines for the management of trauma patients.

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Chapter 2
Injury Prevention

Judith Egly and Robert Ricca

Abstract Thousands of children are seen in emergency rooms in the United States and throughout the world annually due to trauma. Trauma and associated injuries remain the most common cause of death in children in the United States. Injuries have been delineated by mechanism (motor vehicle accident, firearm related, drowning, burn) and by intent (self-inflected, unintentional, etc.). The term injury, rather than accident, is purposeful as accidents typically are unavoidable while research has shown that many of these fatalities and underlying injuries are preventable and can be mitigated by evidence-based guidelines and preventive measures. Use of safety belts and car seats have shown dramatic improvement in the survivability of motor vehicle collisions. Similarly helmet regulations protect the cranium and contents in the event of a bicycle, motorcycle, or all-terrain vehicle accident. Recent efforts have focused on firearm safety. These preventive efforts are part of a broader public health effort to ensure the safety of children and adolescents. This chapter will discuss injury prevention and provide examples of specific injury prevention strategies that are currently in place to decrease the risk of injury in children.

Keywords Injury prevention · Pediatric trauma · Seatbelts · Helmets · Education

Key Concepts/Clinical Pearls
- Traumatic injury is the most common cause of death for children across all age groups.
- Injury prevention is paramount to not only avoid the traumatic event but to also minimize the extent of injury thus saving lives, decrease time spent in the hospital and healthcare costs.

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- Preventive measures enter all facets of life including use of helmets, car seats and safety belts, childproofing of houses and electrical outlets, protective equipment for sporting events and gun safety to name a few. Proper education and legislation are important to reinforce injury prevention.
- Numerous organizations provide advocacy and guidelines for injury prevention. These include the Center for Disease Control and Prevention, the American Pediatric Surgical Association, Pediatric Trauma Society, Safe Kids Worldwide, The Injury Free Coalition and the Consumer Product Safety Council.

From 2010 through 2019, preventable injuries were the leading cause of death for children ages 1–19 according to the Centers for Disease Control and Prevention's (CDCP) National Center for Injury Prevention and Control (2008–2018) (Fig. 2.1). In 2019, more than 7000 children died in the United States due to unintentional injury, which equates to 20 children each day [1]. The topic of injury prevention is so important with regard to pediatric trauma that it is highlighted in the pediatric trauma chapter in the Advanced Trauma Life Support student manual [2]. It is suggested that up to 80% of pediatric trauma injuries could have been prevented with the institution of simple measures either in the home or in the community [2]. These measures are not only important for saving the lives of countless children but also prevent devastating effects on lives of the individual and families that are affected by trauma. Furthermore, injury prevention is also associated with a significant reduction in healthcare expenditure regarding pediatric trauma. It is estimated that for every dollar spent on injury prevention, four dollars are saved in hospital care [2]. This

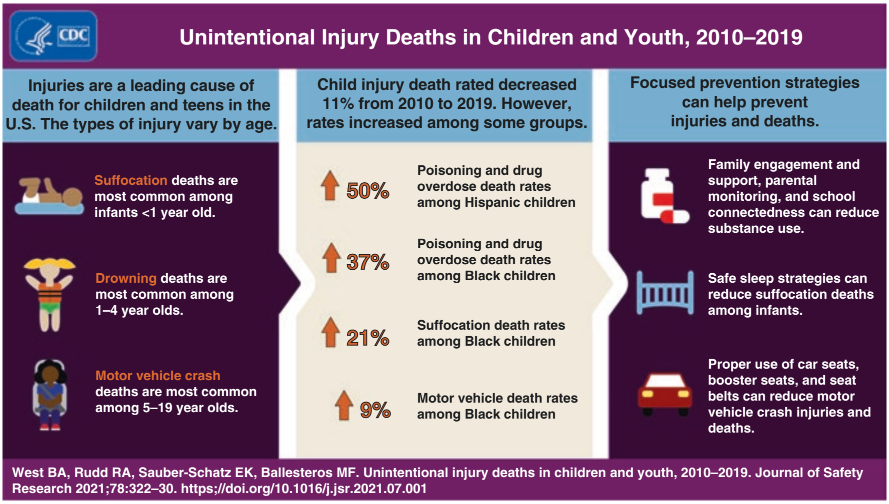

Fig. 2.1 Unintentional injury deaths in children and youth, 2010–2019. (Source: Injuries among Children and Teens. Centers for Disease Control and Prevention. https://www.cdc.gov/injury/features/child-injury/index.html, Accessed 26 Oct 2021)

becomes even more important when placed in the context that medical cost of injury of all patients, not just children, accounts for 12% of the national healthcare expenditure [3]. The consequences of preventable injuries to children can result in lifelong disabilities, physical impairments, and psychosocial/emotional impacts. The return on investment that is seen with injury prevention efforts in pediatric trauma is without question some of the most important efforts of pediatric trauma providers. It exemplifies the saying – an ounce of prevention is worth a pound of cure.

Multiple organizations nationally advocate for child safety and injury prevention such as the Consumer Product Safety Commission, Safe Kids Worldwide, American Academy of Pediatrics and of course, the CDCP [1, 4–6]. The American College of Surgeons Committee on Trauma requires injury prevention and outreach activities to be conducted by Trauma Centers nationally [3]. This is covered in an entire chapter in their text Resources for Optimal Care of the Injured Patient. A trauma center's injury prevention program activities should be reflective of their trauma data results on mechanism of injury and targeted to local communities affected. Focusing on those injuries that occur most frequently is important, but a focus on those injuries that cause the most impact on the child, the most disability, to help reduce or eliminate those injuries is crucial as well. Pediatric surgeons can be critical in helping to get the message of injury prevention out to the public [3]. The American College of Surgeons notes that an effective injury prevention program has the following key elements [3]:

- Target the Community (know the injuries in the community)
- Work Upstream (identify the root causes of injuries and precipitating factors)
- Choose preexisting proven or promising programs (work with what works)
- Partner with other organizations (look regionally or nationally)
- Embrace the media (use the media to spread the message)
- Be politically savvy (work with governmental agencies)
- Do not forget the data (surveillance and monitoring is paramount)

Data can be obtained from many places including medical examiner's offices, state vital records, local and state law enforcement offices, and other governmental agencies. Recognizing the proximate cause of the injury including risk factors such as access to firearms, high risk behavior, use of alcohol or other illicit drugs is important in any injury prevention program. Trauma centers can also partner with regional and national organizations for prevention efforts. Pediatric trauma has multiple organizations that show regional or national efforts to study trauma and identify opportunities for injury prevention practices [7–9]. Injury prevention education should be presented both in person with interactive programs including education and activities. Safety messaging should be presented through the media and using social media outlets. During the COVID outbreak, many injury prevention messages had to be adapted for virtual presentations and through social media to reach the public.

Building upon this framework, Pressley et al. identified the ABDCE's of injury prevention. In their manuscript they note that "mechanisms of injury are rooted in a complex web of social, economic, environmental, criminal, and behavioral factors that necessitate a multifaceted, systematic injury prevention approach" [10]. They describe a successful injury prevention program that began in a resource-limited neighborhood impacting an urban minority community. They utilized interventions that were aimed at changing both the community and home environments. Safe play areas were instituted as well as other home interventions. Utilizing a well-known mnemonic of trauma, the authors describe an Injury Coalition Free model of [10]

A—Analyze the data
B—Build a local coalition
C—Communicate the problem and raise awareness
D—Develop intervention and injury prevention activities
E—Evaluate the programs with ongoing surveillance

The results of this program are staggering. The initial programs focused on reducing several causes of injury for school-age children, such as motor vehicle pedestrian injury, assaults, firearms, and falls and was run out of Harlem Hospital in New York City. The interventions were a success with a decline, compared to pre-intervention rate, of 36% in traffic injuries, 45% in pedestrian injuries, 46% in violent injuries due to firearms and assaults. In 2001, Harlem had a 60% reduction in the overall injury rate in children. What is further remarkable is that the improvement in injury rates have been sustained with hospital admissions for children and adolescents under the age of 17 due to injury continuing to be 60% lower than pre-intervention rates [10]. These efforts have become national and have resulted in the Injury Free Coalition for Kids [9].

Adopting a plan for injury prevention education can make educational efforts easy. Focusing education based on seasonal activities that children and families engage in is very effective. In the spring, for example, children are getting outside again, so bike safety and helmet use are hot topics. Promoting correct helmet fit and use and a knowledge of bicycle traffic laws is important. Playground safety that includes supervision, safe equipment and surfaces is key. In 2019, a pedestrian was killed every 85 min resulting in over 6200 fatalities that year [11]. Pedestrian safety is important for school aged children who may not yet recognize the danger of crossing the road and the fact that a green light does not ensure that it is safe to cross the road. Pedestrian safety focuses on "looking left, right, and left again," crossing at cross walks not mid street or between cars [12]. A community may need to evaluate their public safety plan to include signage and flashing lights in areas such as schools and parks where children spend more time. These efforts emphasize the injury prevention practices mentioned earlier in the chapter that look not only at the home or family involvement but also at community safety. Data showing that many pedestrian accidents occur in a specific area can be obtained from law enforcement and utilized with local government to place crosswalks or streetlights that can mitigate traffic accidents.

As summer approaches, water, pool, and boating safety become necessary to promote while continuing pedestrian and bike safety topics. More children aged 1–4 die from drowning than from any other cause except congenital birth defects [13]. Every year there are on average 3960 deaths due to unintentional drowning. While it would make sense that the highest rates of death occur in states in the southern part of the United States; Alaska, Oregon, Montana, Idaho, and Wyoming were 5 of the top 12 states for drowning deaths between 2015 and 2019 [14]. Teaching children to swim is an essential parental responsibility. The American Red Cross and the YMCA are two community-based organizations that provide swimming classes [15, 16]. Utilizing lifejackets for all children on boats or near water is critical even for those that do not live near a water source. As families travel to vacation sites during the summer proper planning and education about the risks of summer activities are important to ensure safety. Fireworks and severe weather education such as lightening safety are also needed in the summer. According to the Consumer Product Safety Commission, there were 18 deaths due to fireworks in 2020. Furthermore, there was a 50% increase in deaths and injuries when compared to 2019 with 15,600 individuals treated in the emergency room due to firework related injuries. Children under 5 accounted for 11% of the total firework injuries [17].

In the winter, sledding, skiing, and ice-skating safety topics prevail along with winter travel safety. Messages such as “sledding feet first” and “ensuring safe runoff spaces for sledding” are essential. Proper clothing and safety equipment such as helmets are important to mitigate cold injury such as frostbite as well as traumatic injury. Home safety is important all year long with education on hot water temperatures, window safety guards, stair gates, crib and bed rails, safe storage of medications, cleaning solutions and other household items, and smoke and carbon monoxide detectors. Safe storage of firearms in the home is important for children of all ages. Gunshot wounds have an increasing prevalence in pediatric patients with nearly 1300 fatalities and 5790 nonfatal injuries annually [18]. Due to multiple factors including new purchases of firearms, financial strain, psychosocial stress and anxiety, the rate of firearm injuries increased during the recent COVID-19 pandemic [19]. Firearm violence is clearly an increasing public health issue nationally. In 2000, one in three homes with a child under 18 in the United States had a firearm [20]. The American Academy of Pediatrics states that the safest home for a child is one without guns. Mitigation strategies include ensuring proper storage of firearms at home safely with the firearm unloaded and stored separately from the ammunition. Lockboxes and gun safes can be acquired through commercial vendors [21].

Another topic essential all year long is car seat safety education. Since motor vehicle injuries are a leading cause of injury for children and teens, becoming familiar with some of the recommended car and booster seats for children and teen driving safety topics is key. Infants and toddlers should remain rear facing as long as possible, until the child outgrows their car seat’s maximum height and weight guidelines. Rear-facing is the safest. For older toddlers and preschool size children, use a forward-facing seat with 5-point harness for as long as possible, again up to the maximum size allowed by the seat. Booster seats for young school age children should be used to ensure proper position of the lap/shoulder belt systems until the child is 4 ft 9 in. tall, between age 8–12, and above 80 lb [22]. The rear seat is the safest for all children. Some general car seat safety is to never leave a child unattended in or around a vehicle, ensure the straps fit snugly and are correctly positioned, avoid wearing bulky winter coats under the car seat harness as it can affect the fit, and all children younger than age 13 are riding in the back seat. Involving a certified car seat technician to ensure child passenger safety by providing car seat education, checking car seat installation in a vehicle and fitting children in car seats

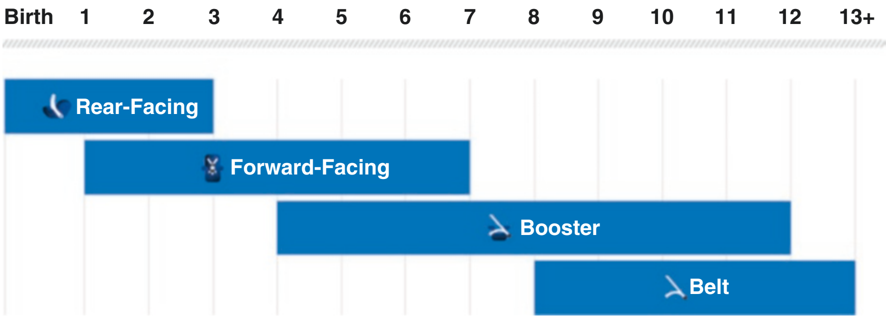

Fig. 2.2 Recommended car seats based on your child's age and size. (Source: Car Seats and Booster Seats. National Highway Traffic Safety Administration. https://www.nhtsa.gov/equipment/car-seats-and-booster-seats, Accessed 26 Oct 2021)

Table 2.1 The 5-Step test for children to ride in a vehicle using a seat belt without needing a car seat or booster seat. (Adapted from: Take the 5-Step Seat Belt Fit Test. Safe Ride 4kids. https://saferide4kids.com/blog/take-the-5-step-seat-belt-test/, Accessed 26 Oct 2021)

	The 5-Step test for children to ride without a car seat or booster seat
1	Shoulder belt crosses over top of shoulder, not against neck
2	Child can sit with lower back against the vehicle seat back
3	The lap belt crosses the upper thighs against the hip bones, not the abdomen
4	Child can bend knees at end of seat while back is against seat back
5	Child can comfortably ride this way for entire ride

is beneficial [22]. Many local police, State Police and fire companies help to meet this need (Fig. 2.2). It cannot be emphasized enough, children are not ready to use a car seat belt restraint alone until they achieve a weight of 80 lb, a height of 4 ft 9 in., and age 8–12-years-old [1]. Car restraints are designed to fit adults, not children. Before allowing children to ride in a car with only a seat belt, they should be able to pass the 5-step-test annotated in Table 2.1.

Ensuring teens are safe and capable drivers is an important task as they become more independent. In 2019, there were a reported 2042 individuals killed in motor vehicle collisions involving drivers between the ages of 15 and 18 years [23]. All 50 states and the District of Columbia have instituted graduated driver license systems that provide for periods of supervised driving prior to the ability to be a fully licensed driver. These systems can reduce a teen drivers' risk of being involved in a motor vehicle collision by 50% [23]. Information about specific state requirements for licensing of teenage drivers can be found at https://www.ghsa.org/state-laws/issues/teen%20and%20novice%20drivers. Distracted driving is an important topic to discuss with all drivers due to the competing interests of a cellphone or other electronic device and friends in the car. In 2017, 8% of teen (15–19) drivers who were involved in fatal crashes were distracted at the time of the crashes [24]. Seat belt usage is lowest amongst teen drivers. Forty-five percent of teen drivers who died from a motor vehicle collision in 2019 were not wearing a seat belt. Speeding is also a significant risk factor for motor vehicle collisions involving teen drivers.

Speeding was a factor in 27% of fatal crashes involving teen drivers in 2019 [23]. Empowering parents to serve as role models is an important part of injury prevention regarding teen driving. Ensuring parents model safe driving techniques including not speeding, wearing seatbelts, and avoiding other risky behavior or distracted driving can have a positive influence on teens [23].

Nationally, "falls" within the age range of 0–24 cause the highest number of injuries at nearly 29%, followed by "struck by or against' as the second leading mechanism of injury [25]. Every day, approximately 8000 children are seen in United States emergency rooms after having suffered a fall, affecting approximately 2.8 million children yearly [25]. In the pediatric population, instituting fall preventions programs is challenging because of the varied ways children fall. Developmentally we expect young children to fall while learning to walk and run, but it's all the other ways children fall that becomes the challenge. Children fall off bicycles and monkey bars, fall on and off trampolines, riding a scooter, and fall out of shopping carts and off horses. All fall prevention education should be geared toward the developmental level of the child. Looking at your local trauma center data and the surrounding communities should direct your injury prevention program activities. Community involvement is important to ensure proper playground equipment and age-appropriate equipment based upon the community needs. Having safe spaces that are well maintained can help to mitigate unintentional injuries.

As noted earlier in the chapter, when looking at injury prevention we often focus on the most common causes of injury in the community being served, but it is essential also to look at contributing factors as well. These precipitating factors are important to understand to ensure appropriate mitigation practices and injury prevention opportunities. Drugs, alcohol, behavioral and mental health issues, violence, poverty, and several other factors may be involved in poor childhood safety. An inability to afford cabinet or window locks can have a big impact on child safety during the toddler and preschool years. Acquiring grant funds to provide low cost or free resources to families is very beneficial. Several children's hospitals nationally host safety stores to provide low-cost items that underscore their safety and injury prevention efforts.

Conclusions and Take Home Points

Injury prevention is an important part of any pediatric trauma program. Recognizing the fact that most pediatric traumatic injuries can be prevented either with home or community safety measures allows one to focus on interventions that can reduce the morbidity and mortality of trauma. These efforts should not be done in a silo but instead should focus on collaboration with civic leaders, governmental agencies, community-based organizations, and neighborhood coalitions. Partnerships with regional and national organizations can also provide opportunities and additional resources to develop local programs. Utilizing an injury prevention framework such as the ABCDE framework mentioned earlier in the chapter can help to develop a needs assessment as well as appropriate interventions that will be successful in the community. Data acquisition, surveillance and monitoring are important steps to ensure the continued success of an injury prevention program.

- Knowledge of common injuries within a community as well as the root causes and precipitating factors are the cornerstones of any injury prevention program.
- Successful injury prevention programs utilize interventions that are aimed at changing both the community and home environments.
- Surveillance and monitoring of injury prevention programs are paramount to ensure ongoing success and continued improvement.
- Partnerships with regional and national organizations such as the Injury Free Coalition for Kids (https://www.injuryfree.org/index.cfm) can provide additional resources for any intervention program.

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Chapter 3
Trauma Systems and Pediatric Trauma Centers

Pamela M. Choi and Matthew D. Tadlock

Abstract Trauma is the most common cause of mortality in children. While adult trauma care has been well established, the pediatric population represents a distinct and broad spectrum of patients with unique anatomic, physiologic, and psychologic characteristics, particularly in response in to injury. Not every child has the ability to be near a pediatric trauma center; therefore a mature trauma system with strategically placed pediatric trauma centers that can support the injured child is crucial to the community and provides the best opportunity for treatment, survival, and recovery.

Keywords Trauma system · Pediatric trauma center · Prehospital care · Verification · American College of Surgeons

History of the Trauma System

The evolution of the modern trauma system began in the 1960s with the development of state trauma systems along with funding for emergency medical service systems and trauma prevention in the National Highway Safety Act of 1966 and the Emergency Medical Services Systems Act of 1973 [1]. Coordinated trauma care became possible as communication and transportation systems between prehospital care and hospitals became more refined. The American College of Surgeons (ACS) formed the Committee of Trauma and in 1976 and subsequently published the first edition of *Optimal Hospital Resources for Care of the Seriously Injured*, which has undergone several updates and provides the criteria needed for trauma systems and

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trauma centers. The ACS also developed the Advanced Trauma Life Support (ATLS) course in 1979 to standardize trauma care [2].

Because 25% of all traumatic injuries are in children, the need for pediatric-specific trauma care was identified, followed by the development of pediatric trauma centers/systems that evolved from the models set by adult trauma care [2]. Pediatric trauma centers were first established in the 1970s, and a section on pediatric trauma was added to the ATLS course in 1983. The Emergency Medical Services for Children program was established in 1984 by the Department of Health and Human Services and the National Highway Traffic Safety Administration (NHTSA). In addition to state designation as a pediatric trauma center, the ACS also offers an additional separate verification process for pediatric programs.

Overview of the Trauma System

Trauma remains the most common cause of mortality in children; therefore, the impact of a pediatric trauma system is significant [3, 4]. Furthermore, approximately 17.4 million children live outside a 60-min range of a pediatric trauma center [5, 6], and an estimated 28% of children live in counties with no trauma center [7]. Thus, it is incumbent upon the trauma system as a whole to effectively triage, transport, and treat the injured pediatric patient within their geographic region.

The trauma center is not an isolated entity but rather the core of the trauma system. Any pediatric trauma center must fill this role and have the necessary resources to care for injured children. The trauma center is the leader in developing the infrastructure required of a successful trauma program and is responsible for coordinating of resources throughout the entire care continuum, including prehospital care and rehabilitation (Fig. 3.1) [8]. This includes active participation in prehospital trauma training, developing and linking field triage criteria to trauma team activation procedures, providing medical oversight, and developing treatment protocols [2]. The trauma center must also be engaged in quality assurance/process improvement endeavors, research, advocacy, outreach, and injury prevention programs [2, 8].

To be a pediatric trauma center, state designation is first required and is determined by state or regional criteria. Pediatric trauma center verification is an evaluation process conducted by the American College of Surgeons (ACS). Not all designated trauma centers are ACS verified. Criteria for designation may vary from state to state or region to region, while the criteria for ACS verification are standardized.

The importance of pediatric trauma centers has been demonstrated throughout the literature. Quite simply, injured children have better outcomes when treated at a pediatric trauma center. This includes decreased overall mortality and improved functional outcomes [7, 10–16]. These superior outcomes in pediatric trauma centers have persisted across different mechanisms, ages, and quality metrics.

Byrne et al. utilized the NHTSA Fatality Analysis Reporting System and found that counties with pediatric trauma centers had decreased motor vehicle crash (MVC) mortality in children <15 years old [7]. Similarly, a National Trauma Data

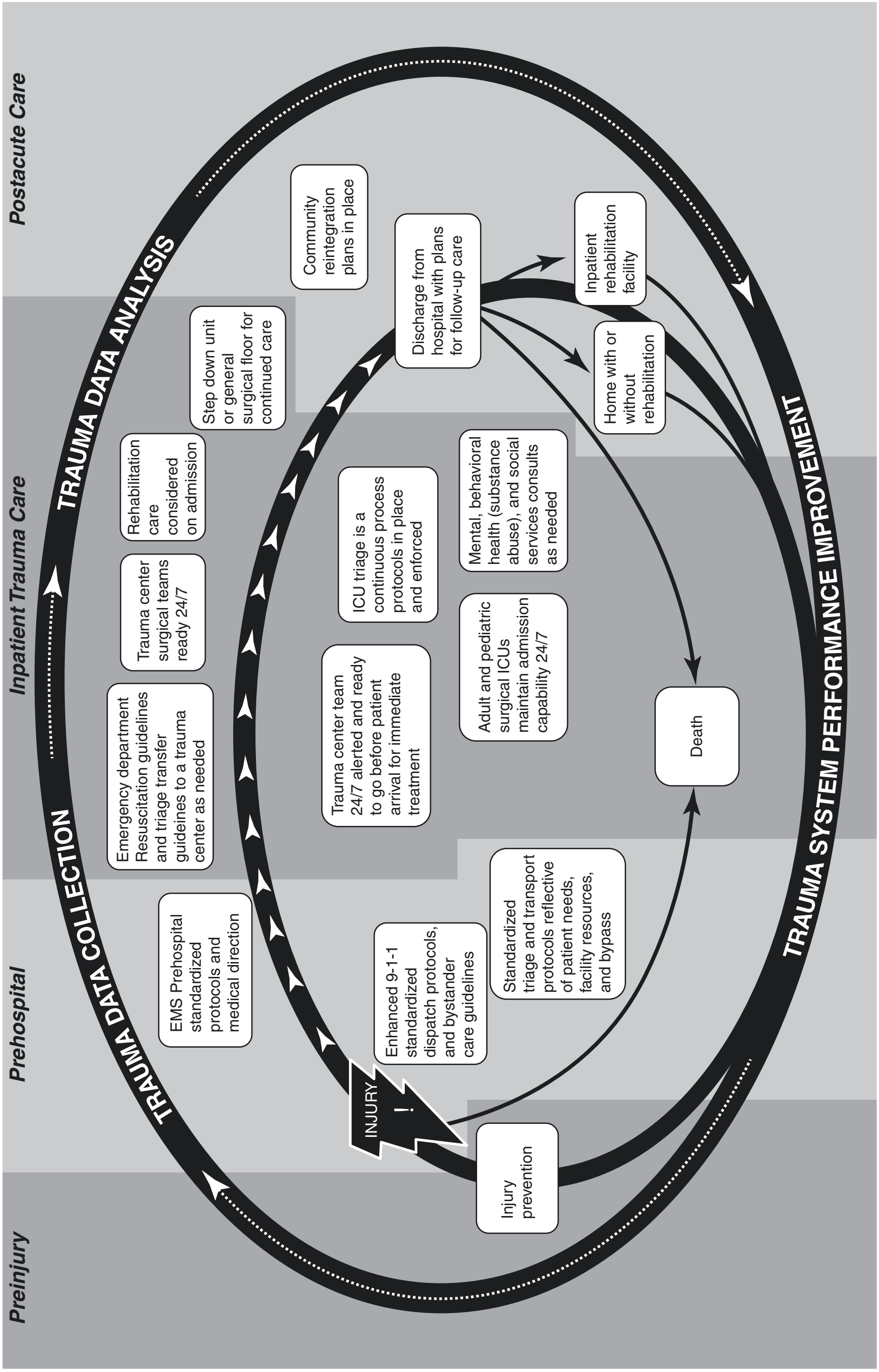

Fig. 3.1 Complex and integrated trauma care curriculum [9]

Bank (NTDB) study also found that children <15 years injured by MVC and treated at an adult trauma center had an increased incidence of pneumonia [17]. The same study also found that pediatric patients (0–17 years) had an increased odds of a laparotomy when treated at an adult trauma center [17].

It had been theorized that adolescents, being much closer to adult size and physiology, would have equivalent outcomes at adult trauma centers. However, this is not true. Instead, adolescents treated at adult trauma centers had increased mortality when compared to pediatric trauma centers [16, 17]. Severely injured adolescents (15–19 years, Injury Severity Score (ISS) >25) also had increased length of stay, lower home discharge rates, increased imaging, and increased invasive procedures at adult trauma centers compared to those treated at pediatric trauma centers [18]. Furthermore, when cared for at pediatric trauma centers, adolescents (15–18 years) with penetrating injuries also had decreased operative interventions and decreased mortality [19].

Nonoperative management of blunt solid organ injuries has become the standard of care in pediatric trauma; therefore, rates of operative intervention have become a quality metric. Adult trauma centers have higher rates of operative intervention in children than pediatric trauma centers [20–23]. Several NTDB studies have found that adult trauma centers had an increased likelihood of splenectomy for blunt splenic injury in pediatric patients [23, 24]. Rates of angioembolization for blunt splenic injury were also higher at adult trauma centers without any improvement of outcomes [21, 25].

Computed tomography (CT) can be an essential diagnostic tool in evaluating the injured patient; however, minimizing radiation exposure in pediatric patients whenever possible is also important. In one study, not only were patients with pelvic fractures treated at pediatric trauma centers found to have a decreased complication rate, but CT scan utilization was also reduced [26]. In general pediatric trauma centers have lower rates of CT scan utilization [26–28], and when CT scans are conducted, children are exposed to lower doses of radiation [29, 30].

Prehospital Trauma Care

The importance of the entire trauma system cannot be understated. Often, this begins with prehospital trauma care that is organized, timely and standardized. It is not economically nor practically feasible to have a Level-I pediatric trauma center within 60 min of every child in the country. Therefore, a structured system must be developed to guide prehospital personnel to transport “the right child to the right hospital at the right time”—a mantra for all emergency medical services.

Prehospital care encompasses dispatch systems, communications with hospitals, as well as medical care and transportation from the scene to the hospital [8]. The Emergency Medical Services for Children (EMS-C) program was created in 1984 to optimize prehospital care for ill/injured children. Pediatric trauma centers often develop prehospital care education, protocols, and guidelines for pediatric trauma triage [31–33]. A joint policy statement from the American Academy of Pediatrics, American College of Emergency Physicians, Emergency Nurses Association, National Association of Emergency Medical Services Physicians, and National Association of Emergency Medical Technicians has also outlined multiple recommendations for pediatric readiness for emergency medical services systems (Table 3.1) [34].

Table 3.1 Pediatric readiness in emergency medical services systems [34]

Include pediatric considerations in EMS planning and the development of pediatric EMS dispatch protocols, operations, and physician oversight (for example, as outlined in the National Association of Emergency Medical Services Physicians position statement "Physician Oversight of Pediatric Care in Emergency Medical Services")
Collaborate with medical professionals with significant experience or expertise in pediatric emergency care, public health experts, and family advocates for the development and improvement of EMS operations, treatment guidelines, and performance-improvement initiatives
Integrate evidence-based, pediatric-specific elements into the direct and indirect medical oversight that constitute the global EMS oversight structure
Have pediatric-specific equipment and supplies available, using national consensus recommendations as a guide, and verify that EMS providers are competent in using them
Develop processes for delivering comprehensive, ongoing, pediatric-specific education and evaluating pediatric-specific psychomotor and cognitive competencies of EMS providers
Promote education and awareness among EMS providers about the unique physical characteristics, physiologic responses, and psychosocial needs of children with an illness or injury
Implement practices to reduce pediatric medication errors
Include pediatric-specific measures in periodic performance-improvement practices that address morbidity and mortality
Submit data to a statewide database that is compliant with the most recent version of the National Emergency Medical Services Information System and work with hospitals to which it transports patients to track pediatric patient-centered outcomes across the continuum of care
Develop, maintain, and locally enforce policies for the safe transport of children in emergency vehicles
Develop protocols for the destination of pediatric patients, with consideration of regional resources and weighing of the risks and benefits of keeping children in their own communities
Collaborate, along with receiving emergency departments, to provide pediatric readiness across the care continuum
Include provisions for caring for children and families in emergency preparedness planning and exercises, including the care and tracking of unaccompanied children and timely family reunification in the event of disasters
Promote overall patient- and family-centered care, which includes using lay terms to communicate with patients and families, having methods for accessing language services to communicate with non–English-speaking patients and family members, narrating actions, and alerting patients and caregivers before interventions are performed. In addition, allow family members to remain close to their children during resuscitation activities and to practice cultural or religious customs as long as they do not interfere with patient care
Have policies and procedures in place to allow a family member or guardian to accompany a pediatric patient during transport when appropriate and feasible
Consider using resources compiled by the Emergency Medical Services for Children program when implementing the recommendations noted here

Table 3.2 ACS guidelines for highest level trauma activation [2, 43]

1. Age-specific hypotension
2. Respiratory compromise or need of an emergency airway
3. Intubated patient transferred from the scene
4. Transfer from another hospital receiving blood
5. Gunshot wound to chest, abdomen, or neck
6. Glasgow Coma Scale (GCS) score of 8 or less

While prehospital care of the pediatric patient has become more refined over time, education and training to maintain pediatric readiness are constant challenges. A recent survey showed that prehospital transport providers had decreased comfort levels with the management of pediatric trauma patients, including interpreting physiology, medication administration, and airway management [35]. Thus, the trauma system must continue to support prehospital providers and infrastructure in order to provide the best care possible for the injured pediatric patient.

Field triage of pediatric patients is also critical for transporting patients to the appropriate hospital with the appropriate resources, thereby minimizing overtriage and undertriage. The goal for appropriate triage is to utilize scarce resources in a safe and cost-effective manner [36]. The ACS has developed field trauma triage guidelines, meant to identify patients who are at greatest risk for severe injury as well as to determine the most appropriate facility to transport patients [37]. These guidelines state that children <15 years who meet physiologic, anatomic, or mechanism criteria should be transported to a pediatric trauma center. A prospective cohort study found that these guidelines had 87.4% sensitivity of identifying severely injured children aged ≤14 years. While this age group had the highest sensitivity, it still fell short of the national benchmark of 95% [38, 39].

Accurate trauma activations are a crucial component of triage as well. Most trauma centers utilize a tiered trauma activation system. Major activations are reserved for severely injured patients and allow for the early mobilization of resources and medical teams across different departments and specialties.

Major trauma activations are more likely to require operative intervention [40–42]. The ACS recommends six criteria for the highest level of trauma activation (Table 3.2) [43]. A prospective study by Falcone et al. found that the ACS-6 had an overtriage rate of 24% and undertriage rate of 16% [36]. The ACS has recommended an acceptable overtriage rate of 25–35% and an undertriage rate of 5% [43]. As such, many trauma centers further expand on the ACS-6 and develop their own protocols and procedures with regards to trauma activation.

Interhospital Transfer

Specialty care for children is a limited resource. It is common for injured children to be taken to a local hospital or adult trauma center for initial management/stabilization prior to transfer to a pediatric trauma center for direct care. The trauma system must develop written guidelines which (1) define which patients/injuries should be transferred, (2) identify methods for physician-to-physician communication between facilities and discussion of patient injuries, treatments, and transportation mode, (3) state when to consider ground vs. air transportation and what type of personnel is recommended, and (4) identify documentation requirements (Table 3.3). The InterFacility Tool Kit for the Pediatric Patient is an excellent resource that provides examples of transfer agreements and guidelines [44].

Defining each institution's resources and capabilities is critical towards determining where patients should be transferred to. Emergency Medical Treatment and Labor Act (EMTALA) laws state that institutions with capabilities greater than the hospital transferring the patient are required to accept the patient [43]. However, direct physician-to-physician contact is essential to provide an assessment of the patient's condition.

Table 3.3 ACS guidelines for transferring patients [2]. *PIPS* Performance Improvement and Patient Safety

Transferring Physician Responsibilities	• Identify patients needing transfer • Initiate the transfer process by direct contact with the receiving trauma surgeon • Initiate resuscitation measures within the capabilities of the facility • Determine the appropriate mode of transportation in consultation with the receiving surgeon • Transfer all records, test results, and radiologic evaluations to the receiving facility • Perform a PIPS review of all transfers
Receiving Physician Responsibilities	• Ensure that the resources required to care for the patient are available at the receiving facility • Provide consultation to the referring physician regarding specifics of the transfer, additional evaluation, or resuscitation before transport • Once transfer of the patient is established, clarify who will provide medical control of the patient during transport • Identify a PIPS process for transportation, allowing feedback from the receiving trauma surgeon to the transport team directly, or at least to the medical director for the transport team and the referring hospital • Provide feedback to the transferring facility regarding the patient's condition, plan of care, and any PIPS issues identified
Management during transport	• Ensure that qualified personnel and equipment are available during transport to meet anticipated contingencies • Make sure that sufficient supplies—such as intravenous fluids, blood, and medications, as appropriate—accompany the patient during transport • Monitor vital signs frequently • Support vital functions (for example, provide ventilation and spinal protection, and support hemodynamics and the central nervous system) • Keep records during transport, and provide them to the receiving facility during patient handoff. Maintain communication with on-line medical direction during transport
Trauma system responsibilities	• Ensure prompt transport once a transfer decision is made • Review all transfers for PIPS • Ensure that transportation resources are commensurate with the patient's severity of injury

Qualifications of a Pediatric Trauma Center

As states have different requirements for pediatric trauma center designation, this section will focus on the requirements set by the ACS for pediatric trauma center verification. To become a pediatric trauma center, a hospital must first fulfill the same requirements as adult trauma centers. This includes training prehospital personnel in pediatric trauma care, developing prehospital protocols specific to the pediatric trauma population, guidelines for interhospital transfer of pediatric trauma patients, as well as the establishment of a dedicated pediatric trauma program.

The hospital must also have the required components necessary for complex pediatric care throughout multiple different departments. A Pediatric Trauma Center requires the full support of the hospital's administration and medical staff to provide the appropriate resources and commitment to the care of trauma patients.

The Trauma Medical Director (TMD) must be a pediatric surgeon who leads the multidisciplinary activities of the trauma program and manages all aspects of trauma care. The TMD is responsible for ensuring compliance and quality assurance of the trauma program. This includes chairing a multidisciplinary trauma peer review, authorizing privileges, coordinating with nursing administration, developing protocols/guidelines, and managing the budgetary process for the trauma program. The TMD is expected to also be a member and active participant in regional or national trauma organizations.

The Trauma Program Manager (TPM) is a full-time and dedicated position that complements the TMD. The TPM is responsible for the organization of services and systems necessary for a multidisciplinary approach to providing care to injured patients. This also includes process and performance improvement activities in regards to nursing and ancillary staff. The TPM is also expected to have a clinical experience in trauma care and participate in regional/national trauma organizations.

The Trauma Resuscitation Team is the team responsible for the care of the patient upon arrival to the trauma center. The size and composition of the team may vary based on injury severity and corresponding trauma activation, as well as hospital resources. The Trauma Service represents the team who provide care to the patient once they are admitted to the surgical service.

The trauma registrars, performance improvement support personnel, and multidisciplinary trauma peer review team (otherwise known as PIPS-Performance Improvement and Patient Safety Program) are responsible for data entry, research, and quality improvement measures.

The additional specific criteria for a Pediatric Trauma Center are listed in Table 3.4. The distinction between a level I and level II trauma center is generally based on resources and volume. Level I pediatric trauma centers are regional resource centers and are generally in population-dense areas. They are considered the highest levels of care. A level I pediatric trauma center must admit >200 injured children younger than 15 years and have at least two pediatric surgeons covering trauma. Additionally, research is considered an essential component. A level II pediatric trauma center must admit >100 injured children younger than 15 years and have at least one pediatric surgeon covering trauma [2].

Although not specifically pediatric trauma centers, there are also level III and level IV trauma centers within the trauma system. Level III centers are required to

Table 3.4 Additional requirements for ACS-verification of pediatric trauma centers (*PTC* Pediatric Trauma Center, *E* Essential, *D* Desired) [2]

Freestanding children's hospital or comprehensive pediatric care unit within general hospital organization	PTC Level 1	PTC Level 2
Pediatric trauma service	**E**	**E**
Pediatric surgeon as pediatric medical director	**E**	**D**
Pediatric surgeon	**E (at least 2)**	**E (at least 1)**
Pediatric emergency medicine physicians	**E**	**E**
Pediatric critical care medicine physicians	**E**	**E**
Other surgical specialists with pediatric specialty experience	**E**	**E**
Pediatric-specific trauma continuing medical education for pediatric medical director and liaisons	**E**	**E**
Pediatric emergency department area	**E**	**E**
Pediatric intensive care unit	**E**	**E**
Pediatric acute care unit	**E**	**E**
Pediatric rehabilitation	**E**	**E**
Pediatric resuscitation equipment in all appropriate patient care areas	**E**	**E**
Pediatric trauma program manager	**E**	**E**
Pediatric trauma registrar	**E**	**E**
Child life and family support programs	**E**	**E**
Pediatric social work child protective services	**E**	**E**
Child maltreatment assessment capability	**E**	**E**
Injury prevention and community outreach programs (pediatric trauma education programs)	**E**	**E**
Pediatric trauma research	**E**	**D**
Minimum number of annual trauma admissions of children younger than 15 years	**200**	**100**
Pediatric trauma performance improvement program	**E**	**E**

provide continuous general surgical coverage and provide the prompt assessment, resuscitation, emergency operations if required, stabilization and arrange for transfer for all patients (including pediatric) who require definitive trauma care. Level IV centers are required to have 24-h coverage by either a physician or a mid-level provider and provide the initial assessment and evaluation, resuscitation and transfer of injured patients based on a defined transfer plan. With adequate field notification, the on call general surgeon must be present in the emergency department upon patient arrival in 80% of all trauma activations in both level III and IV trauma centers [2].

Value of Pediatric Trauma Center Verification

As mentioned earlier, a pediatric trauma center requires state designation, which is based on regional/state criteria. However, ACS-Verification requires additional investment and resources and is considered a voluntary endeavor. The number of ACS-Verified trauma centers in each state is listed in Table 3.5. As of July 2021,

Table 3.5 American College of Surgeons verified pediatric trauma centers

	Level 1	Level 2
Alabama		
Alaska		2
Arizona	1	2
Arkansas	1	
California	6	5
Colorado	1	1
Connecticut	2	
Delaware	1	
District of Columbia	1	
Florida	3	1
Georgia	1	1
Hawaii		
Idaho		
Illinois		
Indiana	1	3
Iowa	1	2
Kansas		1
Kentucky	2	
Louisiana		
Maine		
Maryland	4	2
Michigan	3	4
Minnesota	4	1
Mississippi		
Missouri	1	
Montana		
Nebraska		1
Nevada		1
New Hampshire		1
New Jersey		3
New Mexico		
New York	6	6
North Carolina	3	1
North Dakota		1
Ohio	4	4
Oklahoma	1	
Oregon	2	
Pennsylvania		
Rhode Island	1	
South Carolina	1	2
South Dakota		1
Tennessee	2	
Texas	5	4

Table 3.5 (continued)

	Level 1	Level 2
Utah	1	
Vermont		1
Virginia	1	
Washington		
West Virginia		1
Wisconsin	2	1
Wyoming		

there are 62 ACS-Verified level I trauma centers and 53 level II centers; 11 states do not have any ACS verified pediatric trauma centers. However, studies have suggested that there is an additional benefit to patients who are treated at ACS-Verified pediatric trauma centers. Notrica et al. found a 37% lower injury-related mortality rate in states with ACS-verified level-I pediatric trauma centers compared to states without ACS-verified pediatric trauma centers [45]. Similarly, an analysis of the National Pediatric Trauma Registry found that verified trauma centers had improved survival compared to non-verified centers [46].

There have been other documented benefits of ACS verification asides from improved survival as well. A study of the NTDB found that pediatric patients had decreased rates of complications in ACS-verified centers [47]. Similarly, Choi et al. demonstrated decreases in hospital-acquired complications as well as a decrease in hospital readmission rates after their pediatric trauma center achieved ACS-verification [48]. ACS verification has also been associated with a decrease in PICU utilization and CT scan utilization as well as higher rates of limb salvage in pediatric patients with extremity vascular injuries [48–50]. Children with blunt splenic injury also experienced decreases in operative intervention and cost savings in ACS verified pediatric trauma centers [51, 52]. Children treated at an ACS-verified center for moderate/severe Traumatic Brain Injuries (TBI) had decreased time to initial head CT and decreased frequency of head CT [53]. Finally, an NTDB study found that detection of non-accidental trauma was increased in ACS-verified pediatric trauma centers [54].

Conclusion

The crux of effective pediatric trauma care is a trauma system that is equipped and capable of caring for injured children. Injured children have improved outcomes when cared for at a pediatric trauma center. However, a pediatric trauma center will not be effective unless a patient can be safely delivered to the right hospital, nor will it be effective without the necessary resources to care for an injured child. Enhancing trauma care is a continuous process and requires further research about utilizing resources for this unique population.

Take Home Points

- Traumatic injury is the most common cause of mortality in children, highlighting the need for organized and effective triage, transport and treatment of injured pediatric patients.
- The pediatric trauma center is *not* an isolated entity but an integral component of the overall trauma system that not only provides definitive pediatric trauma care but also provides a leadership role within their respective regional communities. This includes leading process improvement efforts, providing pediatric trauma education, and coordinating regional resources throughout entire continuum of care to include pre-hospital trauma care.
- Each state or region have specific criteria utilized to designate a hospital as a pediatric trauma center. This designation is required prior to American College of Surgeons (ACS) trauma center verification; a voluntary and separate process from designation.
- ACS-verified pediatric trauma centers have demonstrated decreased injury related mortality and improvements in quality related metrics compared to non-ACS-verified centers. Pediatric trauma center ACS verification has been associated with improvements in hospital related complications, re-admission rates, cost savings and decreased operative intervention for blunt spleen injuries.

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Chapter 4
Rural Trauma

Alfred P. Kennedy Jr

Abstract Regardless of the setting, despite dollars spent, injury remains the most common source of mortality amongst our children in the United States. Much of the United States remains rural, with the majority of Pediatric Trauma Centers clustered within metropolitan areas. This leaves critical access hospitals with the burden of initial resuscitation of injured children. Children suffering injury within the rural setting are unique with regards to injury mechanism, injury severity, and mortality. Falls are the most common mechanism of injury. Distinct mechanisms pertain to agricultural lifestyles and the pitfalls therein. Disparities also exist in regards to resources, education, and injury prevention. Although there are different definitions of rural trauma, a trauma system, and the population it serves may be deemed such when care is *delayed* by geography, weather, distance, or resources (American College of Surgeons, Rural trauma team development course. 4th ed. http://www.facs.org/quality%20programs/trauma/education/rttdc, 2015). Addressing these issues requires a combined effort between rural facilities and partnered trauma centers, such as those employed by the Rural Trauma Team Development Course (American College of Surgeons). Other modalities such as simulation, web-based education, and telemedicine can also assist.

Keywords Trauma · Injury · Pediatric trauma · Rural trauma

Key Concepts/Clinical Pearls
- Rural areas comprise a large portion of the underserved patient population in the United States.
- Trauma that occurs in rural regions represents a unique population with barriers to timely healthcare.

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- In addition to mortality, outcomes of children suffering trauma within the rural environment are beset with disparities in relation to resources, education, costs, access, and preventive strategies.
- Patients sustaining similar injuries in a rural setting are more likely to suffer mortality.
- As in any venue, rapid assessment and treatment of life-threatening injuries while arranging for appropriate transfer to a higher level of care is paramount for survival.

Illustrative Case (Initial Management)
A 4-year-old male is the unhelmeted, unbelted passenger in a multiple rollover ATV accident in a densely forested region. After several attempts, cell phone service to call 911 is established. Local EMS arrives 45 min later to find the child partially conscious with a bleeding scalp laceration and obvious leg deformity. The closest trauma center is one hour by ground. The closest pediatric trauma facility is an hour by air. After a lengthy ride on gravel roads, EMS is met by medevac (helicopter) and transported directly to the Pediatric Trauma Center, passing over a local trauma center and critical access facilities. Upon arrival, the level of alert is immediately upgraded as the extent of injuries coupled with hemodynamic instability becomes evident. There is evidence of acidosis and coagulopathy on the initial lab query. After an initial crystalloid bolus, whole blood with a warmer is initiated for ongoing hypotension and hypothermia. Focused Assessment with Sonography in Trauma (FAST) exam is positive. After further resuscitation, a CT exam reveals a Grade IV liver laceration accompanying his femur fracture. Massive Transfusion Protocol (MTP) is initiated. The child is transported to the operating suite hybrid room for laparotomy, liver packing with damage control as well as embolization of a branch of the right hepatic artery. Pediatric anesthesia transports the ventilated child to the PICU with a negative pressure VAC dressing within the open abdomen. An air splint is applied to the lower extremity fracture with plans to return to the OR after further balanced resuscitation and warming.

Regardless of the setting, initial management of the injured child should follow Advanced Trauma Life Support (ATLS) guidelines focusing on the ABCDE of the primary survey. As is discussed in this scenario, differences within the rural trauma setting relate to time to initial care and potential lack of resources. Care must also be focused on the role of hypothermia as it relates to resuscitative efforts. Hypothermia is commonplace, recalcitrant to therapeutic measures available in the rural setting and independent of the time of year in which the event occurs.

Definition

The definition and scope of rural trauma is multifactorial. In its simplest form, it can be defined in reference to its occurrence within rural areas of the United States. However, with its associated disparities in resources, education, trauma centers, prevention, and even mortality, the definition of rural trauma is more insidious. Most of the United States is rural. When optimal care of the injured is delayed or limited by geography, weather, distance, or resources, the scope of the problem becomes more definable. Trauma Systems are deemed "rural" when such care falls into their purview [1]. A report in JAMA in 2005 listed 46.7 million Americans within an hour of a designated trauma center lived mostly within rural areas [2]. A near equal number of Americans live within an urban zip code had access to a trauma center. Since then, closures of trauma centers have accelerated at a disproportionate rate within rural United States [3].

Disparities

There exist disparities in resources and services within the rural environment. Pre-hospital care of the injured within the rural environment is challenging at best. Injuries may occur in places that are difficult to access and difficult to respond. Often, these injuries may go unwitnessed. Response times may be dampened by weather, terrain, and communication. Cellular communication has improved this. Mobilization of rescue personnel may also be hindered by the same situations surrounding the incident. Adding to this disparity may be the lack of pre-hospital training and recognition of injuries specific to children. Many of these responders may have little in the way of training, experience, or equipment necessary for proper initial recognition and treatment of the pediatric trauma patient. Many EMS services in rural America are voluntary, and maintaining skills where trauma has a lower incidence is challenging, particularly in the setting of an injured child. Some answers to these challenges have been addressed in the form of simulation [4, 5] and the American College of Surgeons Rural Trauma Team Development Course (RTTDC) [1].

Pediatric trauma patients are usually taken to the nearest emergency center. Many of these are critical access hospitals, ill-equipped to provide care specific to children, with a potential for traumatic injuries to go undertreated or unrecognized. Pediatric trauma is a low volume event in the arena of a non-pediatric specific rural facility. Additionally, health care providers in the rural environment may have little in the way of experience or the clinical acumen necessary. Access to bonafide pediatric centers, equipped and capable of care of the injured child, represents another disparity within the realm of rural trauma.

Allocation of pediatric trauma centers is random. Timely access to these centers remains inadequate in the United States. Despite the Institute of Medicine espousing coordination and regionalization of pediatric emergency services, an estimated 17 million children do not have access to a pediatric trauma center within the golden hour. Access to appropriate facilities is significantly reduced in rural, underserved America by a factor of 4 [6]. Allocation of designated trauma centers within rural regions could increase this access [7].

Disparities may include the cost of medical care. Traumatic brain injury is the leading cause of death and disability among children and adolescents in the United States regardless of setting [8]. Families of children who suffer traumatic brain injury may incur significant health care costs [9]. Health care utilization, access and insurance coverage may be challenging to the rural population. Total health care costs after head injury may be higher for rural children despite lower utilization of services. Differences in health service access and utilization may exacerbate geographic disparities and outcomes within this population [10].

Preventive strategies in this regard remain elusive, too. Helmet laws across state legislatures are inconsistent. All-terrain vehicles (ATVs) are a source of recreation and integral to agricultural work. Despite local laws, the use of ATVs by children along with the lack of helmets, seatbelts, roll bars and other protective gear is commonplace in rural America. Cultural norms supplant legislature and "common sense" preventive strategies. Similarly, farm equipment with its attendant injuries persists with significant incidence despite increased safety guards placed by manufacturers. Many of these guards are removed for ease of reparations and costly replacement (Fig. 4.1). Additional education and prevention disparities (opportunities) involve fire, firearms, and water park safety, including boating, jet, and water skis. Most of

Fig. 4.1 Power Take Off (PTO) with and without guard. PTOs operate at 540 RPMs. Guards are removed for ease of maintenance

these mechanisms of injury occur to no surprise in remote locations. Finally, there seems to be a tacit acceptance of injuries associated with the rural lifestyle (personal communication, Kenneth Sartorelli, MD) mitigating any preventive strategies put in place by legislature, industry, or healthcare. This is most especially pronounced amongst the Anabaptist with their dependence on agrarian commerce.

There is a significant difference in mortality with regards to setting. Unfortunately, little advancement has been made on the mortality associated with pediatric trauma, urban or rural. The probability of sustaining death is inversely proportional to population density. Patients injured within the rural setting are more likely to succumb within 24 h at an out of hospital site or outside a designated trauma facility [11]. Rural residents are 14% more likely to die following trauma compared to their urban counterparts. This disparity is especially prominent in Level I, II and IV centers [12]. Motor vehicle crashes, a leading cause of death among children, are more likely to be fatal in rural counties. Additionally, among these rural children, non-Hispanic black infants and American Indian/Alaska Native children are particularly at risk [13]. This disparity is likely related to distance and time to treatment, along with regional differences in prehospital care and trauma system organization [12].

Unique Injuries

Mechanisms

The National Transportation Data Base (NTDB) lists falls, motor vehicle crashes, transport (ATV, etc.), and struck by vehicle as the most common mechanisms of injury in rural America in decreasing incidence. Similar mechanisms apply to urban, suburban and wilderness venues [14].

Firearm Injuries

Guns are a cultural way of life in rural America. Controversy exists concerning access to firearms, sales of firearms as well as proposed legislature reform in the face of strong support for the Second Amendment.

Access to firearms in the United States is unrivaled. In fact, the proportion of gun-related homicide has steadily increased from 1996 to 2016 [15]. Similarly, crimes involving a firearm, including suicide and unintentional firearm death, are disproportionately high compared to other high-income countries. Most firearm deaths occur in the United States. Over 90% of children killed by a firearm are killed within our borders (National Trauma Data Bank 2016). Although not as frequent as falls or motor vehicle crashes or falls, case fatality by mechanism of injury is highest by Firearm (11%) [14]. Children who are injured from a firearm in rural counties are more likely to be hospitalized, as likely to die, and more likely to have committed suicide than their urban counterparts [16, 17].

The American Pediatric Surgery Association (APSA) supports a public health approach to firearm injury. Specifically, APSA supports strong child access protection laws and a minimum purchase age of 21 [18]. Similar advocacy for firearm injury prevention is endorsed by the American College of Surgeons, including safe storage and prevention research [19].

Farm Injuries

Rural United States is home to America's farms and the agricultural industry. Labor reports have documented an increase in the number of youths hired to provide assistance on farms, in addition to the children who already work on their homestead. Nearly two million youth are exposed to farm hazards at home (Center for Disease Control, 2020 Agricultural Safety Report). We queried the NTDB retrospectively to identify pediatric patients who sustained a farm-related injury between 2008 and 2016. Over this 9-year period, the incidence (0.083%) of these injuries remained stable. Unique injuries include falls from structures (hay holes, silos), machinery-related mishaps (chainsaw, power take-off, mowers, hydraulic pumps) and animal-related injuries (kicked by animals). ATVs or UTVs are also frequently used to move products as well alongside tractors and track devices. For youths working on a farm, the tractor or similar equipment is the most likely source of injury. For those youths visiting, a kick from an animal is the most likely culprit.

Anabaptist

The Anabaptist ("one who baptized again") communities comprise the Mennonites, German Baptist Brethren, Amish, and Hutterites are a conservative branch of the Protestant church. Agriculture represents their chief source of income. Challenges to healthcare providers include distrust of outsiders, skepticism in western medicine, lack of healthcare insurance (federal exemption), lack of modern transportation and communication. They rely solely on drivers or horse-drawn carriage for locomotion which presents a unique traffic hazard, especially after dusk. Delayed presentation to treatment is commonplace, and follow-up is almost non-existent in our experience. Approximately one third of children had an ISS >15 among the 201 patients our institution treated over a 25-month review. Boys were more commonly injured 3:1; with mechanisms of falls, machinery entrapment, animal-drawn vehicle, and struck by an animal most commonplace. Another retrospective study from

Fig. 4.2 Properly constructed Hay Hole left open for demonstration

Pittsburgh, found similar results. Most children suffered blunt force trauma with a higher ISS. Hay hole falls were a unique source of injury [20] with a high ISS often requiring treatment of craniofacial fractures including surgery (Fig. 4.2). Paramount is extensive communication with families and the Elders to gain trust and support for treatment decisions as well as follow-up care.

All-Terrain Vehicle (ATV)/Utility Terrain Vehicle (UTV)

As mentioned, the ATV or UTV has become an integral part of rural agriculture and even recreation. There are no speed limits. Not every state requires the use of helmets or driver's license. The laws surrounding age of operation are for the most past ignored. Additionally, these laws do not apply to use on private property. Most of what can be said about the hazards associated with their use apply to snowmobile operation in the northern climates during winter months. ATVs are powerful and potentially dangerous vehicles [21]. Four-wheeled ATVs (or UTVs) are somewhat less likely to rollover compared to their three wheeled counterparts. Either way, similar design features including a high center of gravity, short wheelbase, short turning radius, weight more than 1000 lb, and high-powered engines allow for speeds of up to 70 mph. Many models have no rollover bars, and few if any safety belts.

The number of ATV accidents has increased in all states in recent years. Pediatric trauma constitutes one third of all ATV related deaths. Ten percent of crashes seen in the Emergency Department require hospital admission [27]. In 1998, the Consumer Product Safety Commission (CPSC) reached an agreement with ATV manufacturers would no longer market "three wheelers" and provide information and safety education [22].

Rollover accidents are the most common mechanism of injury. ATV crashes involving unhelmeted riders and rollover accidents result in significant medical costs [23]. In 2001, Helkamp showed a two-fold increase in ATV-related mortality in states without helmet laws [24]. Other safety measures involve not operating ATVs on paved roads, not allowing children under 16 years of age to operate an adult-sized vehicle, not operating the ATV with a passenger, proper use of safety equipment (helmet, eye protection, gloves, long-length clothing) and completion of a hands-on safety course [21].

Lawnmower

Lawnmower injuries are common in any environment, but more so in the rural setting. They are tragic, life changing, and again preventable. Most injuries stem from a lack of awareness and education. Unsurprisingly, most occur in the summer months. Many riding mower mishaps occur during operation with the mower deck engaged while the child is sitting on the parents' lap. Most injuries involve mangling of the lower extremity [25]. Lawnmower instructions are diminutive with no user training. Tissue necrosis, polymicrobial infection, long hospital stays and multiple trips to the operating room are the norm. Psychological trauma for the child and family alike is unquantifiable [26].

Non-accidental Trauma (NAT)

Non accidental trauma or child abuse, either by commission or omission, is not exclusive to the urban or suburban environment. There are some regional differences that are worth noting. NAT occurs at approximately twice the incidence in the rural setting. Abusive head trauma is particularly lethal owing to the diffuse nature of the injury and delay in presentation. Approximately 10% of pediatric admissions in the rural venue are secondary to NAT [27]. Recidivism is common with “minor” injuries documented prior to the sentinel event. The mean age is lower compared to their accidental counterparts. Mortality remains higher for the NAT cohort [28].

Conclusions and Take Home Points

Rural trauma is the “neglected disease” of the twenty-first century. The definition of rural pediatric trauma is not one-dimensional. A trauma system may be considered “rural” when the optimal care of the injured patient is limited by geography, weather, distance, and resource availability. The tenets for initial treatment and stabilization are no different for children affected in the rural setting with regards to principles enumerated within ATLS and PALS. Disparities exist in resources and available services. Unique complicating factors include the availability of specialty providers, availability of transport, infrastructure, lack of communication, lack of funding, lack of education and prevention along with cultural barriers (Anabaptist, agricultural workforce necessity, tacit acceptance of injuries).

Addressing issues surrounding these disparities is possible, albeit costly, to implement. There is no one algorithm to address the dynamics of geography, infrastructure, education, poverty, access, and prevention in which they interact within the rural venue. Some answers can be found within affiliation of critical access hospitals with regional trauma centers to serve as guidance for education and access including transport. The American College of Surgeon’s Rural Trauma Team Development Course (RTTDC) can assist with the preparation of a rural facility for appropriate care and early transfer through more effective communication and establishment of an effective performance improvement process.

Additional processes may include outreach for injury prevention and education. This is a requirement for most trauma center’s accreditation. Telemedicine is also another tool that has, albeit unfortunate, an increased utility during the COVID-19 pandemic. Telemedicine may improve the early management, diagnosis, and outcomes of rural trauma patients by connecting the local provider with a remote trauma specialist. Telemedicine can assist in streamlining the process of transfer to definitive care with improved mortality and decreased length of stay [29, 30].

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Chapter 5
Disaster Management

Douglas M. Pokorny, Andrew C. Kung, and Jennifer L. Gordon

Abstract The keys to the success of any disaster management program are the identification of vulnerabilities, preparation to address identified weaknesses, and continued education aimed toward risk mitigation. Whether accomplished through mass education, hands-on training, emergency services integration, or simple communication, a comprehensive disaster management plan can help even the most remote regions to succeed under duress. A robust disaster response begins with extensive preparation through preventative measures. In conjunction with these preventative measures, risk mitigation develops plans to prevent the unnecessary loss of life or property. Preparation, the final phase before the actual disaster event, enacts the actual mitigation measures identified in previous steps. The response phase, the first portion to take place after the actual event, focuses on addressing the actual threats and protecting public interests. In this phase, the Emergency Operations Center and Incident Command System establish a chain of command. Lines of communication are created, human casualties undergo triage, and assets are dispersed in the most effective manner possible to treat all those in need. After the conclusion of the immediate response, the community as a whole begins to rebuild, and new opportunities for change are identified. With recovery, the cycle continues as lessons learned from the prior incident drive future prevention, mitigation, and preparation efforts.

Keywords Disaster management · Mass casualty · Risk mitigation · Incident command

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Key Points/Clinical Pearls

- Utilization of a triage algorithm such as the pediatric-specific JumpSTART can help improve outcome of all patients.
- Thorough planning for potential disasters is important to prepare for all possibilities and includes a through analysis of strengths and weaknesses.
- The Emergency Operations Center and Incident Command System establish a chain of command and ensure lines of communication are maintained.
- Partnering with other hospitals, local and state governmental organizations and federal assets can overcome previously identified vulnerabilities
- A thorough review of any disaster event and after-action evaluation is important to plan and prepare for future events.

Learning Objectives

- Identify the five phases of disaster management
- Understand the structure and function of an Incident Command System
- Develop an understanding of basic triage principles
- Identify the differences in pediatric and adult triage algorithms

Initial Management of the Trauma Patient

Rapid assessment and immediate triage of casualties in disaster scenarios are essential in order to provide the greatest benefit to the largest number of people. Patients may quickly be grouped into minimal, delayed, immediate, or expectant categories based upon simple observations or criteria. Once the primary triage is completed, the process is repeated until all casualties have been either treated or expired.

Initial Radiographic/Ancillary Studies

Implementation of the Model Uniform Core Criteria (MUCC) utilizing triage algorithms such as Simple Triage and Rapid Treatment (START), Sort-Assess-Life Saving Interventions-Triage (SALT), or the pediatric-specific JumpSTART can help to improve outcomes of all patients involved in disaster scenarios.

Introduction

Although we cannot predict catastrophic events, we must make every effort to prepare ourselves for the moment a disaster strikes. Attributed to Benjamin Franklin more than 200 years ago, the adage “by failing to prepare, you are preparing to fail” has remained timeless. Whether accomplished through mass education, hands-on training, emergency services integration, or proper communication, a comprehensive disaster management plan can help any group to succeed under duress [1]. In this section, we will provide an overview of the five phases of disaster management, define the concept of an incident command system, and highlight the use of disaster management planning in mass casualty situations.

The Five Phases of Disaster Management

Prevention

In order to effectively plan and prepare for a disaster, a group must first identify their vulnerabilities. Whereas coastal communities bear the overarching burden of major weather events such as hurricanes and flooding, inland dryer climates are at constant risk of fire and drought. Large, urban areas become targets of Active Shooter/Hostile Event (ASHE) type incidents, such as terrorist events, whereas rural communities may be devastated by a smaller industrial hazard. Regardless of the nature of a disaster, we can more readily mitigate the ensuing fallout if we identify our vulnerabilities and plan accordingly. The first phase of disaster management, prevention, involves planning for possible disasters and enacting small changes that help prepare for those scenarios. Examples of preparation include outlining evacuation routes from buildings, setting muster points for evacuees, and performing drills pertaining to natural disaster or ASHE-type events. While prevention planning contributes to the overall preparation for a disaster, this phase does not involve making major changes to policy or procedure.

Mitigation

The second phase of disaster management, mitigation, involves making actual changes keyed toward minimizing loss of life and destruction of infrastructure. Mitigation must occur before the actual disaster event. When performed well, this step assists a group in protecting the public, preventing injuries or loss of life, decreasing fiscal losses, and enhancing recovery efforts. According to the Federal Emergency Management Association (FEMA), hazard mitigation involves four steps: (1) organize the planning process and resources, (2) assess the risks, (3) develop a mitigation strategy, and (4) adopt and implement a plan [2–4]. The first step, organizing the planning process and resources, begins after creating a comprehensive list of actual and hypothetical risks. Once these risks or vulnerabilities are identified, experts are contacted to address every aspect possible. As preparation begins, local agents must communicate their concerns to both the regional and territorial (state) levels. Vulnerability varies by region and by available resources. In times of duress, the division of assets between communities can be a very valuable strategy [5].

Risk assessment is accomplished through many avenues. Structural engineering surveys can identify physical hazards that have not been addressed. Common structural questions include: are windows impact rated, are structures secured to the ground or freestanding, do runoff areas have adequate drainage, etc. Education assessments may include determining if residents have been taught basic first aid and if they know where emergency shelters are located. Policy revision during risk assessment may evaluate whether or not proper codes are being followed and if the land is zoned appropriately. Once the assessment has been completed, it is then the responsibility of those in charge to develop a strategy to address areas of vulnerability and enact a plan of change.

Preparedness

The third phase of disaster management, preparedness, is the final phase before the actual disaster event. Once a mitigation plan has been created and opportunities for improvement are identified, preparation for each event begins. Initially, there is a focus on education. Countless training courses addressing common knowledge deficits are available through various government agencies such as the National Fire Academy (NFA), the Center for Domestic Preparedness (CDP), and the Emergency Management Institute (EMI). Through a combination of education, training, tabletop exercises, drills, and simulation, we as a whole are able to better prepare for the majority of our vulnerabilities [6].

The Organizations Preparing for Emergency Needs (OPEN) training site (https://community.fema.gov/opentraining) highlights ten specific steps that should be addressed in preparing for any major incident. Whether it is a terror attack, natural disaster, or industrial accident, the following steps are critical in preparing the community to respond. The ten steps to be addressed are:

1. Understanding our risks
2. Safeguarding critical information
3. Identifying the population to be served
4. Mitigating risks
5. Establishing communication plans
6. Determining essential activities
7. Establishing supply chains
8. Testing and updating strategies
9. Formalizing plans
10. Training all individuals that are necessary to success [7].

The crucial aspect is of these ten specific steps is training the individuals. A proper plan can only be executed if the personnel involved understand the process and train accordingly so that they are equipped for any complications that may arise.

In March of 2011, the President of the United States formally addressed the issue of disaster preparedness by publishing Presidential Policy Directive 8 (PPD-8). PPD-8 called for the establishment of the National Preparedness System (NPS); “This directive is aimed at strengthening the security and resilience of the United States through systematic preparation for the threats that pose the greatest risk to the security of the Nation…” [8]. The goal of the NPS was to create “a secure and resilient nation” while providing a framework to sustain our preparatory efforts.

Response

Arguably the most important phase of disaster management, the response phase occurs immediately following the disaster event. In this phase, attention must be focused on addressing the actual threats, enacting previously created plans, and protecting the safety of all those affected. The first main objective is to rescue people and personnel in harm's way while neutralizing any immediate threats. Once people are safely evacuated, it becomes easier to address the dangers at hand. However, it may occasionally be necessary to address any immediate threats prior to evacuating the affected parties. An example of this scenario involves shutting down power grids in structure fires so that emergency personnel may effectively move through a space without concern of electrical injuries to themselves.

Once the safety of people and property has been established, the second main objective is to begin triaging immediate needs. Upon identifying these needs, it becomes possible to adequately dispense resources. After cataloging the scope of the disaster, the available assets are then divided, and the "clean-up" begins. Local assets are engaged, relief measures are mobilized, and all attention is directed toward restoring normal order and operations. In addition to aiding the immediate recovery, attention is also turned toward planning for the long-term recovery effort that will be required.

Recovery

The final phase of disaster management, recovery, begins after the immediate response efforts have concluded. Recovery is a long-term phase that may last months, years, or even decades. In the short term, essential aspects such as food supply chains, water treatment facilities, and adequate shelter must be re-instated. Additionally, restoration of public utilities such as electricity, sewage, and fuel supply assist with supporting the operations of necessary institutions such as hospitals. Once people are able to return to their homes and places of work, a recovery plan can be created that prioritizes restoration assets. In some cases, demolition of damaged structures may be more beneficial than repair. One of the most important parts of the restoration phase is documentation of lessons learned to facilitate better preparation for future events.

The Incident Command Structure

Whether bracing for or mobilizing in response to an imminent threat, a structured hierarchy of personnel must be identified with the establishment of a clear, unified command. An incident command system (ICS), a well-organized, pre-planned response tree establishing a chain of command, is an invaluable tool for disaster preparation. The ICS incorporates all available assets (emergency services, equipment, communications centers, etc.) into one fully functional web of services, all functioning together to move toward recovery. The National Incident Management System (NIMS) identifies six areas critical to an effective ICS: (1) establishment of a clear command presence, (2) appointment of an operations manager, (3) development of a planning division, (4) development of a logistics division, (5) intelligence collection and investigations, and (6) creation of a finance/administration division [9].

The command presence, often located in the Emergency Operations Center (EOC), acts as the control node and ultimately organizes all information to or from the scene. The incident commander, ultimately in charge of all assets, leads the ICS from the EOC. While individual chains of command may still be enacted, the incident commander is granted unified authority over the entire response. The planning division develops an action plan and modifies it based on immediate needs. The operations division assists the incident commander by tracking all progress and enacting the action plan. The logistics division, a close partner of operations, assists with tracking personnel and provides the actual assets as needed. The intelligence/investigations division is uniquely tasked with identifying the cause of the incident and collecting any information that may assist in neutralizing the threat. Finally, the finance/administration division monitors the costs of the response and provides guidance as to the distribution of fiscal assets. A graphical depiction of the ICS can be seen in Fig. 5.1 below [10].

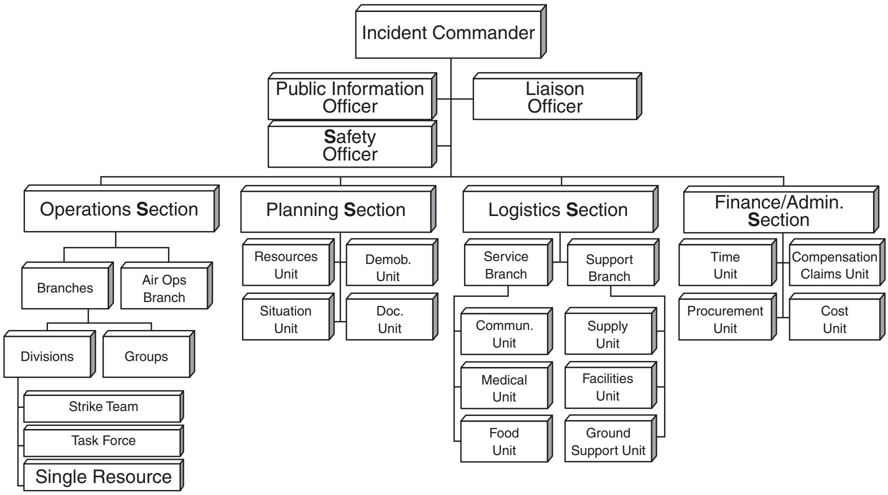

Fig. 5.1 Recommended structure of the incident command system. [Federal Emergency Management Agency—May 2008]

Specific Considerations in Mass Casualty Events

Immediate Triage

In the event of a large-scale disaster, human casualties may be inevitable. The American College of Surgeons Committee on Trauma (ACS COT) published a consensus statement in 2003 regarding disaster management, specifically the management of events resulting in massive numbers of casualties [11]. As numbers rise, the system can rapidly become overwhelmed. Because a large percentage of critical injuries require surgical intervention, it is essential to involve surgeons at the local, regional, state, and national levels when planning for a response. The ACS COT offers multiple education courses to providers throughout the world in an effort to instill at least basic training in the stabilization of traumatically injured patients. Advanced Trauma Life Support (ATLS) and Rural Trauma Team Development Courses both target hospital-based providers in smaller systems to familiarize them with the basic triage of injured patients. Completion of these courses by emergency personnel aids preparation for disaster response as it trains providers to identify weaknesses, utilize available assets, and incorporate them into the regional network as required. Additionally, the Department of Homeland Security established a course entitled "You are the Help until Help Arrives" that outlines five life-saving acts any member of a community can reasonably perform in the event of an emergency. These acts include: calling 9-1-1 to activate emergency personnel, ensuring the scene is safe for responders, stopping any obvious bleeding through packing and compression, strategically positioning injured patients, and providing comfort while waiting for trained personnel to respond [12].

The single most important step in the prehospital setting involves proper triage of the patients. Triage, from the French "to sort," in the setting of mass casualty situations, is the initial process of prioritizing patients based on the care they require. Secondarily, their care is weighed against the number of casualties present and the number of assets available to assist. This care is rendered with the mantra "the greatest good for the greatest number of patients" in mind [13, 14]. The classic triage system, also known as the START (Simple Triage and Rapid Treatment) categorized patients according to four colors with corresponding tags that could be placed on the patient. These four colors represented four patient categories: the walking wounded (green tag), those with a delayed need for care (yellow tag), those with an immediate need for care (red tag), and those patients you expect to succumb to their injuries (black tag). However, traditional triage methods have proven to be cumbersome in providing the initial screening and do not take into account constantly fluctuating needs. To prevent mistriage and avoidable delays, a more modern approach has been suggested to rapidly triage patients [15].

The Model Uniform Core Criteria (MUCC), a proposed universal standard for field triage, relies upon three major concepts to establish the triage priority of injured patients; these three concepts comprise the "SALT" (Sort-Assess-Life Saving Interventions-Triage) method [16]. The first concept, "Global sorting," relies upon the idea that patients with the least severe injuries are more readily able to comply with basic commands. Using the Walk, Wave, Still approach, patients demonstrate tasks in decreasing complexity to help stratify the severity of their injuries [15]. Upon initial arrival, patients are ordered to stand and walk to a designated area. Those who are strong enough/capable enough to move on their own oftentimes do not have any significant injuries. With this decreased threat of imminent collapse, the "walking wounded" become the lowest priority for evaluation. Next, the remaining patients are asked to perform a task such as waving at the provider. Accomplishing a complex task such as "wave with your right hand" implies the integrity of higher order processing and again tells you that a patient is not in imminent danger; these patients become a second-tier priority. Finally, all those who lay still and do not walk or wave are identified, and an immediate evaluation is performed.

After sorting into the above categories, each patient is examined individually. Starting with the "still" group, life-saving interventions such as hemorrhage control, airway adjustment,or chest decompression are performed [16]. If the patient is breathing, they are then re-triaged to the more traditional categories. If they are not breathing, they are declared unsalvageable and moved to the expectant collection point. If the patient is breathing, demonstrates purposeful action, has a palpable pulse, and has no obvious source of ongoing hemorrhage, they are triaged as either delayed or minimal. Delayed patients, by definition, have more significant injuries, whereas minimal patients have minor injuries only. For patients whose distinction is unclear (those who fail to demonstrate purposeful movement, are breathing erratically, do not have a pulse, or are continuing to hemorrhage), they are classified as either immediate or expectant. Immediate patients are likely to survive with proper intervention, whereas expectant patients are likely to die from their injuries. Figure 5.2 below provides a basic outline of the SALT triage algorithm.

JumpSTART is a pediatric triage tool that uses a similar algorithm during mass casualty incidents. This algorithm is equivalent to a combination of START and SALT triage methods [17, 18]. Starting with the walking assessment, there is a quick transition to the individual assessments. Any child who is able to walk over is taken to a separate location for secondary triage. All remaining patients undergo primary triage. Patient evaluation order in primary triage starts with infants and toddlers, moves to young children who cannot walk on their own, and is followed by children carried over by adults.

The JumpSTART assessment differs from adults in that breathing is not a simple yes or no question. If the patient is breathing, other vital signs such as pulse and respiratory rate are considered. An abnormally high or low pulse rate or respiratory rate is indicative of an emergent condition requiring immediate intervention. If all vitals are appropriate, triage then moves on to the evaluation of the mental status of

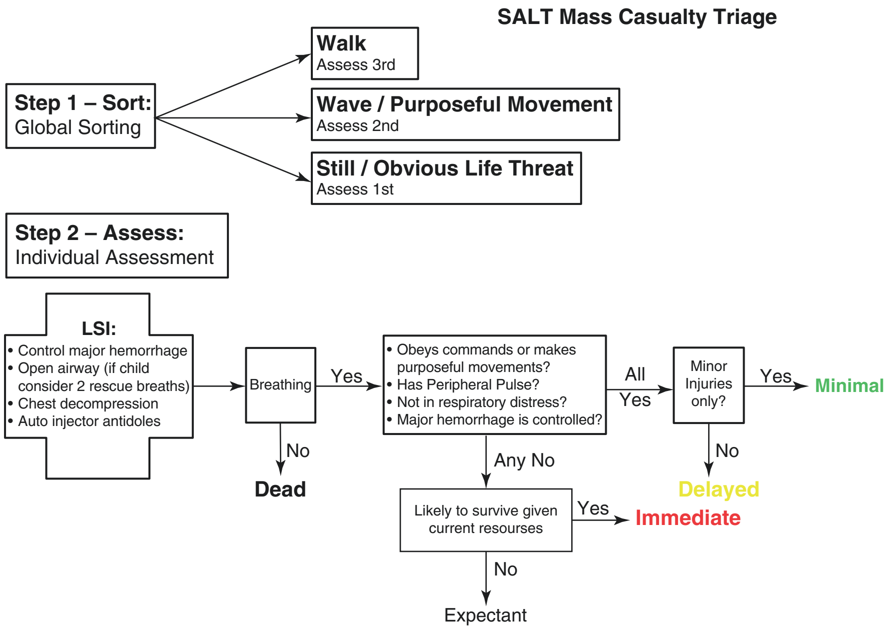

Fig. 5.2 The sort-assess-lifesaving interventions-triage/treatment (SALT) triage algorithm. *LSI* Lifesaving intervention [National Disaster Life Support Foundation—2020]

the patient through an AVPU exam (Alert, responsive to Verbal, responsive to Pain, Unresponsive). Any unexpected findings in the AVPU exam place the patient in an immediate category, whereas a non-concerning exam pushes the patient to delayed status. If the patient is not breathing during the initial phase of the assessment, the airway is repositioned, and the patient re-examined. If breathing resumes, they are labeled immediate; if breathing does not resume, they are given five rescue breaths. Successful resuscitation of the patient after rescue breaths places the patient in the immediate category. If none of the maneuvers mentioned are successful and the patient is not breathing and has no pulse, the patient is considered deceased (Fig. 5.3).

Although primary triage occurs rapidly, the process as a whole remains dynamic. Patients are reassessed, and their triage status is constantly revised; delayed patients can easily become immediate or expectant, and expectant patients may survive long enough to be re-triaged as immediate. Re-evaluation of patients, known as secondary triage, must occur on a regular basis until all patients have either expired or received appropriate treatment. Patient tracking must also be strictly maintained in an effort to document what interventions have occurred and where a patient has moved through the system.

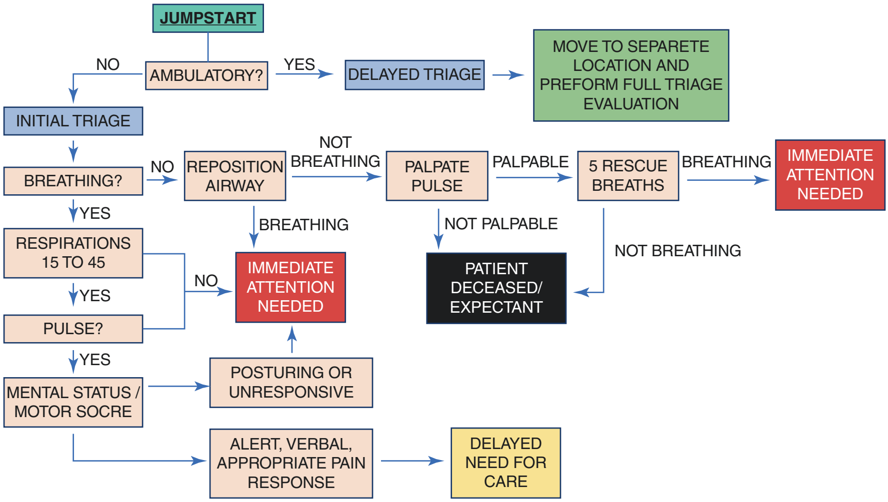

Fig. 5.3 The JumpSTART algorithm for triage of pediatric mass casualty incidents

Transportation

Disaster events can be classified as either static or dynamic [15]. *Static events* are limited in duration, and the scope of the threat is known. Examples of this are motor-vehicle crashes, farming accidents, or industrial events. There is one single moment where disaster strikes, and the event is concluded in a short period of time. In a static event, patients are more likely to remain at the scene and wait for traditional forms of assistance. Depending on the nature of the event, traditional vehicles (ambulances) may work in tandem with personally owned vehicles, air transit, or other modes of transportation. Tracking all modes of transportation and establishing sufficient lines of communication is necessary to follow transfers of patients to secondary locations. This line of communication is typically established via an EOC or incident commander on scene.

Dynamic events, situations where the scene is constantly evolving and stability does not exist, are much more difficult to manage. Examples of dynamic incidents include active shooter scenarios, bombings, natural disasters, and Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) type events. In a dynamic scenario, patients are more likely to flee the scene as threats continue to develop. Casualties are transported to hospitals and clinics by any means necessary, which can jeopardize prehospital triage. Mass confusion becomes a concern after disruption of the typical triage processes. Dynamic events rely heavily on a system's ability to adapt as multiple facilities, agencies and personnel are forced to deviate from traditional practices.

Hospital Based Triage

Although triage is primarily a prehospital priority, the assessment continues into the hospital phase. Arriving casualties undergo an additional evaluation to determine operative order and treatment priority. After procedures are complete, patients are again triaged by need into various units within the facility. Occasionally, a tertiary triage is performed that uncovers a need for escalation of care. A common example would include patients with major vascular injuries that are stabilized in a facility without vascular surgery capability but require vascular repair. Again, hospital triage must adapt to the situation at hand and promote the delivery of appropriate care in a timely fashion.

Real World Example

On November 5, 2017, a lone gunman opened fire on a rural church in Sutherland Springs, Texas. In the initial assault, 25 people were killed and 23 others injured [19]. The immediate location of the incident was in a very small rural community with extremely limited resources. Upon radio confirmation of a mass casualty incident, the EOC established a chain of command by directing all assets to report to the Incident Commander. The closest medical facility, a small community hospital with one emergency room (ER) physician and two to four ER nurses on staff, was extremely limited in resources that could be provided. Roughly 60 min away in San Antonio, there were two large urban level 1 trauma centers with extensive capabilities, including pediatric trauma staff.

After confirming the scene was secure, local and regional assets were mobilized to the area. Knowing the large volume trauma centers were an hour away by ground, the incident commander sent all available helicopter units to the scene to assist with critical transportation. Primary triage was completed by walking wounded and law enforcement officers. Patients were rapidly assessed and triaged into common categories. Air assets were launched to transport the most critically injured while ground transport was sent to transport the less critical in a delayed fashion. Patient destinations were split as evenly as possible by the EOC to prevent over-saturation of the receiving facilities. Because of good communication, the staff at both trauma centers were able to call for assistance which arrived in a timely enough fashion to help stabilize all critical patients.

One young patient, categorized as immediate and often referred to as the sickest patient on scene, was in obvious need of immediate, life-saving intervention. After suffering numerous gunshot wounds resulting in a pelvic fracture, femur fracture, extensive soft tissue injuries, and hemorrhagic shock, the patient was very tenuous.

Fearing the patient would not survive transport to the pediatric trauma center, the decision was made to divert the to the closest available facility. After emergent transfusion at this small facility with aggressive wound packing with hemostatic gauze, this patient was re-triaged as immediate and sent to a trauma center for definitive intervention.

As patients arrived in the receiving facilities, appropriate secondary and tertiary triage were performed. Patients were again categorized based on their need for significant intervention. Ultimately, after all patients had been transported from the scene, the incident commander relinquished command and returned operations to the normal flow. Because of the rapid mobilization of assets and expedient transfer from the scene to treatment facilities, 22 of the 23 injured patients survived the event. Most notably, the pediatric patient diverted for resuscitation prior to air transport, was successfully treated at the tertiary center and survived all injuries. The compilation of lessons learned contributed to many advancements in the region including the widespread teaching of the ACS COT sponsored Stop the Bleed® course and the creation of a large scale, prehospital whole blood resuscitation program [20].

Conclusion

The keys to the success of any disaster management program are the identification of vulnerabilities, preparation to address identified weaknesses, and continued education aimed toward risk mitigation. Whether accomplished through mass education, hands-on training, emergency services integration, or simple communication, a comprehensive disaster management plan can help even the most remote regions to succeed under duress.

Take Home Points

- A robust disaster response begins with extensive preparation through preventative measures. In conjunction with these preventative measures, risk mitigation develops plans to prevent the unnecessary loss of life or property. Preparation, the final phase before the actual disaster event, enacts the actual mitigation measures identified in previous steps.
- The response phase, the first portion to take place after the actual event, focuses on addressing the actual threats and protecting public interests. In this phase, the Emergency Operations Center and Incident Command System establish a chain of command. Lines of communication are created, human casualties undergo triage and assets are dispersed in the most effective manner possible to treat all those in need.
- After the conclusion of the immediate response, the community as a whole begins to rebuild, and new opportunities for change are identified. With recovery, the cycle continues as lessons learned from the prior incident drive future prevention, mitigation, and preparation efforts.

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Chapter 6
Paediatric Trauma in Settings of Limited Resource

Bethleen Waisiko, Jason Axt, Chelsea Shikiku, and Jacob Stephenson

Abstract Trauma is the leading cause of death and disability across the globe. The principles of caring for the injured child are unchanged in the developing world, but the available resources can be minimal. This chapter will apply the Advanced Trauma Life Support pathways to encourage the reader to prepare techniques and equipment to be able to continue to provide high level trauma care in humanitarian or deployed settings. The authors are primarily African surgeons at a tertiary referral paediatric trauma center in Kenya.

Keywords LMIC · Humanitarian · Missions · Deployed · Africa

Learning Objectives

- Define the magnitude of trauma epidemiology in the developing world and consider how you might impact delivery of trauma care.
- Describe primary, secondary, and tertiary plans for airway management with limited paediatric specific resource.
- Consider how damage control objectives apply in a setting with minimal critical care follow on options.
- Ethically consider the impact that severe childhood trauma such as brain injury and burns might have on the family involved in a resource constrained setting.

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Introduction

Yearly it is estimated that one million children die due to injury and violence [1]. Tens of millions are treated for wounds, many of whom survive with some form of lifelong disability. The burden is highest amongst the poor, with more than 95% of all childhood injury deaths occurring in low-and middle-income countries (LMICs). In an era of increasing urbanization of the developing world, paediatric trauma will continue to rise. Though it is the leading cause and death and disability in children worldwide, paediatric trauma care remains a low priority throughout the developing world. Funding for research and development of trauma systems for children lags far behind other diseases and makes up less than 1% of the international financial assistance given to LMICs [2, 3].

Motivated societies can prevent childhood injury and improve safety. Mortality from injury in high-income countries has been roughly halved in the three decades since Dr. Haller's seminal report [4–6]. This improvement in childhood safety in the developed world has been due to multi-faceted injury prevention measures as well as the development of trauma systems that prioritize care of the wounded child from the point of injury through successful rehabilitation. Throughout most of the global south, children continue to live in higher-risk environments with less supervision and family resources. Few resources are available to invest in their safety [7].

Despite the massive roadblocks, there is hope that the plight of the injured child in the developing world can improve. Awareness is increasing and surgeons in LMICs are leading the push to effect a change in political will to value child safety. Funding initiatives of groups such as the Fogarty International Center of the National Institute of Health are seeking to produce data that can guide proper trauma system development [8]. Paediatric surgeons in the developed world must advocate for injury prevention, speak out against violence, and partner with our global colleagues to develop strong paediatric trauma systems.

Trauma care within lower resource settings requires creativity and flexibility not necessary in other places. We will use the outline of the Advanced Trauma Life Support (ATLS) [9] system to look practically at modifications that might be made to care for patients in a more austere setting.

Initial Assessment and Management

Prehospital care is often lacking in LMICs [10]. The paediatric patient is most likely to be transferred from an accident scene by medically untrained observers, thus initial patient stabilization will likely start at the hospital. Clinicians should follow the ATLS principles in patient assessment and stabilization. Knowledge of local equipment and usual practice is essential. Modifications that may apply in a resource limited setting are italicized in the table below:

System	Intervention
Airway	• *Use basic maneuvers such as jaw thrust, chin lift* • *Suction airway (a bulb syringe or 60 mL syringe with a Foley catheter may be used as a suction device)* • *Disposable equipment may be sanitized and reused* • *In line stabilization of the C-spine:* • *Appropriately sized c-collar may be difficult to find, tape the head to a firm backboard using towels or saline bags as supports beside the head* (refer to the spine trauma section)
Breathing	• Chest auscultation • Pulse oximetry • Supplemental oxygen administration (*oxygen concentrators may be used)*
Circulation	• *Use portable ultrasound for FAST exam* • *Use bedsheets for pelvic binding* • *Use make-shift splints (cardboard, pieces of wood) to splints fractures*
Disability	• Intubation if GCS score < 8 *(sanitize and reuse equipment)* • Anti-seizure medication
Adjuncts	• Nasogastric tube insertion • Chest Xray • FAST exam • Foley catheter insertion • Musculoskeletal xrays

In many centers, imaging such as basic x-rays are only available in a separate location than that where the patient is initially received and resuscitated.

Airway and Ventilatory Management

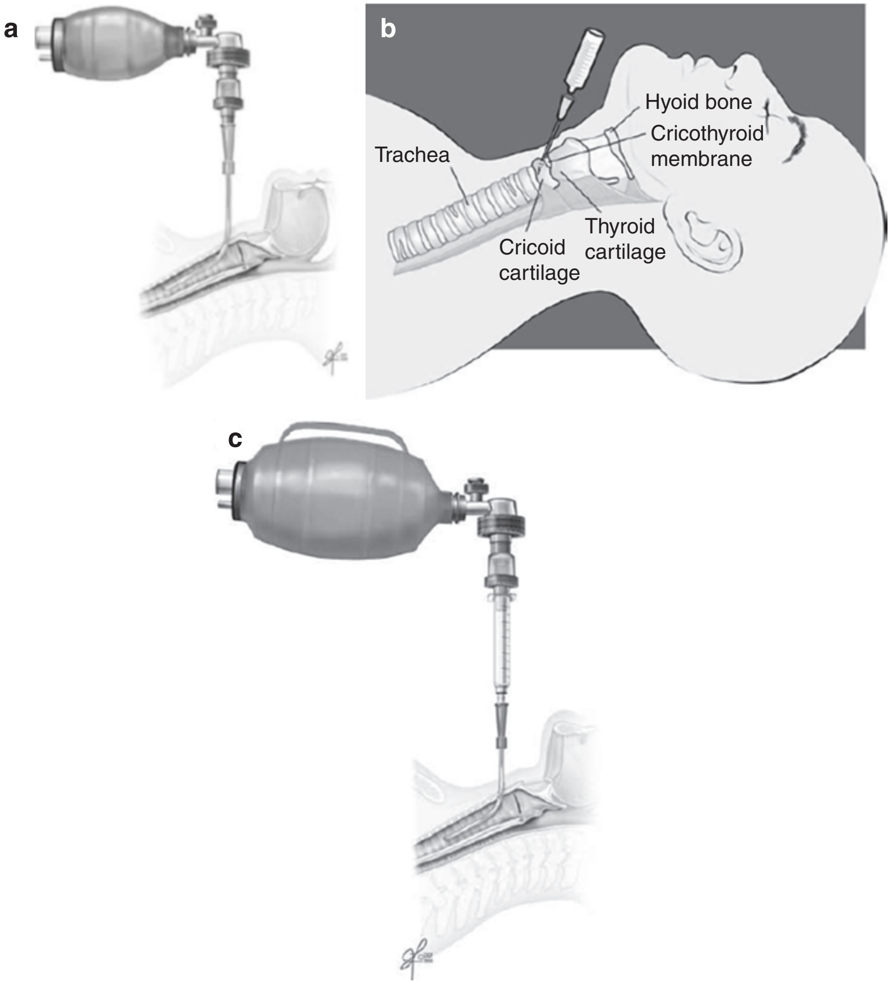
Familiarize yourself with the equipment available for airway management. In many centers, appropriately sized airway devices are not readily available, with many being re-used multiple times by soaking them in a sterilizing solution such as 1: 100 sodium hypochlorite solution for 30 min [1]. Oxygen will often be supplied from oxygen cylinder, it is important to confirm the adequacy of the oxygen supply [11]. Portable oxygen concentrators may be used, though they only provide a maximum of around 5 L/min.

Basic airway opening maneuvers such as head tilt chin lift maneuver and jaw thrust, if well done, may be the only interventions needed. In the event airway suctioning is necessary, a patient who is well secured to a spine board may be turned to either side allowing clearance of the airway by gravity or a finger sweep. A 60 mL catheter tip syringe may also be used as a suction device alone or connected to a catheter. Nasal cannulas are generally available though they may have been reused multiple times. Inspect them for defects. If non-rebreather masks are utilized, inspect them carefully to assure the integrity of the non-rebreathing valve and the oxygen reservoir. In a pinch a non-rebreather can be used as a bag valve mask for a short time by occluding the exhalation valve with a cupped hand, achieving a tight face seal, and squeezing the reservoir bag.

If a patient is not breathing spontaneously a bag valve mask (BVM) or an anesthesia bag can be utilized to assist ventilation. Oftentimes the air-filled face masks lose their integrity on a reused BVM. These donuts can be reinflated and sealed using electrical, duct or even medical tape. An adult mask will work for a child if inverted so that the nose piece rests on the chin and the rounded portion sits on the face or forehead. A willing family member or concerned bystander can be coached to give rescue breaths if they are willing to expose themselves to bodily fluids. There are often built-in peep valves on BVMs. Ensure that these valves function properly to release excess pressure. Excess pressure has been administered using these bags, especially when they have been reused, causing tracheal injury, pneumomediastinum or pneumothorax.

It may be necessary to secure an airway. In a fully unresponsive patient and in the absence of a laryngoscope, digital intubation can be performed. The provider should beware that their fingers are at risk for a bite injury and a bite block should always be used [12, 13]. Nasotracheal intubation can be performed in a spontaneously breathing patient without the need for a laryngoscope or sedation. A stethoscope tube may be placed inside the endotracheal tube to listen for breathing and the tube is advanced during inspiration. Commercial endotracheal tubes are available that have a tensioning device to bend them to facilitate entering the airway. A similar configuration can be rigged by driving a suture through the tip of the tube and running it along the tubes curved side. The curve in the tube will be accentuated with the suture is placed on tension.

If laryngoscope and blade are available, inspect the tube, especially the cuff well as the failure point for reused tubes is often the cuff. In a cannot intubate, cannot ventilate situation, needle cricothyroidotomy may be performed using a 14, 16, or 18 gauge IV catheter. The catheter can then be connected to a bag valve mask using the adapter from a 3.5 Fr endotracheal tube. An alternative method of oxygenating is to splice a short piece of IV tubing to suction tubing and connect it to the oxygen source [14].



Ventilation using a standard ventilation bag (**a**) using a 3.5-mm pediatric endotracheal tube (ET) adapter; (**b**) using a 7.0-mm adult ET adapter connected to a plungerless 3 mm syringe without a bag-valve–mask attached; and (**c**) using a 7.0-mm adult ET adapter connected to a plungerless 3-mm syringe with a bag-valve–mask attached. (*Courtesy of* S.E. Mace, MS, and J. Loerch, Clinic Cleveland Center for Medical Art and Photography, Cleveland, OH; with permission)

If oxygen is unavailable ventilation can still be performed using a BVM. On some BVMs the oxygen reservoir will need to be removed to allow the device to fill with room air.

Continuous positive airway pressure (CPAP) may be used for supplemental oxygen delivery for younger children, especially in centers where invasive mechanical ventilation is not readily available. A CPAP device can easily be assembled from locally available material: corrugated tubing, water bottle with a seal, oxygen delivery tubing, nasal prongs [15].

Hardwick 1984. Images on digital intubation. The endotracheal tube is introduced by the dominant hand while the non- dominant hand is used to depress the tongue and feel for the epiglottis

Shock

Control of external hemorrhage should be quickly achieved by use of direct pressure or tourniquets. Standard emergency tourniquets are useful in larger children but will not adequately compress arterial flow in younger or malnourished kids. Fortunately, expedient makeshift tourniquets are easier to use in children than adults. Rubber tubing is often available and can function with multiple wraps without the need for a windlass. Open fractures can cause significant bleeding and should be reduced by splinting as soon as possible.

A high index of suspicion of torso injuries and thorough clinical exam is essential because computed tomography scanning is not readily available in most centers. Initial heart rate divided by systolic blood pressure can give a quick SIPA score (paediatric adjusted shock index)—a score over 1.2 is worrisome for hemorrhagic shock. Handheld ultrasound devices that connect to smartphones or tablets are less expensive and becoming more readily available [16]. Trauma providers should become familiar with the focused assessment for trauma (FAST) exam and be able to perform it consistently without assistance. Most literature on use of FAST in the paediatric population emphasize its usefulness to identify bleeding or free fluid but lack of specificity in excluding significant injury. The clinician should maintain a high suspicion for occult bleeding if it seems to be occurring clinically even in the face of a normal FAST exam.

Volume resuscitation is started using isotonic crystalloid IV fluids. A bolus of 20 mL/kg of normal saline is given in the case of shock in a well-nourished child, a second bolus can be administered if there is no clinical response. Monitoring of mental status, heart rate and urine output as clinical determinants of volume status is crucial. If there is no clinical response, whole blood or packed red blood cells should be transfused if available. In the global south blood supplies are unreliable and slow. If a potential blood transfusion need is identified, donors should be sought, and blood donated and cross matched as far in advance as possible. Consider the use of a walking blood bank using quick screening cards to match family member donors.

In the case of difficult IV access, intra-osseous (IO) access can be obtained through use of an 18-gauge needle inserted into the tibial tuberosity or the proximal humerus. Percutaneous cannulation of femoral veins and saphenous cut down can also be performed if IO access fails.

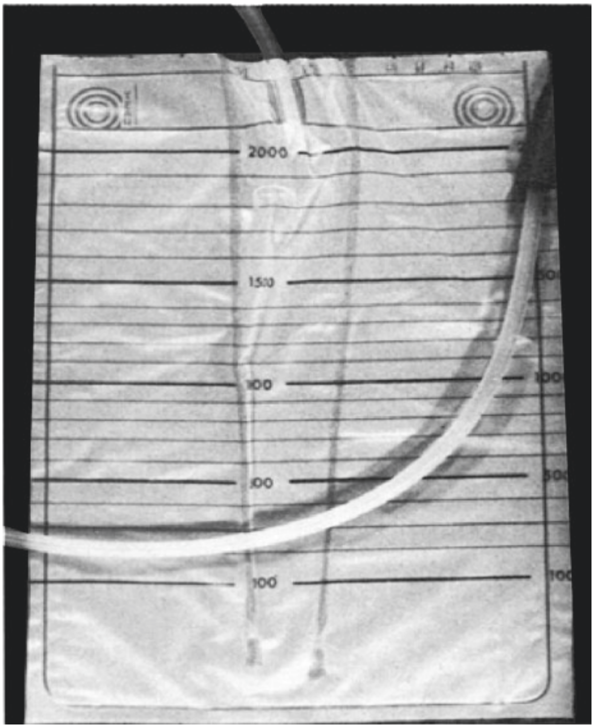
Thoracic Trauma

Most thoracic injuries are blunt, especially in young children given the pliability of their rib cage. Primary and secondary survey examination will pick up on life threatening and potentially life-threatening injuries and thus inform further imaging as necessary for the patient.

Chest x-ray and FAST exam are available in most trauma centers as first line imaging for diagnosis of thoracic injury. ECG can be useful in detection of arrythmias related to blunt myocardial injury.

Injury	Intervention
Pneumothorax	Initial needle decompression Chest tube insertion
Hemothorax	Chest tube insertion
Pulmonary contusion	Adequate pain control Supplemental oxygen administration

Finger thoracostomies can be performed to decompress either hemothorax or pneumothorax if the need for decompression is urgent. Nasogastric tubes, large bore Foley catheters, or nearly any other tubing can be used as a chest tube if no commercial thoracostomy tube is available. An underwater seal device can be devised using sterile saline and several airtight containers [17]. A urine bag may also be modified for ambulatory drainage as shown in the image below [18].



Two soldering lines are used to create a seal within the urine bag

Abdominal Injury

As with thoracic trauma, most abdominal injuries will be blunt. The most injured organs are the liver, spleen, and bowel (especially the duodenum and jejunum in handlebar and seat belt associated injuries). Examine the abdomen for areas of bruising, tenderness, or distension. Abnormal hemodynamic parameters will raise suspicion for internal hemorrhage in the absence of overt bleeding.

Investigations for blunt abdominal trauma include FAST exam, abdominal x-ray and diagnostic peritoneal lavage (DPL). The practitioner should have a lower threshold to perform exploratory laparotomy in a lower resource setting given the absence of advanced imaging, and the difficulties in rapidly marshalling resources in an emergency.

If ventilator and ICU support are not available, damage control surgery can still be performed. The skin can be closed in a temporary running fashion with the bowel in discontinuity or the abdomen packed and the patient can be extubated. Alternatively, the operating room can be utilized as a temporary ICU, ventilating the patient for a while as needed. The ethics of damage control and advanced resuscitation should be discussed in the context of the regional resources, patient, and family wishes.

Head Trauma

Traumatic brain injury (TBI) contributes to a high morbidity and mortality in paediatric trauma. Lack of CT scan imaging in most rural settings and unavailability of neurosurgical services further complicate management. A high index of suspicion based on mechanism of injury as well as clinical signs of raised intracranial pressure (ICP) will aid in detection and subsequent management of TBI. Skull x-rays where available will aid in the diagnosis of possible fractures. Careful attention to the post-resuscitation paediatric Glasgow coma score and pupillary exam is key, as they are most closely linked to outcome. If CT is not available, ultrasound can be used in the young child to evaluate for intracranial hemorrhage; otherwise, the surgeon must rely on clinical exam for lateralizing signs. Trauma craniotomy can be performed with a series of burr holes and a Gigli saw, but long-term outcomes of severe head injury in the developing world are very poor so compassionate care should be considered in the child with GCS score less than 8 after medical management [19].

In most centers, conservative management of TBI is possible and includes:

- Avoidance of hypoxia or hypotension
- Administration of hypertonic saline or mannitol in suspected raised ICP
- Administration of anti-seizure medication
- Elevation of the head of bed
- Temperature regulation
- Pain control
- Family counselling for the child with minor head injury on danger signs on discharge: persistent headaches, nausea, vomiting, fainting spells, visual disturbances, altered mental status.

Spine and Spinal Cord Trauma

Death in spinal cord trauma is most often associated with alterations in the ABCs. Do not neglect basic trauma resuscitation. Protection of the spine can save neurologic function, though often requires improvisation. Any rigid board of the same length and width of the patient and a roll of tape can serve as a spinal immobilization device. Rope, towels, or blankets can be used to secure the patient to the board in the absence of tape. Blanket rolls, styrofoam blocks, or intravenous fluid bags taped on either side of the head can be used to keep the cervical spine aligned. If the patient is well secured, she should not shift if the board is tilted, or even flipped upside down. The patient should be transported supine, but the head of the entire board can be elevated several degrees for comfort if the patient is not hypotensive. The foot can be elevated for the management of shock. The board can also be rolled to the side in the event of vomiting. Transport distances are often long, and a urinary catheter should be placed in anticipation of urinary retention.

Upon hospital arrival, a careful physical examination using a standardized reference such as an ASIA impairment scale should be documented [20]. Initial physical findings and trends can guide discussions about likely recovery that can inform the difficult ethical decisions that may follow.

Available imaging may be only plain films from a fixed machine. Cross table lateral films may not be available. Physical exam should guide the need for further imaging. Although not yet prospectively validated, Pediatric Emergency Care Applied Research Network (PECARN) studies have shown 98% sensitivity in excluding clinically significant cervical spinal injury when **none** of the following are present: altered mental status; focal neurologic findings; substantial torso injury; neck pain; torticollis; conditions predisposing to cervical injury; diving; high-risk motor vehicle crash [21]. If imaging is unavailable and none of the above risk factors are present, immobilization can be discontinued provided the patient and or family are instructed to return for pain or neurological deficit.

In a developing world context, it is ethically conscientious to consider the long-term implications of definitive care. For example, it may not be possible to obtain or afford home ventilator care for a high cervical spine fracture. Care of a totally dependent and medically intense patient may bankrupt a family, and even their neighbors and friends, forcing others to withdraw from education, forgoing needed medical care, or even do without food and clothing. The difficult ethical decisions about what level of treatment is appropriate in each setting must be made with the patient (if possible), the family, and those who know the social, medical, and economic realities of a location.

A patient who is initially able to ventilate adequately but then deteriorates should have recovery of a similar level of function after spinal edema resolves. Thus, ventilation may not be required indefinitely and should be considered in this circumstance.

Non-surgical treatment of injuries can often be pursued with external splinting. Often halo vests or spinal orthosis can be fabricated by orthotists or physical therapists. Creative local artisans can be engaged in producing these devices. 3-D printing may be used to create device components customized to a patient.

Musculoskeletal Injuries

Road traffic accidents and falls are the leading two causes of musculoskeletal injuries. Resources for pre-hospital management are rare [22] and most of these children will be transported without immobilization by family or well-wishers acutely. Some will present as referrals from other facilities.

Often presentation is delayed as some communities prefer to have musculoskeletal injuries managed by traditional bone setters (TBS) and modern health care is accessed only if complications arise. Complications of TBS management vary in severity ranging from mild defects with minimal functional compromise to limb loss and death. Community socio-cultural practices drive most of these decisions. Most bone setters utilize repeated manipulation and massage of the fractured bone. Some use herbal pain relievers, and others combine herbs and pharmaceutical agents [23].

Alegbeleye 2019: Fracture splint by traditional bonesetter

Upon arrival, physical exam is crucial to identify injuries. The treating practitioner should identify obvious limb deformities, open wounds, skin changes, and neuro-vascular deficits. Vascular injuries must be identified early to prevent limb loss. It's important to look out for inconsistent patterns and scars that may be suggestive of child abuse since this age group is quite vulnerable. A staged approach to hemorrhage control is utilized applying direct pressure, compression dressing, splints and tourniquets as needed.

The fractures are reduced and stabilized temporarily with splints prior to further transportation to reduce further soft tissue injury and to preserve distal vascular flow. Materials available include plaster of paris (POP) and Thomas splints for femur fractures [24]. If POP is not available carton board and cotton wool can be used.

For open fractures, these general principles apply: early antibiotic and tetanus toxoid should be administered, and the open fracture should be stabilized following debridement. Some patients will have local wound irrigation plus or minus closure in other facilities prior to presentation. We strongly advise repeating irrigation and formal debridement.

X-rays are obtained to further characterize fractures and determine definitive care. CT scans are not readily available in most local facilities and if needed require transfer to a county/tertiary hospital.

Management of fractures can be classified into non-operative and operative groups dependent of the type of fracture. Non-operative options include casting, traction, arm-sling, and RICE (Rest, ice, compression and elevation) in patients with sprains. Operative options include external fixation in the setting of open fractures. These can be used either temporarily or for definitive management.

Postgraduate training in orthopedic surgery is growing but most centers will not have an orthopedic surgeon on site. The majority of paediatric orthopedic trauma care will be offered by Medical Officers and general surgeons. Consideration on the need for patient transfer to a facility with an orthopedic surgeon for definitive care should be given. It is important to note that throughout sub-Saharan Africa, most general surgeons are trained to manage these injuries.

Vascular Injury

Penetrating vascular injuries of the torso carry a four-fold increased rate of lethality as compared to other injury patterns [25]. Military experience suggests that applying adult vascular repair tenets to extremity vascular wounds in children can result in high limb salvage rates even in austere environments and acceptable limb growth and functionality [25, 26]. Tourniquets can be improvised using cloth material and a stick or rubber tubing. Any non-permeable tubing such as a small chest tube, nasogastric tube, or feeding tube can be used for temporary shunting in damage control situations. The best option for revascularization is often a contralateral reversed saphenous vein graft with interrupted sutures and liberal use of fasciotomy due to the often-unavoidable delay in presentation.

Thermal Injuries

According to the World Health Organization (WHO), an estimated 180,000 fire-related deaths occur yearly with 95% of fatal fire-related deaths occurring in LMICs. Children are the over-whelming preponderance of burn victims, with the mean age of all burn patients around 10 years of age; the highest incidence is seen in under 5-year-olds [27]. A majority of burns occur at home, with scalds and flame burns being the most common [28, 29].

Socioeconomic and cultural factors have significant contribution to the epidemiology of burns in Sub Saharan Africa. These include overcrowding, absence of caretaker and use of kerosene lamps [28]. Deliberate burns of the feet are still seen in Nigeria, where this practice was more rampantly used in the past as “treatment” of epilepsy [30].

Even in otherwise healthy children, mortality rate with burns over 50% total body surface area (TBSA) in LMICs approaches 100%. Compassionate care rather than aggressive surgical treatment could be considered in such circumstances. The lethal TBSA at which 50% of patients die (LA50) ranges from 36 to 55% [27, 31, 32]. Malnutrition further decreases LA50 of paediatric burn patients, increasing the mortality with even smaller TBSA burns [33].

Burns less than 15–20% should be considered for aggressive early excision and grafting, which can speed up recovery and minimize cost [34]. Blood loss in larger burns is not well tolerated, so careful wound care is needed with either silver-based solutions or alternatives such as natural honey gauze [35]. Ketamine anesthesia can be useful to allow for thorough wound cleansing every few days. Z-plasty techniques can be applied for burn wound contracture release [36].

Caustic Ingestion

Caustic burn to the esophagus is now extremely rare in the developed world, but a source of lifelong complications in children of LMICs. Soap is often manufactured in the home by traditional methods utilizing alkaline solution stored in soda bottles or glass jars, which is mistaken for water by the child [37]. The presentation to health care is sometimes delayed up to 1 month and marked by drooling and inability to swallow solids or liquids [38]. A flexible or rigid endoscope can be used to evaluate the degree of injury, and a nasogastric tube is placed across the esophagus with mild-moderate injury to minimize stricture. With severe injury, gastrostomy is performed to allow for nutrition and retrograde access, but long-term patency requires multiple dilations and has a low success rate [37]. A small silastic tube (discarded VP shunt or broviac catheter) across the esophagus greatly aids recovery and facilitates wire placement for Savary dilations.

Intentional Violence

Intentional violence in children is grossly underreported, but it is estimated that 1 out of every 4 living children worldwide has been physically abused. Approximately 53,000 children are murdered every year, with the rate in LICs twice as high as that in HICs. For every 1 child who dies from physical violence, 20–40 will present for hospital treatment, many of whom will require surgical care [39]. Mandatory reporting does not exist in most LMICs, but the surgeon can be instrumental in protecting the child from further violence by advocating on his behalf to law enforcement. There may be other local authority structures in place who should be involved to protect injured children. Local chiefs, or spiritual practitioners may have the influence or authority to intervene. One should be sensitive to the local standards of privacy and parental autonomy but not hesitate to challenge those standards if children are harmed.

Sexual violence is a particularly egregious form of childhood trauma, with estimates of roughly 10% of adolescent girls and 3–5% of boys reporting forced sexual acts at some point in their life. Occasionally, these assaults lead to severe physical injuries. Anogenital injuries should be approached first with careful examination under sedation, and then repaired primarily or in a manner consistent with a posterior sagittal anorectoplasty (PSARP) to provide the best sphincter preservation [40]. Protective colostomy may be necessary.

The risk factors for violent injuries are complex, and include cultural, societal, community, family, and personal components. Programs such as the Violence Against Children Surveys (VACS) are attempting to gain a better understanding of the degree of impact that violence has on the world's children to guide prevention measures. Because the unique factors of abuse differ between countries and cultures, no universal policy change will bring about an end to child abuse, but a global focus on the prevention of violence against children is needed to spur individual governments to act on the child's behalf.

Conclusion

Despite increased awareness and global advocacy, injuries represent the greatest threat to the health of children in low-and-middle-income countries. Paediatric surgeons must be actively engaged in the development of culturally and socially sensitive injury prevention campaigns and paediatric trauma care systems. Our experience in civilian and military trauma care can be leveraged to build capacity for excellent care for injured children in settings of limited resource. The strength of our voice is primarily born in the gentle healing touch that we can offer when face to face with a wounded child. Opportunities abound for surgeons from the developed world to meet those children at the point of injury and provide care in a way that brings hope and builds a platform for effecting a real change to the safety of our global society's youngest members.

Take Home Points

- Childhood trauma is the leading cause of death and disability in the developing world.
- ATLS principles can successfully be followed in a setting with limited resources, using creative solutions with multipurpose equipment.
- Ethical and culturally sensitive consideration of the family impact of severe trauma in children is paramount to care in resource constrained settings.

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Chapter 7
Initial Trauma Resuscitation

Torbjorg Holtestaul and John Horton

Abstract The initial management of the pediatric trauma patient should follow Advanced Trauma Life Support (ATLS®) guidelines, prioritizing airway, breathing, and circulation. While the general management principles of the pediatric airway are similar to those of adults, anatomic differences in children can make treatment in the emergency setting more difficult. In small children, the preferred emergent surgical airway is a needle cricothyroidotomy. Most emergent chest trauma in children can be addressed with a tube thoracostomy. A clinical diagnosis of hemothorax or pneumothorax is enough to proceed with chest tube placement, and a chest x-ray is not mandatory prior to placement. Tachycardia and poor perfusion are often the first signs of shock and should not be overlooked. Resuscitation of the pediatric trauma patient should begin with an immediate infusion of 20 mL/kg of crystalloid followed by balanced blood product administration if necessary. Initial imaging in pediatric trauma differs significantly from adults, and a selective approach should be utilized to minimize radiation exposure.

Keywords Pediatric trauma resuscitation · Initial trauma survey · Balanced product resuscitation

Key Concepts/Clinical Pearls (Learning Objectives)

- The initial management of the pediatric trauma patient should follow Advanced Trauma Life Support (ATLS®) guidelines, prioritizing airway, breathing, and circulation.
- Most emergent chest trauma in children can be addressed with a tube thoracostomy.
- Early recognition of circulatory compromise in children is crucial; the first signs include tachycardia, poor skin perfusion, and diminished capillary refill.

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- Resuscitation of the pediatric trauma patient should begin with an immediate infusion of 20 mL/kg of crystalloid followed by balanced blood product administration if necessary.
- Initial imaging in pediatric trauma differs significantly from adults, and a selective approach should be utilized to minimize radiation exposure.

Initial Management of Trauma Patient

The initial management of the pediatric trauma patient should follow ATLS guidelines, prioritizing airway, breathing, and circulation. The details of this management are the focus of the discussion below. We have summarized the basic principles in this section to serve as a rapid reference.

Airway

- Indications for intubation:
- Respiratory distress
  - Impaired mental status (GCS ≤ 8)
  - Actual, impending, or potential airway obstruction
- In hemodynamically unstable children, consider transfer to the operating room prior to induction of anesthesia.
- In small children requiring surgical airway, needle cricothyroidotomy is the preferred approach and is a temporizing measure while resources are gathered for a definitive tracheostomy.

Breathing

- Clinically relevant hemothorax or pneumothorax should be addressed with tube thoracostomy
- The compliant pediatric chest wall predisposes children to underlying pulmonary contusion, often without rib fractures

Circulation

- Early recognition of circulatory compromise in children is crucial:
  - Early signs—Tachycardia, poor skin perfusion, diminished capillary refill
  - Late signs—SBP < 70 + 2x age, mental status changes
- Control external hemorrhage
- Weight-based resuscitation (consider the use of length-based resuscitation tape)
- Access with two large-bore IVs or IO after two failed attempts at IV access
- Limit crystalloid administration in bleeding patients

  – A single bolus of 20 mL/kg, then switch to blood if necessary.

- Adhere to balanced transfusion ratio, aiming for 1:1:1 Fresh Frozen Plasma (FFP): packed Red Blood Cells (pRBC): Platelets (PLT).
- Initiate massive transfusion protocol if >40 mL/kg product anticipated.
- If initiating massive transfusion, administer Tranexamic acid (TXA) (1 g or 15 mg/kg dosing within 3 h of injury followed by continuous IV infusion at 2 mg/kg/h for >8 h or until bleeding stops).

Initial Radiographic/Ancillary Studies

Initial trauma labs should be drawn as soon as possible once the child arrives. The following studies are recommended for all children meeting criteria for a trauma activation:

- Complete blood count (CBC)
- Basic metabolic panel (BMP)
- Arterial blood gas (ABG)
- Urinalysis (UA)
- Prothrombin time (PT)/International normalized ratio (INR)
- Liver enzymes (AST/ALT)
- Amylase
- Type and screen (T&S)

Indications for initial imaging studies in pediatric trauma differ significantly from adults. While "pan-scanning" has demonstrated mortality benefits in the adult literature, this practice is not applicable to pediatric trauma. Radiation exposure from imaging should be minimized in children as there is evidence linking childhood radiation to adult cancers. That said, appropriate imaging should be obtained in a timely manner, and clinical prediction rules to help determine which children should receive cross-sectional imaging is an ongoing area of research. Initial imaging studies by anatomic regions are discussed below:

Head

The Pediatric Emergency Care Applied Research Network (PECARN) developed a clinical prediction rule (CPR) to identify children at very low risk of clinically important traumatic brain injury in order to minimize unnecessary computed tomography (CT) studies. The resulting CPR, which identifies children that can forgo a CT head, separates children into two age groups: for children younger than 2 years, patients at low risk include those with a normal mental status, no scalp hematoma (except frontal), no loss of consciousness (LOC) or LOC for less than 5 seconds, non-severe injury mechanism, no palpable skull fracture, and acting normally according to parents. For children 2 years and older, patients at low risk have a normal mental status, no loss of consciousness, no vomiting, a non-severe injury mechanism, no signs of basilar skull fracture, and no severe headache [1].

Cervical Spine

In children, the primary imaging modality for evaluation of the cervical spine is plain radiographs. The Pediatric Trauma Society (PTS) provides recommendations for appropriate imaging of the cervical spine based on the NEXUS criteria [2]. If the patient has midline tenderness, altered level of alertness, intoxication, focal neurologic deficits, or a distracting injury, the clinician should place or maintain a c-collar and obtain plain films (AP and lateral). In cooperative children over 8 years old, an additional odontoid view should be obtained. If a patient does not meet any of the NEXUS criteria, range of motion should be assessed, and if the child has pain, plain films should be obtained as above. If films cannot be obtained or if there is a concerning clinical mechanism, a CT c-spine should be obtained [2]. If the child has an abnormal neurologic exam, magnetic resonance imaging (MRI) should be considered, particularly if there is a concern for SCIWORA (spinal cord injury without radiographic abnormality).

Chest

A chest x-ray should be obtained in all patients undergoing evaluation for trauma. The breadth of its diagnostic ability cannot be overstated: it evaluates bony injuries of the chest, spine, proximal humerus, scapula and ribs, intrapleural problems such as pneumothorax, pulmonary contusion, hemothorax, and aspiration, diaphragm injury, intra-abdominal free air, and tube and line positioning. It also allows for evaluation of occult or old injury, which is important as child physical abuse should always be considered on the differential diagnosis. Radiation exposure from cross-sectional imaging should be minimized in the evaluation of blunt thoracic injury. CT of the chest can evaluate for great vessel injury and increase the diagnosis of contusion, atelectasis, pneumothorax, and fractures in comparison to chest x-ray; however, the additional information obtained does not usually change management [3, 4].

Abdomen and Pelvis

The Pediatric Surgery Research Collaborative (PedSRC) created a clinical prediction rule (CPR) to identify children at low enough risk for intra-abdominal injury to avoid an abdominal CT scan. The five variables of the CPR include abdominal pain, abdominal wall trauma, tenderness or distention on physical exam, abnormal chest x-ray, abnormal pancreatic enzymes, and AST > 200 U/L. [5] This CPR was externally validated using the Pediatric Emergency Care Applied Research Network dataset with a negative predictive value of 99.3% and a sensitivity of 97.5% for intra-abdominal injury [6].

While the focused assessment with sonography for trauma (FAST) is an integral portion of the trauma exam in adults, it has a low sensitivity for intra-abdominal injury in children and misses intra-abdominal injury requiring intervention [7].

Blunt Cerebrovascular Injury (BCVI) Screening

BCVI in children is relatively rare but has significant morbidity and mortality [8]. BCVI screening in children is an area of active research, as utilization of the adult screening criteria can result in over-exposure to radiation. The McGovern-Utah screening score was developed to help identify children at risk for BCVI who should undergo CT angiography and includes GCS <8 (1 point), focal neurological deficit (2 points), carotid canal fracture (2 points), mechanism of injury (motor vehicle accident or auto-pedestrian accident, excluding bicycle accidents and falls) (2 points), petrous temporal bone fracture (3 points), and cerebral infarction on CT (3 points). A child with a score ≥ 3 points has a high risk for BCVI and should undergo CT angiography [9, 10]. In a review of the pediatric TQIP database, skull base fracture had the strongest association with BCVI, and additional significant associations included cervical spine and mandible fractures [11].

Airway

While the general management principles of the pediatric airway are similar to those of adults, anatomic differences in children can make treatment in the emergency setting more difficult. Similar to the adult population, a child's airway can be quickly evaluated based on phonation; if the child is speaking or crying, one can be reasonably reassured that the airway is intact.

Indications for intubation are the same as for adult patients: respiratory distress, impaired mental status (GCS $\leq$ 8), and actual, impending or potential airway obstruction [12]. If airway patency is in question, adjuncts such as a jaw thrust, nasopharyngeal or oropharyngeal airways can be helpful as temporizing measures. Children have several anatomic differences that can complicate intubation. The disproportionately large occiput results in flexion of the cervical spine in the supine position, which causes anterior buckling of the pharynx (a shoulder roll can help maintain a more neutral position). The soft tissues of the oropharynx, such as the tongue and tonsils, are also proportionally larger, which can make visualization difficult. The larynx and vocal cords lie more anterior in children, and cricoid pressure during direct laryngoscopy can help bring the vocal cords into view. A large, floppy epiglottis can sometimes be more easily retracted with a straight Miller blade rather than a curved Macintosh blade. Finally, one should avoid inadvertently placing the endotracheal tube in the right mainstem bronchus due to the short trachea.

Importantly, if the airway is patent in a hemodynamically unstable child, one should consider transfer to the operating room prior to induction of anesthesia. These children are prone to cardiovascular collapse with loss of sympathetic tone, particularly in the setting of penetrating trauma. The authors recommend the use of the ATLS algorithm for rapid sequence intubation [13]. A general overview includes preoxygenation, atropine for infants followed by an induction agent (e.g., etomidate, midazolam or ketamine) and a paralytic (e.g. rocuronium, vecuronium or succinylcholine). Pediatric patients can have a more pronounced vagal response leading to bradycardia with laryngeal stimulation.

An emergent surgical airway can be a high intensity situation for a patient of any age, and particularly so in children. Compared to adults, cricothyroidotomy is very difficult to perform on small children (e.g., children <12-years-old) and is not recommended. A reasonable alternative to a surgical airway is a needle cricothyroidotomy, which is comprised of a large bore IV placed through the cricothyroid membrane and attached to high flow oxygen (delivered at an interval of 1 s on, 3 s off). This method inherently cannot provide adequate ventilation, and as such is a temporizing measure while the appropriate resources for a definitive tracheostomy are coordinated. In children ≥12-years-old with a palpable cricothyroid membrane, a cricothyroidotomy is a reasonable approach.

Breathing

When evaluating a child's respiratory status, one should inspect the chest wall for abrasions, contusions, lacerations, or other obvious external injuries. Asymmetrical chest wall motion or paradoxical movement is concerning, as is tenderness, instability, or crepitance on palpation. The trachea should be evaluated for deviation, and the lung fields should be auscultated looking for bilateral breath sounds.

The pediatric chest wall is more pliable and compliant than that of adults, leaving children more prone to pulmonary contusions with blunt trauma in the absence of rib fractures. The relative mobility of the mediastinum allows for the rapid development of tension pneumothorax and predisposes children to tracheobronchial injuries.

Most emergent chest trauma in children can be addressed with a tube thoracostomy. A clinical diagnosis of hemo- or pneumothorax is enough to proceed with chest tube placement, and a chest x-ray is not mandatory prior to placement. As discussed above, a plain radiograph of the chest is often sufficient for evaluation of chest trauma as CT does not often contribute to diagnoses requiring additional intervention.

Circulation

Pathophysiology

The recognition of shock in children depends on an understanding of age-dependent physiologic variation, such as in estimated blood volume and vital signs. A child's weight is a critical data point for evaluation and resuscitation, and it can be determined based on caregiver history, a length-based resuscitation tape, or an estimate using the formula (2 × age) + 10 kg. The estimated blood volume for an infant is 80 mL/kg, for a child 1–3 years old is 75 mL/kg, and for a child >3 years old is 70 mL/kg. Pediatric patients have a fixed stroke volume, and their cardiac output is maintained by increasing their heart rate. Thus, tachycardia and poor perfusion are often the first signs of shock and should not be overlooked. Hypotension can portend advanced shock and subsequent rapid decompensation, as children can compensate for up to a 30% loss in their circulatory volume with a normal blood pressure. The mean normal systolic blood pressure in children is (90 + (2 × age)) mmHg and the lower limit of normal is (70 + (2 × age)) mmHg. Other signs of circulatory compromise include progressive weakening of peripheral pulses, narrowing of pulse pressure to <20 mmHg, skin mottling, cool extremities compared to the torso, confusion or other subtle mental status changes, and a decreased level of consciousness with a dulled response to a painful stimulus [12, 13]. A quiet child who doesn't respond appropriately to IV placement or uncomfortable parts of the exam should heighten clinical concern.

In addition to hemodynamic compromise, coagulopathy is an important consideration in the evaluation and treatment of circulation. Coagulopathy is traditionally defined as an INR > 1.5, although viscoelastic monitoring has increased the depth of understanding of an individual patient's coagulopathic components. Acute traumatic coagulopathy (ATC) is directly related to injury severity and is associated with increased mortality [14]. Coagulopathy and acidosis can predict the amount of packed red blood cells (pRBC) transfused in pediatric trauma patients [15].

Access

As soon as a child arrives at the trauma bay, two large-bore intravenous (IV) catheters should be inserted. This can be difficult in pediatric patients, particularly if they have a diminished circulatory volume, and an intraosseous (IO) catheter should be inserted after two failed attempts at IV access [13]. IO catheters can be inserted in the proximal or distal tibia, distal femur, or proximal humerus. Percutaneous femoral vein access can be attempted but is often challenging. Jugular and subclavian lines should be avoided as initial vascular access in pediatric trauma due to the risk of vascular injury or pneumothorax. Another option for access is a venous cutdown on the saphenous vein, but this is often time consuming.

Resuscitation

Resuscitation of the pediatric trauma patient should begin with an immediate infusion of 20 mL/kg of crystalloid. In accordance with recommendations by the American Pediatric Surgical Association (APSA), the authors recommend a crystalloid-sparing, early transfusion approach in which resuscitation following the first bolus of crystalloid is comprised of blood products [12]. More than one bolus of crystalloid has been demonstrated in a prospective multicenter study to be associated with poor outcomes, such as longer ventilation and hospitalization [16]. Another retrospective study at a level 1 trauma center demonstrated poor outcomes with >60 mL/kg/day of crystalloid in the first 48 h post-injury [17].

The definition of massive transfusion in children is the subject of ongoing research, but a general consensus is 40 mL/kg of blood product. In a review of severely injured children in the Trauma Quality Improvement Program (TQIP) database from 2014 to 2015, a transfusion volume of ~40 mL/kg (37 mL/kg) predicted the need for hemorrhage control procedures and early mortality [18]. Similarly, a retrospective review of the Department of Defense Trauma Registry (DODTR) defined massive transfusion in military pediatric patients as 40 mL/kg in the first 24 h [19]. Massive transfusion is used rarely in pediatric centers, and there is significant variability in massive transfusion protocols (MTPs) across pediatric hospitals, to include activation criteria and products administered. In a survey of MTPs in 46 hospitals in the US and Canada, physician discretion was the most common activation criteria (89%) [20].

A balanced product resuscitation strategy is recommended including a 1:1:1 ratio of FFP, pRBCs, and PLT. Multiple studies have evaluated various ratios of product administration and demonstrated improved survival with balanced resuscitation among both civilian and military pediatric trauma patients [21–24]. Whole blood administration, which contains plasma, red blood cells, and platelets, is not common due to logistical challenges with availability and a sufficient donor pool and a theoretic risk of transfusion reactions and hemolysis. The safety of whole blood administration in children was demonstrated in a small prospective study at a single Level 1 Pediatric Trauma Center with no evidence of hemolysis or transfusion reactions [25], although additional studies with larger cohorts are needed to evaluate outcomes.

The authors recommend tranexamic acid (TXA) administration for children undergoing massive transfusion for trauma (>40 mL/kg blood product) at a dose of 1 g or 15 mg/kg within 3 h of injury plus continuous IV infusion at 2 mg/kg/h for >8 h or until bleeding stops. Multiple retrospective reviews of both civilian and military pediatric trauma patients have demonstrated decreased mortality with administration of adult dosing TXA without an increase in thromboembolic complications or cardiovascular events [26, 27]. The Hospital for Sick Children Massive Hemorrhage protocol recommends TXA administration based on hypotension (<80 mmHg in children <5 years old and <90 mmHg in children >5 years old), poor blood pressure response to crystalloid (20–40 mL/kg), and obvious significant bleeding [28].

Adjunct Treatments

Resuscitative thoracotomy is controversial in pediatric patients as outcomes are prohibitively poor. In a retrospective review of the 2013–2016 National Trauma Data Bank of patients 16 years or younger undergoing emergency department thoracotomy (EDT) within 30 min of arrival, mortality after thoracotomy was 90%. There were no survivors among patients who arrived with no signs of life [29]. In another review of published literature from 1980 to 2017 on EDT in pediatric patients, mortality for penetrating trauma was comparable to adults for penetrating thoracic trauma; however, no patient younger than 15 years old survived after EDT for blunt trauma [30]. Adolescents have better survival rates than younger children (5% for patients 16–18 years old vs. 0% for children ≤15 years old), which may reflect a higher incidence of penetrating trauma in adolescents versus blunt and multisystem trauma in younger children [31].

Resuscitative endovascular balloon occlusion of the aorta (REBOA) is a minimally invasive hemorrhage control procedure used primarily in adults,which may provide an alternative to resuscitative thoracotomy. There is limited available evidence for the use of REBOA in children, but as in EDT, adolescents likely have a similar survival rate to adults. In a review of the American Association for the

Surgery of Trauma (AAST) AORTA (Aortic Occlusion for Resuscitation in Trauma and Acute care surgery) registry from 2013–2020, 11 adolescent patients were identified with a median age of 17 who underwent REBOA with a survival rate of 30% [32]. In a separate review of 7 adolescent patients who underwent REBOA from 2013–2017 at two urban tertiary care centers, in-hospital mortality was 57% [33].

Predictive Scoring for Transfusion

One active area of research is predictive scoring systems to determine which children will require transfusion. The ABC (Assessment of Blood Consumption) score is a commonly accepted adult non-laboratory dependent scoring system that predicts the need for transfusion [34]. The system is based on penetrating mechanism, positive FAST exam, SBP <90 mmHg, and heart rate >120 bpm, and a score of 2 or greater are 75% sensitive and 85% specific for predicting massive transfusion. Unfortunately, this system does not work in children due to the use of adult vital sign cutoffs [35].

To address this deficiency, Acker et al. investigated the SIPA (Shock Index (HR/SBP) Pediatric Adjusted) to identify children with severe intra-abdominal injuries requiring transfusion, and those at highest risk of death [36]. SIPA is defined by maximum normal heart rate and minimal normal blood pressure by age (shock index (SI) >1.22 (age 4–6), >1.0 (age 7–12) and >0.9 (age 13–16)). In one review, elevated pre-hospital/initial emergency department SIPA values were associated with blood transfusion in pediatric patients with blunt liver or spleen injuries [37]. In the military setting, SIPA was independently associated with the need for blood transfusion and emergent surgery among inured children in warzones [38].

The ABC-S score combines the ABC and SIPA scores by replacing SBP and HR with the SIPA value in children. In a retrospective review of 50 children, an ABC-S score ≥1 was 65% sensitive and 84% specific for predicting the need for massive transfusion. The authors of this review did note that further research is needed to develop a score that accounts for the rarity of penetrating trauma and positive FAST exams in children [35]. Further improvements were made in the scoring system with the development of the ABC-D score, which adds elevated serum lactate and base deficit to the ABC-S score. A review of 211 children at a single level 1 trauma registry demonstrated that an ABC-D score ≥3 was 77.4% sensitive and 78.8% specific for predicting the need for massive transfusion [39].

Viscoelastic Monitoring

Conventional coagulation studies, such as PT and PTT, are limited in their evaluation of coagulopathic processes such as the involvement of endothelium, generation of thrombin, clot formation and stabilization, hypercoagulability, and fibrinolysis.

Thromboelastography addresses these limitations, but routine use is currently limited to a few high-volume centers. The most commonly used systems are Thromboelastography (TEG®, Haemonetics), in which a cup containing a patient's blood spins around a stationary pin, and Rotational Thromboelastometry (ROTEM®, Haemoview Diagnostics), in which pin spins around a stationary cup. Both systems are used infrequently and generally in more severely injured patients. In a survey of Pediatric Trauma Society members, viscoelastic monitoring was available to 63% of providers and was only employed by 31% in pediatric trauma patients [40]. A retrospective review of 155 injured children from a single Level 1 Pediatric Trauma Center evaluated outcomes among patients that underwent no coagulation assessment versus conventional coagulation testing versus conventional testing and rapid TEG (rTEG). rTEG was only performed in 23 patients, and these were more severely injured, received more blood products and crystalloid, and had a longer duration of mechanical ventilation and ICU length of stay (although it was not associated with mortality) [41]. In a separate review of severely injured patients <14 years old, rTEG predicted pRBC and FFP transfusion with 6 h in addition to mortality [42].

Disability/Exposure

The final portion of the primary survey is disability and exposure. It is important to determine the child's GCS and perform a pupillary exam prior to induction of anesthesia, and it is helpful to have caregivers present for a comparison to the child's baseline mental status. A secondary injury should be avoided, as in adults, by preventing hypoxia, hypotension, seizures, and hypothermia. All clothing should be removed in order to examine the entire patient. This aspect can be challenging in older or more modest patients and requires a high degree of discretion, explanation, and compassion. The presence of a family member or trusted adult can help facilitate adequate exposure. Active warming should take place in the trauma bay, as hypothermia is associated with increased mortality in pediatric patients. This can be accomplished with warm blankets, forced-air warming devices, and warming of necessary resuscitative fluids.

Conclusions and Take Home Points

- The initial trauma management of pediatric patients should follow ATLS guidelines, prioritizing airway, breathing, and circulation.
- As pediatric patients have different cardiovascular physiology than adults, their response to trauma is different. As such, our evaluation and treatment of children in the traumatic setting is unique and tailored to a child's weight and age.

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Chapter 8
Airway Management in Pediatric Trauma

Robert O'Donnell and Matthew Haldeman

Abstract Establishing and maintaining a patent airway is necessary to prevent hypoxemia, anoxic brain injury with its subsequent comorbidities, and ultimately death. Accordingly, physicians and other healthcare providers who care for traumatically injured children must be skilled in mask ventilation, the use of airway adjuncts, endotracheal intubation, and supraglottic and surgical airway techniques.

Trauma patients, in particular, may have altered mental status, bleeding, and altered anatomy from airway injury that can threaten airway patency. A Glasgow Coma Scale (GCS) less than or equal to 8, for instance, is associated with the loss of protective airway reflexes, hypoventilation, and apnea. Bleeding in the airway can result in aspiration and obstruct ventilation.

The following section will focus on the techniques and practices to ensure adequate oxygenation and ventilation in the setting of airway compromise.

Keywords Trauma · Airway · Pediatric · Surgical airway · Airway adjuncts

Key Points/Clinical Pearls

- Nasal instrumentation is contraindicated in significant head trauma, particularly if a fracture of the cribriform plate is suspected.
- In infants and small children, the tongue is proportionally larger with respect to the mouth, which can worsen obstruction and contribute to difficult laryngoscopy.
- Placement of padding or roll under child's torso will prevent flexion of the cervical spine and loss of airway due to disproportionate size of child's cranium
- Prior to initiating advanced airway management ensure appropriate supplies are at hand using the SOAP IM pneumonic.
- ETT size can be approximated by the size of a child's nares or the size of the pinky finger.

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- A shoulder roll beneath the upper thorax returns the head to neutral and aligns pharyngeal, and laryngeal axes for laryngoscopy.
- Midazolam, fentanyl, and etomidate are very hemodynamically stable drugs, making them helpful adjuncts in trauma-related shock.

Introduction

Several key differences exist between the airway in adults and children. Healthcare providers who provide care to the pediatric patient must be aware of these differences and how they affect management of the airway. A thorough understanding of the airway anatomy is therefore paramount in the management of traumatically injured children.

Upper Airway Anatomy

The upper airway begins at the oral and nasal cavities which meet to form a common pharynx.

The nasal cavity has two nasal passages divided by a central septum. The lateral walls of each passage have three turbinates that warm and humidify air. Nasal mucosa is highly vascularized so care should be taken to avoid injury during instrumentation. Inadvertent injury to the nasal mucosa can lead to significant hemorrhage increasing the complexity of securing an adequate airway. The nasopharynx is bordered superiorly by the cribriform plate, separating it from the intracranial cavity and inferiorly by the soft palate, separating it from the oropharynx. Nasal instrumentation is contraindicated in significant head trauma, particularly if a fracture of the cribriform plate is suspected.

The oral cavity is bordered by the tongue inferiorly and the hard and soft palates superiorly. Most airway instrumentation techniques utilize the oral cavity. A decreased level of consciousness can cause relaxation of the genioglossus muscle and can worsen airway obstruction. In infants and small children, the tongue is proportionally larger with respect to the mouth, which can worsen obstruction and contribute to difficult laryngoscopy.

The pharynx is comprised of the nasopharynx, the oropharynx. It connects the oral and nasal cavities to the trachea and esophagus. The epiglottis separates the oropharynx from the hypopharynx.

The larynx separates the pharynx from the trachea. It protects the trachea from aspiration of pharyngeal contents during swallowing and allows for vocalization of sound. The infant larynx is more cephalad and found at the C3-C4 level, as opposed to the lower C4-C5 level in adults. The larynx contains the vocal cords along with the cartilages, ligaments, and muscles that move them. These movements change the shape of opening between the vocal cords otherwise known as the glottic aperture or glottis.

The cartilages include the thyroid, cricoid, paired arytenoid, and epiglottis. The vocal cords divide the vestibule superiorly from the subglottis inferiorly. While the narrowest part of the adult airway is the vocal cords, the narrowest part of the pediatric airway is the cricoid ring. The cricoid ring is the only circumferential cartilaginous ring in the airway. Infants and small children have a less cartilaginous epiglottis which makes it more prone to fall towards the glottis and impair view during direct laryngoscopy [1].

The trachea consists of incomplete C-shaped cartilaginous rings extending from the cricoid ring down to the carina where it divides into a left and right main bronchus. The posterior wall of the trachea that runs along the esophagus is formed by the trachealis muscle. The right mainstem bronchus takes off from the carina at a more vertical angle than the left mainstem bronchus making the right mainstem the more likely location for foreign body aspiration or intubation from an endotracheal tube placed too deeply [2].

Airway Assessment

During initial airway assessment in a pediatric trauma patient, talking or crying confirms airway patency. Children as young as 2 can answer simple questions and follow simple commands to confirm airway patency, sufficient ventilation, and adequate cerebral perfusion.

Altered consciousness or physical signs of pending airway compromise like facial trauma, bleeding, burns, or evidence of inhalation injury may require tracheal intubation. A properly placed endotracheal tube can provide definitive protection against aspiration, and positive pressure ventilation for adequate oxygenation and prevention of hypercarbia (particularly if closed head injury is suspected). A definitive airway is a ventilating tube placed in the trachea with the cuff inflated below the level of the vocal cords.

The Mallampati airway score (Fig. 8.1) is comparatively less predictive of airway difficulty in children and often limited by poor patient cooperation. Midface or mandibular hypoplasia, often associated with rare congenital diseases, may confer difficulty in both securing a definitive airway and with mask ventilation. The 'LEMON' pneumonic is an airway assessment method commonly utilized in trauma assessments [3].

- L—Look externally (facial trauma, large incisors, facial hair, large tongue)
- E—Evaluate the 3-3-2 rule
  - Incisor distance—3 fingerbreadths
  - Hyoid-Mental distance—3 fingerbreadths
  - Thyroid to mouth distance—2 fingerbreadths
- M—Mallampati Score greater than or equal to 3
- O—Obstruction
- N—Neck mobility (limited neck mobility such as with a c-collar)

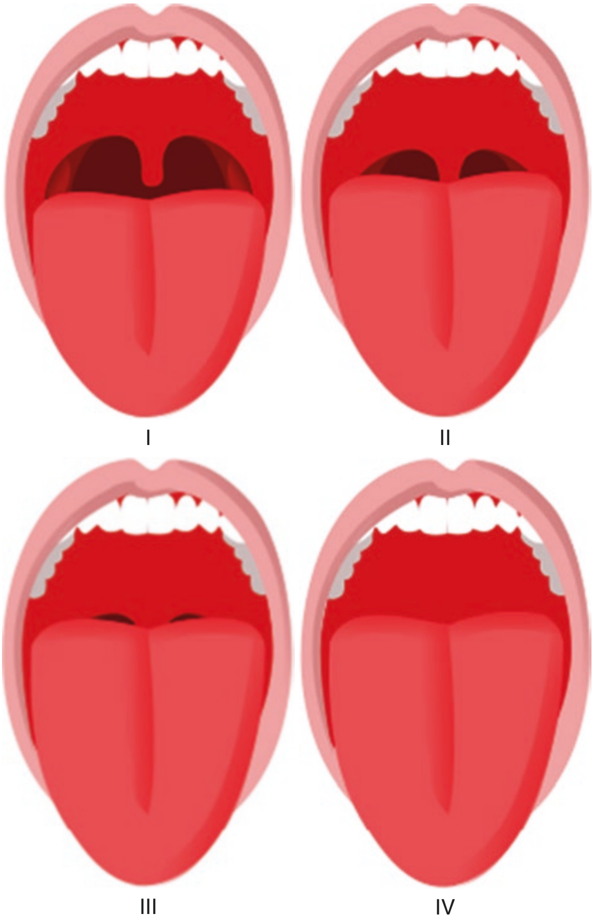

Fig. 8.1 Mallampati Score determination. (Used with permission from Jmarchn under Creative Commons Attribution-Share Alike 3.0. No changes to the images were made)

Airway Management

Initial airway management must focus on ventilation and oxygenation. Ensuring adequate ventilation is most important. In the setting of adequate ventilation with a bag-valve-mask, placing an advanced airway is not an emergency. Proper facemask ventilation skills are critical to the prevention of severe morbidity and mortality related to pediatric airway compromise.

Prior to initiating advanced airway management, ensure the presence of adequate suction, fully connected and flowing, a source of high flow oxygen connected to a bag-valve-mask or other appropriate positive pressure delivery system, oral airways, nasal airways when clinically appropriate, a laryngoscope with light functioning and appropriate blade attached, backup blades available, and a supraglottic airway also available, appropriate medication for intubation, patent intravenous (IV) access and delivery method with flush, and appropriate full clinical patient monitoring devices, to include EKG, pulse oximetry, non-invasive blood pressure monitoring, and a $EtCO_2$ confirmation device or preferably continuous waveform capnography. A helpful pre-procedural checklist pneumonic is SOAP IM.

S —Suction
O—Oxygen
A—Airway
P—Pharmaceuticals

I—Intravenous access
M—Monitors

For a spontaneously breathing patient, head tilt-chin lift maneuver (Fig. 8.2) may alleviate partial or complete airway obstruction. Decreased levels of consciousness result in decreased tone of pharyngeal musculature. A similar physiologic condition exists in snoring or obstructive sleep apnea during sleep. A head tilt-chin lift maneuver serves to tighten the pharyngeal tissue and improve airway patency.

If cervical spine injury is suspected, a jaw-thrust maneuver (Fig. 8.3) with cervical stabilization may alleviate obstruction while reducing the risk of neurologic injury.

Blood, emesis, or other airway debris should be carefully suctioned. If suction is unavailable, the patient can be turned laterally with manual cervical stabilization to allow for gravity to utilize gravity. Supplemental oxygen should also be administered, typically at a high flow rate, via simple face mask or nonrebreather mask in trauma.

Fig. 8.2 Head Tilt—Chin Lift maneuver for airway assistance

Fig. 8.3 Jaw thrust maneuver

Pediatric patients who cannot ventilate with simple airway maneuvers will require skilled administration of positive pressure ventilation. Clear plastic face-masks come in five standard sizes for premature infants through adults. A proper seal requires centering it over the bridge of the nose, sealing it lateral to the nasolabial folds, and sealing it between the lower lips and chin inferiorly. Gentle pressure is used to seal the mask against the face using either the "C-E" hand position with one or two hands or using both palms against the face mask with fingers behind the angle of the jaw. While uncomfortable for the rescuer, a proper seal involves opposing forces of pressing the mask evenly against the face while gently pulling the angle of the jaw upward. A jaw thrust or head-tilt chin-lift can be added if necessary. The fingers supporting the mandible must not depress the submental soft tissues in small children; this can obstruct the airway by displacing the tongue against the palate. Fingers should remain on the mandible only, even if only one finger will fit appropriately to apply the upward force toward the mask [3] (Fig. 8.4).

In an obtunded patient with no gag reflex, a rigid oropharyngeal airway (OPA) can be placed to relieve upper airway obstruction. OPA size is roughly equal to the distance from a patient's lateral lip edge to the angle of the mandible. A small OPA can obstruct the airway by displacing the tongue posteriorly, and a large oral airway can contact the larynx and cause laryngospasm. Placing the OPA with a tongue depressor rather than a rotational technique can help avoid tongue displacement or oropharyngeal trauma. A properly applied OPA provides structure to the upper airway and a channel for ventilation and suctioning.

In patients with a gag reflex, a nasopharyngeal airway (NPA) may be considered, however, an NPA is absolutely contraindicated in patients with signs of basilar skull fractures, facial trauma, and disruption of the midface, nasopharynx, or cribriform plate. The nasal airway may be sized by measuring from the nares to the angle of the mandible. As with the OPA, an undersized length NPA may not alleviate airway obstruction, and an oversized length NPA may contact and stimulate the larynx and cause laryngospasm. The NPA may be lubricated before insertion. The rescuer should not forcefully place an NPA past resistance because trauma to the nasal turbinate can lead to significant bleeding [4].

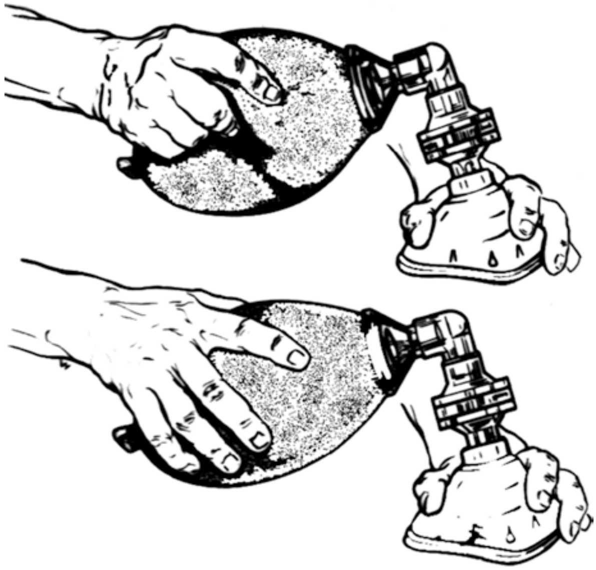

Fig. 8.4 Proper technique for Bag Valve Mask Airway management

A definitive airway or endotracheal tube is necessary for controlled positive pressure ventilation and oxygenation, and for protection against aspiration and insufflation of the stomach. Oral cuffed endotracheal intubation is the usual method of securing the pediatric airway; tubes range from sizes for neonates up to adults. While some situations in pediatric airway management call for an uncuffed endotracheal tube, cuffed endotracheal tubes are more appropriate for dynamic environments, like trauma. ETT size can be approximated by the size of a child's nares or the size of the pinky finger. Alternatively, the equation age divided by 4, plus 4 gives the approximate size for an uncuffed ETT; subtracting 0.5 gives the size of a cuffed tube. Weight varies at a given age making it a less reliable marker for ETT sizing; glottic structures tend to remain constant at a given age.

Endotracheal tube placement first requires proper head positioning of the head with respect to the body and the rescuer. Manual in-line stabilization maneuvers should be considered when there is a known or suspected neck injury. The infant head is relatively larger than the body, and when on a flat surface, the head will flex forward. A shoulder roll beneath the upper thorax returns the head to neutral and aligns pharyngeal, and laryngeal axes for laryngoscopy. The pediatric epiglottis is soft, has less cartilage and is omega-shaped in contrast to the more U-shaped, stiff epiglottis in adults. The straight Miller laryngoscope blade is more appropriate in infants and young children to lift the epiglottis out of view (Fig. 8.5). A curved laryngoscope blade placed in the vallecula can indirectly lift the epiglottis of older children and adults. A rescuer standing at the head of a supine patient should insert the laryngoscope into the mouth from right to left. Sweeping the tongue to the left allows for ETT placement along the right side of the mouth. In infants and young children, the relatively anterior airway, large tongue, and small oropharynx make

Fig. 8.5 Laryngoscope handles with an assortment of Miller blades. (Used with permission under the Creative Commons Attribution-Share Alike 3.0 Unported license. No changes were made)

direct laryngoscopy significantly more challenging than in adults. Video-assisted laryngoscopy can improve the view, decrease the number of attempts, decrease the time to intubation and ventilation. In trauma, when minimal cervical spine motion is indicated, video laryngoscopy can decrease the need for neck extension [5].

In patients that are awake or alert, endotracheal intubation is typically facilitated by sedation and neuromuscular blockade. Aside from patient comfort, sedation and analgesia provide can blunt the physiologic response to laryngoscopy and endotracheal tube placement. The non- blunted response often involves significant tachycardia, hypertension, and cough from airway stimulation. Common sedative hypnotic drugs include midazolam, propofol, ketamine, and etomidate. While propofol is fast-onset, short-acting, and easily titratable, it has a significant vasodilatory effect. Ketamine preserves airway reflexes and spontaneous ventilation and increases heart rate and blood pressure; however, ketamine is a direct myocardial depressant which can be apparent in shock. Conversely, midazolam, fentanyl, and etomidate are very hemodynamically stable drugs, making them helpful adjuncts in trauma-related shock. Etomidate suppresses adrenocortical function for 4–8 h after administration. Fentanyl is also a very hemodynamically stable drug, with strong anti-tussive effects, and can further prevent a hyperdynamic state in response to laryngoscopy and endotracheal intubation, while not itself contributing to hemodynamic depression in a shock state.

Neuromuscular blockers typically improve masseter muscle relaxation, laryngoscopy, and positive pressure ventilation by relaxing the diaphragm and accessory muscles. Common neuromuscular blockers include the depolarizing drug succinylcholine and the non-depolarizing drugs rocuronium, vecuronium, and cisatracurium.

Succinylcholine provides the most rapid muscle paralysis, typically within 30–60 s, but the associated muscle fasciculations cause a transient hyperkalemic response that can be dangerously exaggerated in patients with increased extra junctional nicotinic acetylcholine receptors. Succinylcholine **should be avoided** in patients more than 24 h after major burns, trauma, and major neurologic injury as well as patients who have been non-ambulatory for more than 48 h. Exaggerated hyperkalemic responses with cardiac arrest have also been reported in children with unrecognized muscular dystrophies; the FDA advises against succinylcholine use in children other than as indicated for emergency airway control [2].

Nondepolarizing neuromuscular blocking drugs (NDNMBs) commonly include rocuronium, vecuronium, and cisatracurium. All competitively inhibit postganglionic nicotinic acetylcholine receptors which blocks acetylcholine from its target on the skeletal muscle motor endplate. In infants and young children, the incidental blockade of postganglionic cardiac muscarinic receptors can result in transient tachycardia; this can be confused for physiologic stimulation. The onset of these drugs is slower than succinylcholine, but their duration, up to 1 h, is much longer. They are appropriate for maintaining paralysis or when succinylcholine is contraindicated. Rocuronium, so named as 'rapid-onset-curonium', is the most used NDNMBD; its onset is in 1–2 min and dose-dependent duration is 20–45 min. Vecuronium has an onset of 3–5 min and similar duration. A hazard of these longer acting drugs is the lack of a relatively quick return of spontaneous neuromuscular activity in the event of significant difficulty with intubation and inability to ventilate. Unfortunately, reversal of the blockade is only possible once NDNMB-drug plasma levels have decreased sufficiently by renal and hepatic elimination, or spontaneously in the case of cisatracurium, to be overcome by boosting acetylcholine levels [2].

Injectable acetylcholinesterase inhibitors such as neostigmine, administered with an anticholinergic drug such as glycopyrrolate (to avoid adverse muscarinic effects), were required to reverse NDNMBs by essentially boosting acetylcholine levels at the neuromuscular junction. The relatively high doses of NDNMBDs required for rapid onset, three to four times the ED95 in the case of rocuronium, were often irreversible for this reason. Fortunately, sugammadex, a newer chelating reversal agent for NDNMBs directly binds and inactivates rocuronium and vecuronium without hemodynamic effects. Sugammadex can transiently decrease hormonal contraceptive efficacy so females of child-bearing age should be made aware of this side-effect. Despite ongoing FDA-approval process for sugammadex in children, it is considered safe for use particularly for emergent reversal of neuromuscular blockade. Higher doses may be indicated in infants and neonates because of their greater pharmacologic volume of distribution. Cisatracurium is not an amino steroid NDNMB; it cannot be reversed with sugammadex. It is spontaneously degraded without respect to renal or hepatic function by a process called Hoffman elimination [2].

In the acute trauma patient, a rapid sequence induction (RSI) is often indicated to prevent aspiration and maintain oxygenation and ventilation. All appropriate equipment should be available using the SOAP IM pneumonic. Rapid sequence induction and intubation differs from standard induction and intubation in that the former involves no positive pressure ventilation between induction and confirmed proper endotracheal tube placement. Prior to induction, the patient should breathe 100% oxygen at high flow, to prevent rebreathing, for 3–5 min to pre-oxygenate or de-nitrogenate the lungs. Pre-oxygenation can involve assisted ventilation, but unnecessary overventilation should be avoided. Significantly decreased $PaCO_2$ causes cerebral vasoconstriction and decreased cerebral blood flow, and a patient in shock may already have compromised cerebral oxygen delivery. Pre-oxygenation is important in Infants and young children because they consume greater oxygen per unit mass (5–9 mL/kg/min) vs adults (3–4 mL/kg/min). Additionally, the functional residual capacity (FRC) or store of intrapulmonary oxygenated gas during apnea is significantly less in infants (27–36 mL/kg) vs adults (43 mL/kg). These two factors explain why children are at risk for rapid oxygen desaturation during apnea. We cannot over stress the importance of pre-oxygenation, minimizing apneic time, having proper equipment, and optimizing the conditions for ventilation and intubation [4].

When these conditions have been met, gentle manual pressure is held against the anterior cricoid ring to prevent passive esophageal regurgitation of gastric contents. Then, the induction and paralytic drugs are administered in immediate succession. A positive-pressure capable 100% FiO_2 face mask and bag are kept in place but they are not used unless necessary. Forty-five to sixty seconds after the rapid sequence induction dose of paralytic drug or after fasciculations have stopped, if succinylcholine was used, an appropriately skilled rescuer should place the ETT tube by direct or video laryngoscopy. The rescuer must observe the ETT cuff passing the vocal cords and maintain positive control of the ETT by holding it at the mouth and bracing their hand against the patient's face. At this point, remove the stylet, inflate the ETT cuff, connect the positive-pressure manual ventilation device, and provide positive ventilation. Immediately, observe for chest rise, fog in the ETT, appropriate manual pulmonary compliance, and appropriate continuous waveform capnography. Once both lung fields and the epigastrium have been auscultated to confirm ventilation of both lungs and not the stomach, the assisting skilled healthcare provider can remove cricoid pressure.

If the above criteria are not met, immediate reassessment and intervention is necessary. Mask ventilation may be necessary to avoid hypoxemia and hypercarbia. Although abandonment of the RSI technique raises the risk of aspiration, the morbidity and mortality from hypoxemia and hypercarbia is of much greater consequence. Once the airway is properly secured, manual ventilation with a positive pressure device or mechanical ventilation should continue with age and weight appropriate parameters with goal directed PaO_2 and $PaCO_2$ management. In acute shock, maintenance of high FiO_2 may be warranted. Lastly, consideration should be given to maintaining paralysis and sedation. Sedation is independent of paralysis; awareness under paralysis can be psychologically traumatizing. A bolus or infusion of midazolam and fentanyl or a Propofol infusion for less than 24 h are common for maintenance of moderate to deep sedation. Rocuronium or vecuronium can be used to maintain paralysis. Hemodynamic shock in trauma is often identified by tachycardia and hypotension; however, inadequate sedation under paralysis is likely to present with tachycardia and hypertension.

Per the Difficult Airway Algorithm, if ventilation and oxygenation fail and are refractory to both intubation and mask ventilation techniques, alternative advanced airways should be considered. These include laryngeal mask airways (LMAs), laryngeal tube airways (LTAs), needle cricothyrotomy or surgical cricothyrotomy. In children less than 2 years of age, needle and surgical cricothyrotomy are considered prohibitively difficult, even for airway experts; the probability of success under emergent conditions is low. If should be noted that LMAs and LTAs are supraglottic airways, and do not meet the definition of a definitive airway. Conversely, surgical cricothyrotomy or tracheostomy with placement of either a cuffed endotracheal tube or a cuffed tracheostomy tube are definitive airways. Other advanced techniques that may assist with endotracheal tube placement include awake or asleep fiberoptic intubation and retrograde-wire tracheal intubation. Trauma to the face, head, or neck may provide for poor fiberoptic scope views. Finally, blind nasal ETT placement techniques have been described but should be avoided in trauma patients, particularly if facial or skull fractures are suspected [6].

Laryngeal Mask Airways (LMAs) are available in several designs and sizes for the pediatric population, and some are designed for endotracheal intubation by way of the LMA. Typical LMA placement technique involves administering sedation drugs if the patient is not already in an obtunded state. Adequate placement condition can be assessed by no response to a jaw thrust maneuver. The airway can be opened with a scissoring motion of fingers between the teeth or with a tongue depressor. The LMA can be placed with the cuff inflated or deflated. Once positioned, the cuff should not be inflated to more than 50–60 cm H_2O. While positive pressure ventilation via a laryngeal mask airway may be successful, effort should be made to limit peak positive inspiratory pressures; excessive ventilatory pressures may drive air through the esophagus and into the stomach and increase the risk of emesis and aspiration of gastric contents. In small children, insufflation of the stomach can cause distension that competes with lung expansion. This can reduce the FRC and require higher peak pressures to ventilate and oxygenate. Intubating LMAs (ILMAs) are designed for blind advancement of an ETT through the LMA; however, a flexible fiberoptic bronchoscope and ETT can pass through the lumen of the LMA to confirm and assist with intubation. Laryngeal tube airways (LTAs) are similar to LMAs in that they are also placed blindly and ventilate from a supraglottic position. ILMAs and LTAs have less availability in pediatric sizes, although King LTAs are now available in neonatal sizes.

We will briefly discuss treatment options for difficult ventilation refractory to proper bag mask ventilation, LMA placement, and laryngoscopy. At this point, we assume that the rescuer has adjusted the face mask to achieve a proper seal, utilized and OPA/NPA if appropriate, and administered an appropriate neuromuscular blocking drug unless contraindicated. The cricothyroid membrane is located between the thyroid cartilage and cricothyroid cartilage. Several kits, needle and scalpel based, are available to access the trachea through this membrane. Some kits involve an IV catheter alone while others involve tracheostomy tubes. Smaller lumen and cuffless devices allow the rescuer to provide oxygen but do not provide a way to control ventilation. In children less than 2 years of age, front of neck access can be quite difficult, and a surgeon capable of placing a tracheostomy might be the most appropriate next step. We've discussed rapid desaturation in pediatrics so the availably and presence of these experts should be confirmed before elective or urgent airway procedure. These techniques are not without risk; percutaneous techniques in the neck can cause a pneumothorax, bleeding, or create false tracks within the neck. The methods for confirming endotracheal tube placement are still essential for confirming correct placement of any device into the airway [5].

Surgical Airway

In a trauma setting, a cricothyroidotomy is the appropriate surgical airway in older kids. As noted in the Tenth Edition of ATLS, a surgical airway is rarely indicated in infants or small children. It can be performed in older children who have a palpable cricoid membrane, typically children older than 12 year of age. As was commented on with intubation, if there is adequate oxygenation and ventilation with bag valve mask ventilation, there is no absolute need to proceed with a surgical airway [3].

The child should be placed in supine position with the neck in a neutral position. Cervical spine precautions should be maintained by a separate provider. The procedure should be performed in as sterile a fashion as possible. Palpate the sternal notch and the inferior cricoid cartilage to gain orientation. Anesthetize the area if the patient is conscious. With one hand, stabilize the thyroid cartilage while making a *vertical* skin incision directly over the cricothyroid membrane. A vertical incision decreases the risk of bleeding and may be extended in either direction for improved visualization. Insert either a blunt hemostat or tracheal spreader into the wound and rotate 90° to open the airway. Insert a proper sized ETT or tracheostomy tube into the airway. Finally, inflate the cuff and check for proper positioning. The tube should be doubly fixated with either sutures or twill tape prior to moving the patient.

Potential complications include creation of a false passage, hemorrhage, laryngeal and tracheal trauma with subsequent stenosis and vocal cord paralysis [3].

Conclusion/Take Home Points

As was noted at the outset of the chapter, establishing and maintaining a patent airway is necessary to prevent hypoxemia, anoxic brain injury with its subsequent comorbidities, and ultimately death. Accordingly, physicians and other healthcare providers who care for traumatically injured children must be skilled in mask ventilation, the use of airway adjuncts, endotracheal intubation, and supraglottic and surgical airway techniques. Trauma patients, in particular, may have altered mental status, bleeding, and altered anatomy from airway injury that can threaten airway patency. A Glasgow Coma Scale (GCS) less than or equal to 8, for instance, is associated with the loss of protective airway reflexes, hypoventilation, and apnea. While advanced airway techniques are important skills and can assist in the management of the traumatically injured patient, it cannot be emphasized enough that bag valve mask ventilation that provides both oxygenation and ventilation can be life-saving.

Loss of an airway that has been adequately maintained with bag valve mask ventilation through an errant intubation attempt or complicated surgical airway can have devastating consequences.

- Initial airway management must focus on ventilation and oxygenation. Ensuring adequate ventilation is most important. In the setting of adequate ventilation with a bag-valve-mask, placing an advanced airway is not an emergency.
- Ensuring appropriate supplies, suction, medication and endotracheal tube size prior to attempts at intubation are paramount to successful airway management.
- The anterior airway in children a pitfall of intubation. Proper positioning with a shoulder roll while still maintain cervical spine stabilization is essential and can ensure appropriate visualization of the airway.
- Surgical airways can be performed in older children who have a palpable cricoid membrane, typically children older than 12 year of age.

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Chapter 9
Shock in the Pediatric Trauma Patient

Hannah N. Rinehardt and Barbara A. Gaines

Abstract The Pediatric Advanced Life Support (PALS) 2020 Provider Manual succinctly defines shock as: "a physiologic state characterized by inadequate tissue perfusion to meet metabolic demand and tissue oxygenation. It is often, but not always, characterized by inadequate peripheral and end-organ perfusion. All types of shock can result in impaired function of vital organs." Hemorrhagic shock is the most common cause of preventable mortality in pediatric trauma patients. Early identification and control of hemorrhage in injured pediatric patients is key to preventing mortality. This chapter highlights the physiologic aspects of shock in pediatric trauma as well as the current diagnosis and management of shock.

Keywords Shock · Pediatric trauma · Hypotension · Hemorrhage

Key Concepts/Clinical Pearls (Learning Objectives for the Chapter)

- Hemorrhagic shock is the most common cause of preventable mortality in pediatric trauma patients.
- Correctly identifying tachycardia in pediatric trauma patients is paramount to identifying the level of trauma activation as well as patients who are potentially in need of resuscitation, transfer to a higher level of care, and intervention to control the source of shock.
- The Shock Index, Pediatric Adjusted (SIPA) is a ratio of the heart rate and blood pressure that is useful in the evaluation of the injured pediatric patient.
- The goals of treatment in a pediatric patient in shock include improving oxygen delivery, balancing tissue perfusion and metabolic demand, and supporting organ function.
- Another factor to consider in the resuscitation of the pediatric trauma patient in shock is trauma-induced coagulopathy.

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Table 9.1 Types of shock in pediatric trauma and common causes

Type of shock	Common causes
Hypovolemic	Hemorrhage (internal and external), large burns
Cardiogenic	Arrhythmia, cardiac contusion
Distributive	Spinal cord injury, sepsis, anaphylaxis
Obstructive	Tension pneumothorax, cardiac tamponade, massive pulmonary embolism

The Pediatric Advanced Life Support (PALS) 2020 Provider Manual succinctly defines shock as: "a physiologic state characterized by inadequate tissue perfusion to meet metabolic demand and tissue oxygenation. It is often, but not always, characterized by inadequate peripheral and end-organ perfusion. All types of shock can result in impaired function of vital organs" [1]. Types of shock and their causes are outlined in Table 9.1.

Hypovolemic shock secondary to occult or obvious hemorrhage or burns is the most common cause of shock in the pediatric trauma patient. Other causes such as cardiogenic or obstructive shock can be ruled out by physical exam, focused assessment with sonography in trauma (FAST) examination, or chest x-ray on secondary survey. Distributive shock from sepsis or anaphylaxis is rare in a trauma patient. This physiology would more likely be seen in a patient with a spinal cord injury. It would become apparent due to refractory shock despite fluid resuscitation in a patient presenting with paralysis or numbness, back pain, vertebral deformity, or unstable fracture pattern on CT of the spine.

Hemorrhagic shock is the most common cause of preventable mortality in pediatric trauma patients. Early identification and control of hemorrhage in injured pediatric patients is key to preventing mortality. Tachycardia is one of the earliest signs of shock in children, and unlike adult trauma patients, hypotension is a late finding that may signify impending cardiac arrest. Children often have a normal blood pressure even in the presence of relatively severe shock. The tenth edition of Advanced Trauma Life Support (ATLS®) training states that pediatric patients may lose up to 30% of total blood volume prior to manifesting hypotension [2]. Therefore, tachycardia is the key pediatric vital response to early hemorrhagic shock. Figure 9.1 lists key equations that will be helpful to the practitioner managing a patient with shock physiology.

The etiology of late hypotension in pediatric patients experiencing hemorrhagic shock is related to relatively small stroke volumes. In the setting of the Frank-Starling Law, younger patients depend on adequate heart rate to maintain cardiac output. Older pediatric patients are better able to increase stroke volume and are thus less dependent on heart rate [1]. In hemorrhagic shock, loss of intravascular volume leads to inadequate preload and low stroke volume, ultimately triggering a compensatory increase in heart rate, which manifests as tachycardia. In a study by A Ko et al., heart rate alone was predictive of mortality and need for ICU admission in pediatric trauma patients [3]. Defining tachycardia, however, is not consistent among different sources. As demonstrated in Table 9.2, PALS and ATLS differ in tachycardia thresholds for ages 1–3 and 7–11. Additionally, ATLS does not cite a

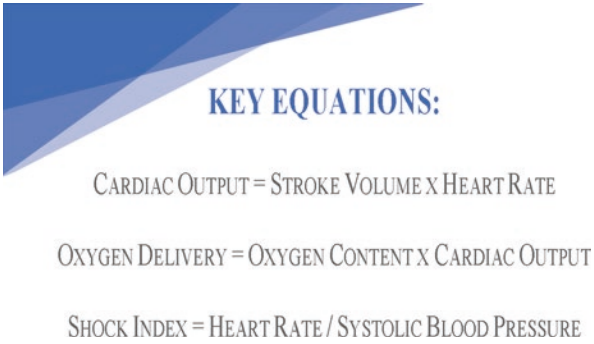

Fig. 9.1 Key equations in the management of shock

Table 9.2 Normal pediatric heart rate by age

Age	Normal Vitals ATLS 10th Edition, 2018 (bpm)	Normal Awake HR PALS Manual, 2020 (bpm)	Pediatric Trauma HR A Ko et al., 2016 (bpm)
1	<160	100–180	120–169
2–3	<140–150	98–140	100–159
4	<140	80–120	80–139
5–6	<120–140	80–120	80–119
7–8	<120	75–118	80–99
9–11	<120	75–118	80–99
12–13	<100–120	60–100	80–99
14	<100	60–100	60–99

lower limit of normal, which is an indicator of decompensated shock. Bradycardia is a late and ominous sign that should also be clearly understood. Ko utilized the National Trauma Data Bank to analyze admission heart rate for 214,254 pediatric trauma patients. This data demonstrates significant disparity from the PALS Manual (2020) and ATLS ranges (10th edition). The pediatric trauma database compared with the ATLS Course Manual identifies a slightly higher threshold for tachycardia age in infants (169 versus 160 bpm) and patients 2–3 years of age (159 versus 150 bpm), and a significantly lower threshold for tachycardia in patients ages 7–11 (100 versus 120 bpm). Correctly identifying tachycardia in pediatric trauma patients is paramount to identifying the level of trauma activation as well as patients who are potentially in need of resuscitation, transfer to a higher level of care, and intervention to control the source of shock.

On the other hand, defining hypotension by age group is more consistent between sources, as demonstrated in Table 9.3. The PALS Provider Manual provides a quick equation to calculate the lower Limit of normal systolic blood pressure in children ages 1–10: SBP = 70 mmHg + (age × 2).

In pediatric patients with hemorrhagic shock, inadequate preload causes low stroke volume and low cardiac output, as well as elevated systemic vascular resistance (SVR). Rising SVR results in lower pulse pressure, delayed capillary refill, cold, pale, mottled, diaphoretic skin, and weak peripheral pulses. These physical

Table 9.3 Lower limit of normal pediatric systolic blood pressure by age

Age	SBP lower limit ATLS 10th edition, 2018 (mmHg)	SBP lower limit PALS manual, 2020 (mmHg)
1	60	70
2–3	70–75	74–76
4	75	78
5–6	75–80	80–82
7–8	80	84–86
9–11	80	88–90
12–13	80–90	90
14	90	90

exam findings on the primary survey should increase suspicion of developing shock in pediatric trauma patients.

As shock progresses and oxygen delivery decreases, blood flow is redirected from the gut, muscles, and kidneys to the brain and heart by selective vasoconstriction. Even in compensated shock, tissue perfusion is compromised, resulting in lactic acidosis and end-organ dysfunction. Altered mental status, while often the result of traumatic brain injury in trauma, may be the manifestation of shock. Oliguria is also seen, and during the resuscitation of pediatric trauma patients, urine output should be monitored closely with a goal rate of 1–2 mL/kg/h.

Once the compensatory mechanisms, such as increased contractility, tachycardia, and selective vasoconstriction, are depleted, the patient progresses into a state of decompensated shock. Decompensated shock presents as a patient in extremis with hypotension and the ominous transition from tachycardia to bradycardia. When oxygen delivery to the myocardium is inadequate, the ultimate result is myocardial dysfunction, cardiovascular collapse, cardiac arrest, and irreversible end-organ injury.

Another clinical sign of shock is skin mottling in infants and young children. Skin mottling is the irregular or patchy discoloration of skin due to intense vasoconstriction from the irregular supply of oxygenated blood to the skin. This may result from shock, hypovolemia, or hypoxemia. Vasoconstriction may also lead to delayed capillary refill and cool or cyanotic extremities compared to the torso. Patients may also exhibit an altered level of consciousness with a dulled response to pain. A visual and tactile dermatologic assessment of the extremities and torso in a pediatric patient on secondary survey can also assist in the assessment of developing shock.

Given the variability in normal vital signs as children mature and the lack of consensus in "normal" heart rate, there is interest in developing a simpler method for the early identification of shock. The Shock Index, Pediatric Adjusted (SIPA) is a ratio of the heart rate and blood pressure that is useful in the evaluation of the injured pediatric patient. SIPA is a simple calculation, dividing heart rate by systolic blood pressure that is predictive of morbidity and mortality, the need for blood products, and operative intervention. The SIPA has a threshold of >1.22 for ages 4–6, SIPA >1.0 for ages 7–12, and SIPA >0.9 for ages 13–16 [4]. (For patients, the shock index threshold is associated with worse outcomes is >1.3) [5]. Delayed recognition of shock in injured children can be deadly. In a study of patients admitted to trauma centers in Pennsylvania, close to 50% of children who were hypotensive at the time of admission ultimately died, suggesting that earlier identification of bleeding and resuscitation is necessary to significantly improve outcomes [6].

The goals of treatment in a pediatric patient in shock include improving oxygen delivery, balancing tissue perfusion and metabolic demand, and supporting organ function. Adherence to the standard of care management of shock may prevent progression to cardiac arrest. (PALS) Oxygen delivery can be improved by the administration of supplemental oxygen even in the absence of desaturation on pulse oximetry and consideration of blood transfusion in a patient with suspected hemorrhagic shock or a low serum hemoglobin concentration. Oxygen demand can be lowered by relieving increased work of breathing with supplemental oxygen, positive pressure ventilation, or mechanical ventilation depending on the clinical situation. Relief of pain and anxiety with analgesics and sedatives is a pillar of lowering oxygen demand. The lethal triad of hypothermia, acidosis, and coagulopathy should be interrupted by balanced resuscitation, warming the patient, and/or addressing the source of bleeding to restore tissue perfusion. Hypothermia is more pronounced in children due to the higher ratio of body surface area to body mass. Temporary hemorrhage control, if external, can be managed with direct pressure or hemostatic agents. Tourniquet application for life-threatening extremity bleeding should also be utilized. Definitive control of massive hemorrhage requires source control in the operating room, or less commonly, in the angiography suite.

The resuscitation of pediatric trauma patients follows similar principles to adult trauma. Recent pediatric data [7] suggests that excess crystalloid administration in injured children is associated with poor outcomes. Therefore, if after an initial fluid bolus of 20 mL/kg of isotonic fluid the patient continues to have hemodynamic instability, blood product resuscitation should be strongly considered.

There is emerging evidence that the use of whole blood for the resuscitation of injured children is both safe and associated with improved outcomes. In a propensity-matched cohort of 56 injured children 1 year of age and up, Leeper CM et al. (2020) recently demonstrated that whole blood transfusion results in faster resolution of shock compared to component transfusion [8]. A follow up study, focusing on those children who required massive transfusion, demonstrated improved outcome, as compared to historical controls, in the group resuscitated with whole blood [9]. If whole blood is unavailable, data suggests that component transfusion, with high ratios of plasma and platelets to red blood cells (1:1:1 resuscitation) is associated with improved outcomes [10]. The adult practice of permissive hypotension during damage control resuscitation is not recommended in injured children, given the high incidence of associated traumatic brain injury.

Another factor to consider in the resuscitation of the pediatric trauma patient in shock is trauma-induced coagulopathy. Mounting evidence demonstrates that coagulopathy, as measured by an elevated INR, is both common and associated with poor outcomes in traumatically injured children [11]. Use of massive transfusion protocols, adjuncts such as TXA, and measuring response to interventions using traditional measurements of hemostasis and thromboelastography are important elements to optimizing the resuscitation from pediatric shock.

Conclusions and Take Home Points

In summary, shock represents a mismatch between oxygen delivery and consumption. In injured children, this is most often the result of hemorrhage. Shock in children can be difficult to recognize, and sustained hypotension is a delayed finding. The use of SIPA as a means of early recognition of shock may result in more rapid initiation of resuscitation, particularly blood product administration. Whole blood is a promising new development in the field of pediatric resuscitation.

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Chapter 10
Massive Transfusion in the Pediatric Trauma Patient

Jessica Rauh and Lucas P. Neff

Abstract Our goal is to distill the massive transfusion (MT) for pediatric trauma into its most essential elements. We hope to provide a framework for practical decision-making as you both prepare for and treat life-threatening hemorrhage. We will equip the reader with an understanding of the complications, labs, order of operations, delivery methods/equipment, the ingredients (blood components), and finish with a brief discussion on how to establish a MT protocol at your institution.

Pediatric massive transfusion is a fairly rare event, but when it occurs, it is lethal (50% mortality). As such, leveraging every opportunity to avoid complications that can create compounding effects leading to death is essential. This is especially true because your supporting team likely knows even less than you do about pediatric MT- not just the scientific literature, but the practical working knowledge to run a MT (how to prime a Belmont rapid transfuser, what the whole blood transfusion limit is for a child, countermeasures to avoid electrolyte derangements, etc.). At the end of this chapter, you will know what a pediatric massive transfusion looks like and how to deliver the best care.

Keywords Massive transfusion · Component blood therapy · Whole blood · Trauma induced coagulopathy · Blood failure

Key Concepts/Clinical Pearls (Learning Objectives)
- Understand the fundamental differences in massive transfusion principles in children that differ from adults.
- Understand why the definition of Massive Transfusion remains undefined in children and why that matters.

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- Understand damage control resuscitation and component therapy and the best evidence for how to administer blood in its various components.
- Understand the utility of whole blood with its potential benefits and limitations.
- Understand the role of prohemostatic adjuncts.
- Understand the basics of establishing MT protocols and capabilities for the resuscitation bay.

Initial Management of Trauma Patient

A 15-year-old male presents to the emergency department as a trauma activation in the setting of multiple gunshot wounds. He had a penetrating injury to the right upper arm and an exit wound in the back with a pelvic x-ray revealing ballistic tracking throughout the pelvis. On initial assessment in the trauma bay, he was obtunded, hypotensive (BP 50/39), and in obvious hemorrhagic shock. The massive transfusion protocol was activated, and he was taken immediately to the operating room after a 7-min stay in the trauma bay. Prior to induction in the OR, the patient lost pulses on the table. A resuscitative thoracotomy was performed with open cardiac massage until the return of spontaneous circulation. He was found to have complete destruction of the proximal left femoral vein and artery. During this initial phase of resuscitation, the patient received over 60 units of product utilizing a rapid infuser in a 1:1:1 fashion. (29 units of packed red blood cells (PRBCs), 23 units fresh frozen plasma (FFP), 5 platelets, 5 cryoprecipitate). Despite an initial pH of <6.8 in the OR, the patient was transferred to the pediatric intensive care unit for further resuscitation with a normal pH, core temperature, and coagulation profile (INR 1.14, PTT 38 s, fibrinogen 199 mg/dL). However, over the next several hours, he continued to bleed. He received an additional 13 units of packed red blood cells, 13 units of fresh frozen plasma, 7 packs of platelets, and 1 pack of cryoprecipitate. He ultimately expired 12 h later from complete blood failure after two bedside re-explorations of his chest and abdomen failed to uncover a surgically correctable source of blood loss.

Initial Radiographic/Ancillary Studies

Initial studies included a type and cross for blood and coagulation profile along with a plain film of the chest and of the abdomen/pelvis to define the extent of the injury and assess for pneumothorax or hemothorax. At the onset of massive transfusion, it is helpful to have a <u>*baseline understanding of what electrolyte derangements might already exist*</u> so that proactive countermeasures against hypocalcemia and hyperkalemia are prepared.

Epidemiology

Traumatic injuries are the leading cause of death in pediatric patients, most often secondary to motor vehicle collisions and falls [1]. Five to fifteen percent of children with traumatic injury require a blood transfusion, with a little less than half of those require a massive transfusion [2]. Life-threatening hemorrhage (LTH) in children is a rare but potentially devastating event. LTH can arise in several clinical scenarios, including surgical and gastrointestinal bleeding. However, trauma accounts for the majority of cases where massive transfusion (MT) protocols are utilized.

Despite this, pediatric MT is still an uncommon event with an incidence as low as 0.04% in the National Trauma Data Bank. While this is reassuring, this incidence is likely an underestimate due to limited data. While rare, the morbidity and mortality of pediatric patients with LTH are much higher than in adults. Knowledge for pediatric patients' epidemiology, outcomes of MT, and typical treatments are only now starting to be systematically studied by groups like the Massive Transfusion in Children (MATIC) consortium. The MATIC study group categorized the cause of LTH into traumatic injury, operative, or medical therapy. The overall 24-h survival following LTH was a staggering 21.6% (trauma, 25%; operative, 9.9%; medical, 35.1%). Preliminary results also suggest children with traumatic LTH have a 28-day mortality ranging from 37% to 50%. When compared to the adult patient population, this mortality is ***200% higher*** than adults with traumatic LTH. For children that do survive, traumatic LTH in is also associated with significant morbidity; acute respiratory distress occurs in 21% and renal failure in 20% of patients.

In adults, MT has been defined in numerous ways. One standard definition is the delivery of over ten units of packed red blood cells or whole blood in the first 24 h. In reality, the exact definition is not as important for clinical decision-making. This is because the definition of massive transfusion is largely used as a research construct to guide retrospective reviews and power prospective studies. Moreover, this definition is difficult to define in pediatric populations. A clear understanding of what "massive transfusion" means can also be misleading because small absolute volumes of blood loss in a child can lead to significant physiologic derangement. In the end, a threshold of 40 mL/kg of all blood products is a commonly cited definition that arguably has more significance for utility in research, than for defining clinical outcomes [3]. Institutions also vary in what clinical triggers they employ for activating a massive transfusion protocol (MTP): physician decision, response to product already obtained, vitals, physical exam, or labs. Taken together, there is room for further work in this field because the therapies commonly used, outcomes related to LTH, and epidemiology have not been fully described in children.

Trauma Induced Blood Failure

In severely injured trauma patients, both pediatric and adults, 25–35% develop shock and coagulopathy. "Trauma-induced blood failure" is the new buzzword for trauma-induced coagulopathy and is intended to be more descriptive of the pathophysiology-particularly because this concept also emphasizes the role of the endothelial dysfunction in the overall derangement and the fact that blood is an organ system. Blood failure is initiated by blood loss, followed by a reduction in preload and decreased cardiac output. This results in insufficient oxygen delivery for aerobic metabolism leading to a cascade of effects on epithelium, immune system, and coagulopathies often worsened by hypothermia, acidosis, and consumption of coagulation factors. New research indicates that hemorrhagic shock very quickly injures the endothelial glycocalyx, a network that projects from the cell surface into the vessel lumen and is integral for facilitating the clotting cascade. This glycocalyx can be partially restored by plasma, but not with standard crystalloid resuscitation [4].

Treating blood as the organ system that it is, this trauma-induced coagulopathy has this holistic and descriptive name, "blood failure". Treatment of blood failure must address each of these components.

- PRBCs improve oxygen delivery and increase intravascular volume, improving cardiac output.
- Similarly, plasma also increases intravascular volume while also providing necessary coagulation factors.
- Platelets increase thrombin formation and can contribute to hemostasis in bleeding patients.
- Cryoprecipitate provides factor VIII, von Willebrand factor, and fibrinogen which can improve clot strength.

In addition to addressing each of these elements individually, fresh whole blood and cold-stored whole blood can simultaneously address these components of blood failure with less overall transfusion and crystalloid volume. This may improve 24-h, 28-day, and in-hospital survival.

Crystalloid Versus Blood

In patients with life-threatening hemorrhage, hemostasis is the initial treatment priority but should occur in tandem with cardiovascular resuscitation. In the past, aggressive fluid administration was thought to be an important element in trauma resuscitations, especially in pediatric patients, given their good kidney and cardiac function. Avoidance of excessive crystalloid resuscitation is now a critical component of hemostatic resuscitation. In the adult patient population, EAST now recommends holding IV fluids in the prehospital setting in patients with penetrating torso injuries, limited administration until active hemorrhage is controlled and titrated with small boluses rather than continuous rates [5]. In pediatric patients, the same posture is reasonable, as excessive crystalloid resuscitation has been associated with increased hospital LOS and the need for mechanical ventilation [6, 7]. Therefore, providers should aim to minimize crystalloid and colloid infusions because they dilute clotting factors and worsen acidosis.

Component Therapy, Ratios

Survival is improved by rapidly activating MTP that provides packed red blood cells, plasma, and platelets in equal amounts in order to simulate the ratio of products lost. The highest-quality evidence for optimal product ratios comes from prospective observational trials of hemorrhaging adult trauma patients. Thus, the applicability of these studies to pediatric trauma patients is uncertain. In comparing FFP:PRBC ratios of 1:8, 1:2.5, 1:1.4, 1:1.14 was associated with improved survival in a retrospective study of combat data and confirmed in civilian populations [8].

This was followed by the Prospective Observational Multicenter Major Trauma Transfusion (PROMMTT) and the Pragmatic Randomized Optimal Platelet and FFP Ratios (PROPPR) trials. The PROMMTT trial concluded a higher ratio of FFP:PRBC decreased mortality in the first 24 h. In the first 6 h, mortality was increased in patients with ratios of less than 1:2 FFP:PRBCs. After the first 24 h, that increased mortality risk diminished. The PROPPR trial took the next step to include platelets in the analysis. They randomized FFP:platelet:PRBC ratios of 1:1:1 compared to 1:1:2 and found no difference in overall mortality. There was, however, decreased death by exsanguination at 24 h and increased hemostasis in the 1:1:1 group. These trials seemed to confirm the intuitive notion that getting as close as possible to replacing what the patient lost (whole blood) is the best strategy.

In contrast to adults, pediatric patients do not have large-scale trials in regard to ideal ratios. When looking at the pediatric patients with trauma from the Department of Defense (DOD) Trauma Registry from 2001 to 2013, Cannon et al. concluded a high FFP: PRBC ratio (greater than 1:2) did not improve survival. A retrospective review of the Pediatric TQIP database looking at low (less than 1:2), medium (greater than or equal to 1:2, but less than 1:1), and high (greater than or equal to 1:1) transfusion ratios found a survival benefit in the high-ratio group at 4 and 24 h. The largest observation study utilizing the TQIP database reported a 51% (adjusted relative risk, 0.49; 95% confidence interval [CI], 0.27–0.87) decrease in mortality following resuscitation using high (>1:1 FFP/PRBC) ratios compared with low (<1:2 FFP/PRBC) ratios. Without the high-quality prospective observational trials in pediatric patients, these retrospective analyses are the current best evidence to support a 1:1 FFP:PRBC ratio in pediatric MTPs.

Whole Blood

Whole blood in the trauma bay is becoming more frequent in the adult trauma population but is uncommon in pediatric patients. At present, only four pediatric level-1 trauma centers in the United States provide access to whole blood for pediatric patients. For pediatric patients, the transfusion limit of up to 40 mL/kg of uncross-matched, leukocyte reduced, low titer (<1:50), group O negative whole blood (LTOWB) in children over the age of 1 in shock as initial resuscitative fluid. LTOWB is utilized to mitigate the risk of allogenic transfusion reactions and massive hemolysis arising from a type-O donor's anti-A or anti-B antibodies attacking the recipient's RBCs [9]. Initial studies have demonstrated efficacy with a good safety profile, similar to adult trauma patients. There were no demonstrated increases in adverse events, including transfusion reactions [10]. Whole blood offers several logistic advantages, including less time to administer with less individual products to deliver and can be administered even with limited access. Whole blood has greater platelet

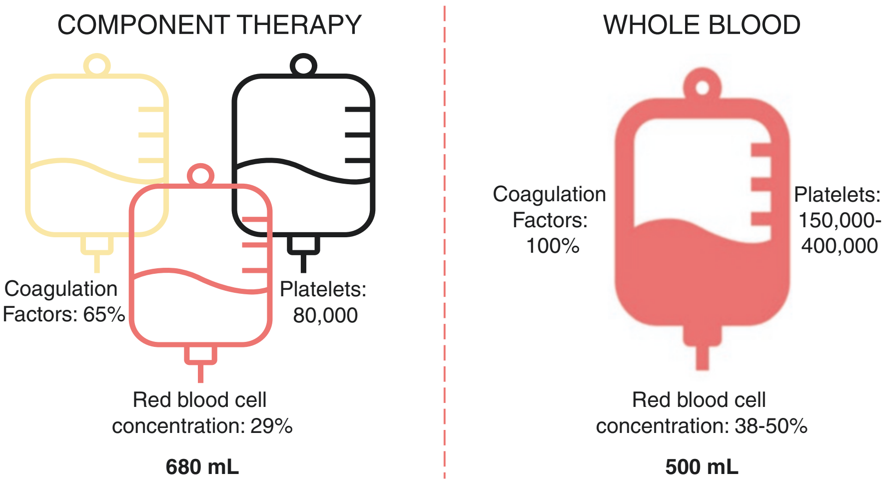

Fig. 10.1 Whole blood versus component therapy. The volume and concentration of products in component therapy versus whole blood

and factor concentrations, higher hematocrit, and requires less overall additive volume than individual component therapy offers (See Fig. 10.1).

Studies of whole blood versus component therapy are limited in the pediatric population. However, a single-center study comparing a propensity-matched cohort that received whole blood to conventional components had a faster resolution of acid-base deficits, reduction in post-transfusion INR, and decreased volumes of plasma and platelet transfusion [11]. There was no reduction in mortality, but this is largely secondary to low numbers of children treated with whole blood and inherent limitations of a propensity-matching technique and single-institution study.

The limitations of whole blood therapy are largely operational. Training staff, restocking and recycling unused products, cost of unused products, and having a blood bank that is fully invested in a whole blood program are the key components to success.

Adjuvants

Tranexamic Acid

Tranexamic acid (TXA) is a lysine analogue that inhibits plasminogen activation and thus prevents fibrinolysis. The plasminogen inhibition prevents plasmin formation and, therefore, the breakdown of fibrin and subsequently prevents clot disruption. TXA has been thoroughly studied in military and civilian populations as a part of LTH resuscitations. The Pediatric Trauma and Tranexamic Acid (PED-TRAX) study described pediatric patients with blast or penetrating injury mechanisms that received TXA. It reported that TXA was independently associated with decreased mortality among all patients with no significant difference in thromboembolic complications [12]. In contrast, studies that have looked at TXA in civilian adult populations have not shown the same decrease in mortality and the possible increase in non-hemorrhagic neurologic complications [13, 14]. In adult patients, there have been several large randomized controlled trials that report no statistically significant increase in adverse events [15]. An additional meta-analysis that included six randomized control studies, TXA was associated with substantially reduced mortality in the instances of traumatic brain injury [16]. Based on the current data, it is reasonable to include TXA as an adjunct in MTPs. Notably, TXA has also been evaluated for administration through intraosseous administration, and it was found to have similar bioavailability and efficacy [17, 18].

Recombinant Factor VIIa

Recombinant activated coagulation factor VII (rFVIIa) is utilized as an adjunct to massive transfusion to reverse the profound coagulopathy with less volume than FFP. Efficacy data is limited and only includes adult patients but does hint at an overall decrease in product usage without increased thromboembolic events [19]. While this may have a potential role in the future as an adjunct in MTPs, it is not recommended in children at this time due to limited data.

Cryoprecipitate

One of the first factors depleted in trauma-induced coagulopathies is fibrinogen, a major component of cryoprecipitate. As such, it is often incorporated in massive transfusion protocols. A retrospective cohort study utilizing the Pediatric TQIP data found that patients who received cryoprecipitate had a significantly lower 24-h mortality when compared to those who did not. In children with penetrating trauma that received at least 100 mL/kg of total blood products, cryoprecipitate use was associated with significantly lower 7-day mortality [20]. Thus, it is routinely included as part of most pediatric MT protocols.

Prothrombin Complex Concentrate

These concentrates contain either three (II, IX, and X) or four (II, VII, IX, and X) clotting factors. It is most often used for urgent reversal of warfarin, but more recently, it is being explored in the management of trauma-induced coagulopathy.

Thromboelastography (TEG) and Rotational Thromboelastometry (ROTEM)

TEG and ROTEM provide real time feedback that can be used to guide product administration. These methods provide timely information on how long it takes the patient to clot (clotting time or reaction time), the strength of the clot (maximum clot formation, maximum altitude) and how long does the clot endure (lysis index). For example, if the clotting time is prolonged, FFP or PTC would be indicated, or in the case of hyperfibrinolysis it can be corrected with TXA. TEG/ROTEM are widely used in adult populations, with limited guidelines and parameters for pediatric patients. (Refer to Chap. 13 for further details about TEG.)

Delivery

Access

The standard of care is establishing large-bore intravenous (IV) access quickly. If this is unable to be obtained, then additional measures can be considered. Intraosseous access is a quick method that still lends the opportunity to provide transfusion while establishing more secure access and should be utilized if IV access is not obtained in three attempts or 90 s (whichever is sooner). Central access utilizes either a vascular catheter (provides highest flow rates) or a multi-lumen access catheter (MAC). The flow through different size catheters is governed by the Hagen-Poiseuille equation describing the flow through a cylinder. The length of the IV tubing and viscosity of the fluid are inversely proportional to flow and proportional to the fourth power exponentially to the radius of the IV catheter [21].

Rapid Transfusers

There are several commercial rapid transfusers that are available pictured in Fig. 10.2a, b. They necessitate a large-bore catheter. They are able to transfuse crystalloids, RBCs and plasma, and are not for use with platelets, cryoprecipitate, or medications. Rapid transfusers provide several advantages including, but not limited to, warming fluids in a reliable, high-speed manner with built-in safety measures.

Storage

Major considerations for the storage of whole blood are storage time and temperature. Whole blood can be safely stored at 2–6 °C for up to 21 or 35 days, depending

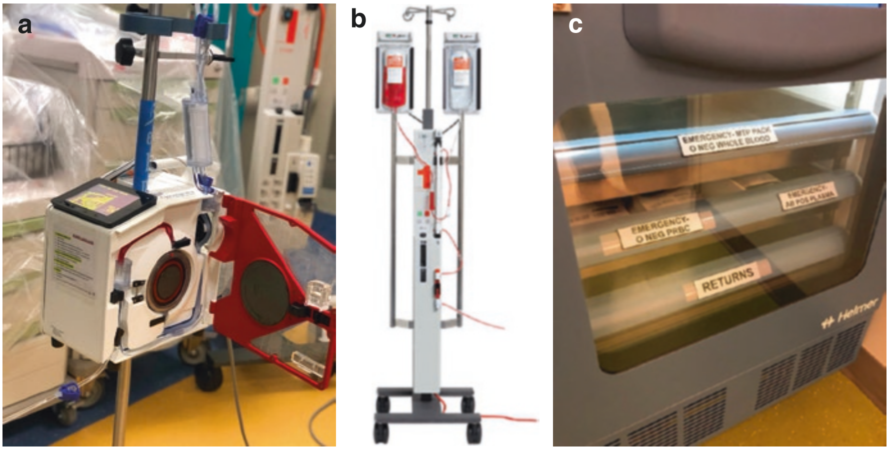

Fig. 10.2 Rapid transfusers, (**a**) Belmont (**b**) Level 1. Figure (**c**) is a storage refrigerator designed to maintain products at −4 °C and can be available in emergency departments for quick access

on the storage solution [22]. Commercial refrigerators are available to improve access to safely stored blood products in the trauma resuscitation bay (Fig. 10.2c).

Complications

Irrespective of the clinical scenario, the actual delivery of large volumes of blood products creates a significant risk for the patient. The specific complications related to giving large amounts of blood can range from minor to fatal. This includes electrolyte abnormalities, transfusion reactions, immunosuppression, and hypothermia. Each of these elements must be carefully and frequently monitored and should be considered when developing massive transfusion protocols.

Metabolic Derangements

The most common complications of MTP are metabolic derangements. Hypocalcemia resulting from the chelation of circulating ionized calcium by the citrate preservative in blood components is the most common problem. This well-known phenomenon is further accentuated in neonates that have a decreased ability to metabolize citrate because of their immature parathyroid hormone response. As a countermeasure, prophylactic intravenous calcium should be given when a large volume transfusion seems imminent. Signs of citrate toxicity itself include tetany, prolonged QT interval, decreased cardiac contractility, and hypotension. The associated severe hypocalcemia from citrate binding causes profound circulatory depression, hypotension, pulseless electrical activity, and ventricular fibrillation.

Hypomagnesemia also arises from large volume infusions of magnesium-poor fluids and the binding of magnesium to citrate. Hyperkalemia can arise from intracellular potassium leaking into additive solution or red blood cell breakdown/destruction during component storage, and transfusion can lead to fatal cardiac arrhythmias. While electrolyte derangements cannot wholly be avoided, they can be reduced by simple, thoughtful measures like utilizing large-bore catheters, the use of blood warmers, frequent monitoring of potassium, and use of fresh PRBCs when possible. Hypokalemia can occur with re-entry into transfused RBCs, metabolic alkalosis, stress hormone release, and infusion of potassium poor solutions. This need for the most robust and freshest blood products is the rationale behind the "last in, first out" method of blood product supply and logistics in most hospital blood banks. The newest products are generally the first ones to be released for transfusion.

Hemodilution and citrate toxicity are notable complications, specifically with individual blood component therapy transfusion. When compared to whole blood, there is approximately three times the amount of additive solution and citrate anticoagulation.

Transfusion Reactions

Transfusion-related acute lung injury (TRALI) is defined as acute lung injury within 6 h of transfusion and can be difficult to distinguish from transfusion-associated circulatory overload (TACO). TRALI is a result of increased pulmonary capillary permeability, whereas the pulmonary edema from TACO is driven by increased hydrostatic pressure across the capillary interface. The Canadian Consensus Criteria defines TRALI as acute pulmonary edema following transfusion without other ARDS risk factors and in the absence of circulatory overload. The National Healthcare Safety Network defines TACO as pulmonary edema including 3 or more of the following within 6 h of transfusion: evidence of left heart failure, positive fluid balance, elevated B-type natriuretic peptide (BNP), elevated central venous pressure, acute respiratory distress, radiographic pulmonary edema. When American Red Cross began preferentially using male donors for plasma (to avoid donor leukocyte antibodies from previously pregnant females), there was an 80% reduction in passively reported TRALI. Avoiding this complication is the main impetus for judicious plasma and platelet administration and enhanced product processing. TACO can be further mitigated by slowing transfusion rates and volume reduction strategies like utilizing whole blood over component therapy [23].

Immunological Complications

While the exact mechanism remains uncertain, the transfusion-related immunomodulation (TRIM) includes transfusion-associated microchimerism (TA-MC), where donor allogeneic leukocytes from the donor engraft in the transfusion recipient and persist for decades. This is exceedingly important in pediatric patients that have decades of potential need for further blood product administration because it increases the risk of alloimmunization. Transfusion is also associated with a significantly increased risk of bacterial and nosocomial infections.

Hypothermia

Hypothermia can occur secondary to the nature of trauma evaluation and treatment, including exposure and opening of body cavities, but the infusion of cold fluids and blood products can also contribute to worsening hypothermia [24]. Hypothermia is associated with a number of complications including decreased citrate metabolism, decreased production of clotting factors and reduction in the coagulation factor activity and ability to form stable clots, decreased hepatic metabolism, decreased drug clearance. Several methods should be employed to minimize hypothermia, including elevating the room temperature, using heating lamps and blankets, and using rapid transfusers for product administration.

How to Guide: Development of a Massive Transfusion Protocol

Objective: To provide a clear, concise document that can be used as a framework to establish an institutional massive transfusion protocol.

1. Engagement and Scope

   MTP should be a written document developed by all stakeholders, accepted by the medical center, and available to all. Staff should be trained with the procedures with interval refreshment and drills. This is especially important in pediatric centers where the incidence of MTP activations is rare. MTP should ensure immediate availability of red blood cells, plasma, platelets, and if possible, whole blood. A component of MTP should also include assessment and treatment of coagulopathies, acidosis, hypocalcemia, and hypothermia.

   There are several stakeholders that should be involved in development including but not limited to:

   - blood bank leadership (managers and pathologists/hematologists)
   - emergency department (especially nursing leads and educators)
   - trauma surgeons
   - anesthesiologists
   - nursing staff in the ED and OR environments

The following should be addressed and will be further described below: triggers for initiation, resuscitation in the trauma bay including availability, storage, and delivery to the trauma bay, and administration of blood products, continuation of

MTP following the trauma bay, transfusion goals, adjuvant therapies and termination of MTP.

2. Activation of Massive Transfusion Protocol
   - Hemodynamic shock with one or more of the following variables: tachycardia, hypotension, positive FAST, penetrating torso injury
   - Persistent hemodynamic instability
   - Active bleeding requiring intervention
   - The "trigger" for MT activation is something that adult trauma surgeons have tried to develop scoring systems to address. The pediatric data is not robust enough. In reality, it is at the physician's discretion, but the threshold should not be too high.
3. Availability and Storage
   - Universally compatible RBC from group O Rh-negative donors.
   - Liquid plasma or fresh frozen plasma, thawed. Ideally, AB plasma with low titers <1:200
   - Whole blood, if possible, from group O Rh-negative donors with low titers <1:50
   - Coolers
4. Delivery
   - For RBC and plasma: Rapid transfusion through a blood warmer. Platelets and cryoprecipitate should not be administered through a warmer.
     - Level 1
     - Belmont (must have well-established processes for equipment to seamlessly move with the patient from one department/care environment to the next—this should be addressed ahead of time)

Barriers to Establishing and Implementing a Massive Transfusion Protocol

Massive transfusion is fortunately a rare occurrence and as a result there are many difficulties with standardizing pediatric massive transfusion protocols. These can be divided into systems issues and individual factors based on each unique resuscitation. Due to the infrequent nature, a common impedance to MTPs is lack of familiarity with high-volume rapid transfusion devices, transfusion-related complications, blood warmers, transfusion tracking systems, and product availability and administration. Notably, many centers with pediatric MTP have immediate availability of PRBCs but less than had thawed FFP or liquid plasma available.

Conclusions and Take Home Points

Massive transfusion in children is a rare but frequently lethal event. Massive transfusion protocols for pediatric patients have largely been derived from adult data. As illustrated in the clinical case discussed in this chapter, the injury leading to life-threatening hemorrhage combined with the actual act of massive transfusion is an exceedingly difficult clinical challenge.

- Massive transfusion in children has a range of definitions, but most commonly used is requiring over 40 mL/kg in a 24-h period.
- Crystalloid should be limited in children with life-threatening hemorrhage. When utilizing component therapy, aim for a balanced resuscitation with equal components of RBCs:FFP:platelets. Whole blood can be a logistical challenge to initiate in pediatric trauma centers, but more data is emerging to demonstrate a clear benefit.
- The complications and metabolic derangements resulting from of MT need to be considered and addressed when establishing a massive transfusion protocol. This is a life-saving measure, that we need to avoid life-threatening complications from.
- Establishing a massive transfusion protocol with the necessary stakeholders can streamline an infrequent but critical, element of pediatric trauma care.

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Chapter 11
VTE Prophylaxis and Treatment

Rachael M. Sundland and Mark B. Slidell

Abstract Venous thromboembolism (VTE) is considered a preventable cause of major morbidity and mortality (Beckman et al., Am J Prev Med 38(4 Suppl):S495–501, 2010; Henke et al., Circulation 141(24):e914–31, 2020; Mahajerin et al., J Trauma Acute Care Surg 82(3):627–36, 2017). The disease is known to lead to increased healthcare costs, length of stay, and risk for chronic complications in both children and adults (Henke et al., Circulation 141(24):e914–31, 2020; Candrilli et al., Pediatr Crit Care Med 10(5):554–7, 2009). The Surgeon General issued a call to action regarding the prevention of VTE in 2008, and most recently, the American Heart Association (AHA) has called to reduce overall VTE events by 20% by 2030 (Henke et al., Circulation 141(24):e914–31, 2020; Office of the Surgeon General (US); National Heart L and BI (US). The Surgeon General's call to action to prevent deep vein thrombosis and pulmonary embolism. Office of the Surgeon General (US), Rockville, MD, 2008). The precise annual incidence of VTE events is unknown, but it is known to increase with age. Among hospitalized pediatric patients, the incidence of VTE events has a bimodal distribution which peaks in those under 1 year of age and again in those over the age of 13. While the overall incidence in the pediatric population is low, there has been a significant increase since the early 2000s. This risk is further elevated among children hospitalized after trauma and is estimated to be roughly 0.1–0.8% (Mahajerin et al., J Trauma Acute Care Surg 82(3):627–36, 2017; Candrilli et al., Pediatr Crit Care Med 10(5):554–7, 2009; Van Arendonk et al., JAMA Surg 148(12):1123–30, 2013; Connelly et al., JAMA Surg 151(1):50–7, 2016; Georgeades et al., Pediatr Surg Int 37(6):679–94, 2021). In admitted pediatric trauma patients, several tools are being developed to assess the risk for VTE events; however at this time, there is no clini-

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cally applicable measure for the prediction of VTE events. The current Pediatric and EAST Trauma Society recommendations state that prophylactic enoxaparin should be given to children over the age of 15 or patients younger than 15 who are post-pubertal with severe injuries (Mahajerin et al., J Trauma Acute Care Surg 82(3):627–36, 2017). In this chapter, we will review VTE complications and risk factors, current risk stratification tools, society recommendations, and suggest a potential algorithm for use in admitted pediatric trauma patients.

Keywords Venous thromboembolism (VTE) · Deep vein thrombosis (DVT) · Pulmonary embolism (PE) · Thromboprophylaxis · ROCKIT score

Key Concepts/Clinical Pearls (Learning Objectives)
By the end of this chapter, we hope that you will be able to understand and apply:

- What is the prevalence and incidence of VTE events among the pediatric population?
- What are important risk factors for the development of VTE events in children? Does the rate of thrombosis in children ever match those of young adults?
- What current risk stratification tools are available or in development to assess risk for DVT/VTE in pediatric trauma patients?
- What are current trauma society recommendations for VTE prophylaxis in children?

Initial Management of Trauma Patient
Patients who are 13–15 years old and at high risk for VTE events should be considered for chemical thromboprophylaxis. Patients less than 13 years old and post-pubertal at high risk for VTE events should be considered for chemical thromboprophylaxis.

Our recommendations for the management of VTE prophylaxis are an updated version of an excellent 2017 summary from the Pediatric Trauma Society and EAST [1].

- All children over the age of 15 who are admitted after trauma should be considered for chemical thromboprophylaxis, regardless of VTE risk.
- High risk patients who are 13–15 years old, or high risk patients who are <13 years old and post-pubertal, should also be considered for chemical thromboprophylaxis.
- Children 13–15 years old who are at moderate VTE risk should be considered for mechanical prophylaxis.
- In low risk patients 13–15 years old, or children <13 who are at low to moderate risk for VTE events, early ambulation alone may be sufficient.

Important risk factors to consider are central venous lines, obesity, head injury, intubation, transfusion of blood products, pelvic or lower extremity fractures, spinal cord injury, and major surgery. Patients who are high risk have at least three risk factors, those who are moderate risk have one to two risk factors, and those who are low risk have zero risk factors. All patients should be carefully assessed based on risk for VTE and risk for bleeding.

Initial Radiographic/Ancillary Studies
For children in whom there is a suspicion for deep vein thrombosis (DVT), the first test should be a venous duplex ultrasound of the extremity. Other options for work-up include computerized tomography (CT), magnetic resonance imaging (MRI) and venography, which can be used if the ultrasound study is non-diagnostic. If there is a strong clinical suspicion for pulmonary embolism (PE), the gold standard test is a CT angiogram (CTA) of the chest to evaluate the pulmonary vasculature. For further recommendations regarding the work-up and treatment of DVT/PE, see the suggested readings from the American Society of Hematology and CHEST guidelines [2, 3].

Introduction

Venous thromboembolism (VTE) is considered to be a preventable cause of major morbidity and mortality [1, 4, 5]. This disease is known to lead to increased healthcare costs, length of stay, and risk for chronic complications in both children and adults [2, 5]. In 2008, the Surgeon General issued a call to action regarding VTE prevention, and in 2020, the American Heart Association set out to reduce VTE events by 20% by 2030 [3, 5]. In this chapter, we will briefly review the epidemiology, complications, and risk factors associated with the disease. We will then examine risk stratification tools to identify pediatric trauma patients at the highest risk for VTE. We conclude the chapter with a summary of the current pediatric trauma society recommendations for VTE prophylaxis and propose an algorithm for use in clinical practice (Fig. 11.1).

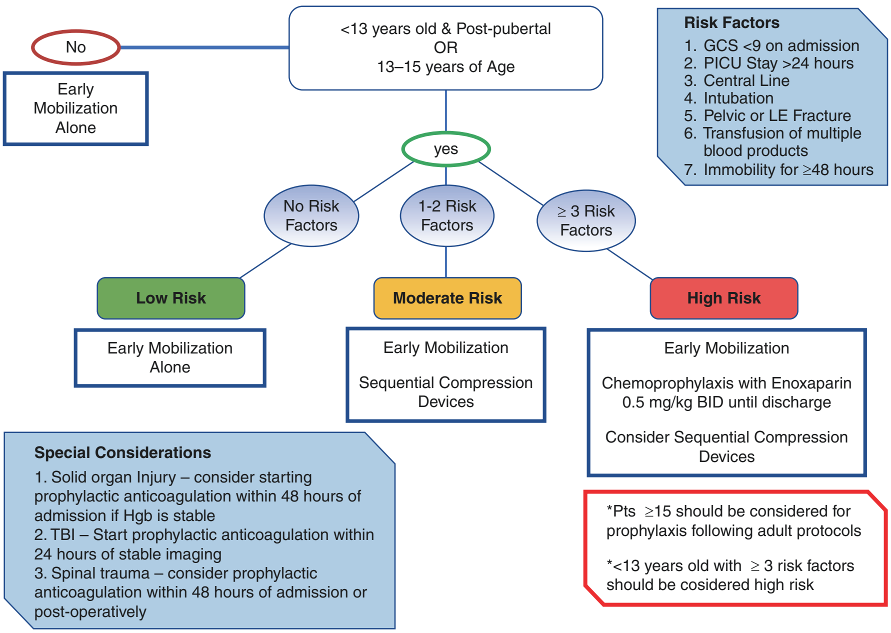


Fig. 11.1 Proposed flow chart for VTE prophylaxis in the pediatric trauma patient

Background and Epidemiology

Venous thromboembolism can refer to deep vein thrombosis, pulmonary embolism, or both. In the general population, the precise annual incidence is unknown, but it is estimated to be between 1 and 2 per 1000 [3–5]. Studies have found that the incidence of VTE increases with age. Estimates for children and adolescents range from 0.03 to <0.5 per 1000, whereas in the adult population it increases to >2 per 1000 among those 80 years and older [4, 6–8]. The incidence of VTE is significantly increased among hospitalized children, and has been reported as possibly high as 5.3 per 10,000 children in 2007 [9].

While this incidence is low compared to the adult population, reports of VTE events have risen over the last decade, likely due in part to increased surveillance. From 2001 to 2007, there was a reported increase of 70% in the diagnosis of VTE among hospitalized children from 34 to 58 cases per 10,000 hospital admissions [9]. In hospitalized children, we see a bimodal distribution of VTE events. When analyzing national data, it has been reported that children 0–1 and 15–17 have significantly higher rates of VTE events compared to those 2–14 years old [10]. Children 15–17 years old had a rate of 11.4 per 100,000 children per year compared to Children 2–14 years of age had a rate of 2.4 per 100,000 children per year.

The risk for VTE events is significantly increased among hospitalized children, particularly in the adolescent age group. As seen in adults, this risk is further increased among children who are hospitalized after trauma, estimated to be roughly 0.1–0.8% [1, 2, 11–13]. When analyzing pediatric trauma discharge data, the reported rate of VTE was 2.7 per 1000, which is considerably higher than what we have found among both the general population and hospitalized pediatric patients [2]. As the incidence of VTE events increases, understanding the acute and chronic complications becomes even more important.

Complications Associated with VTE

The local obstruction of venous flow due to DVT formation leads acutely to pain and swelling of the extremity. If left untreated, the thrombus can lead to phlegmasia, cerulea dolens and limb-threatening ischemia. In addition to the acute complications, DVT formation can lead to chronic issues, including increased risk of recurrence and post-thrombotic syndrome [1].

- Post-thrombotic syndrome can occur in up to 50% of all patients after a first DVT. In pediatric patients, the estimated incidence is reported as 20–25% [14, 15].
  - Patients with post-thrombotic syndrome can develop chronic swelling, pain, varicose veins, and even changes in skin texture and venous stasis ulcers. These complications can have significant effects on quality of life [12].

Other complications may occur following embolization of a thrombus, such as pulmonary embolism, paradoxical stroke, and even sudden death [1]. Given the potential for severe complications and death, it is essential that we identify patients at the highest risk for VTE events [15]. Understanding the acute and chronic morbidity, and potential mortality associated with this disease, further highlights the importance of identifying patients at the highest risk for VTE events.

Risk Factors

The inciting factor for a VTE event is usually due to alterations in a component of Virchow's triad. Virchow's triad consists of venous stasis, vascular endothelial injury, and hypercoagulability. In pediatric trauma patients, the factors which are known to alter Virchow's triad and are consistently associated with increased risk of VTE events are obesity, age, ICU admission, central venous access, transfusion of blood products, and prolonged immobility [12, 13, 16, 17]. Central venous lines are the single largest risk factor for VTE events in all pediatric age groups when controlling for other risk factors [18, 19]. It has also been shown that perioperative transfusions of red blood cells, specifically 5 or more units of prolonged storage age, are independently associated with increased odds of VTE [20]. We know that as the pediatric patient population ages, the incidence of VTE events increases. Utilizing data from the National Trauma Data Bank, it has been reported that the odds of VTE events are 1.96 among 13–15-year-old's and 3.77 among those older than 16 years of age when compared to those under 12 years of age [11]. This suggests that the odds of VTE after the age of 13 nearly doubles, and then nearly doubles again in patients over the age of 16 and likely approaches a similar rate to that found in young adults.

In hospitalized pediatric trauma patients, trauma remains an independent risk factor for VTE events [1, 2]. Patients with head injuries, spinal fractures, spinal cord injuries, pelvic fractures, lower extremity fractures, and vascular injuries are at the highest risk for VTE events [13, 18].

Methods of Prophylaxis: Mechanical Vs Chemical

- Early mobilization
  - The most important prophylactic measure for all ambulatory patients is early mobilization.
  - For pediatric patients at low risk for VTE events, early mobilization alone may be sufficient to prevent VTE and has been shown to decrease length of stay [21, 22].

- Intermittent Pneumatic Compression Device
  - The use of mechanical VTE prophylaxis has been shown to decrease the risk of lower extremity DVT in adult trauma and hip fracture patients [23].
  - There is no data to show that the use of pneumatic compression devices in pediatric patients has the same efficacy in reducing the risk of DVT as there is in adults [1, 21, 24].
  - The practice comes with minimal risk to the patient, and it should therefore be considered in all moderate and high-risk pediatric patients in whom a device can be appropriately fit, particularly those at high bleeding risk [1].
- Pharmacological Prophylaxis
  - The most common medication choices for DVT prophylaxis are low molecular weight heparin (LMWH) or low dose unfractionated heparin (UFH).
  - Recent trials suggest that LMWH may reduce the risk of VTE events with similar risk of major bleeding events when compared to UFH [25–27]. Two recently published, single-institution reviews of LMWH compared to UFH in admitted pediatric trauma patients showed that LMWH is superior to UFH in preventing VTE after controlling for ISS, GCS, and other confounding factors [28, 29].
  - The most recent recommendations from the Western Society for Trauma are for the use of LMWH over UFH in adults [30]. Following the recommendations in the adult literature—the Pediatric Trauma Society/EAST Guidelines also recommended the use of LMWH over UFH [1].
- Bleeding from anticoagulation administration is a known risk and can be problematic in the post-traumatic or post-surgical patient. Understanding when the risk of VTE events increases allows clinical guidelines to address the age at which the risk of complications from anticoagulation administration no longer outweighs the risk of VTE events.
  - The incidence of bleeding events is relatively low, and trials examining the use of VTE prophylaxis consistently show no increase in major bleeding complications [26–28].
  - There appears to be a significant decrease in VTE events without an increase in the risk of bleeding in patients admitted after trauma who were started on chemical thromboprophylaxis within 24 h of admission. This was significantly less than those started between 24 and 48 h or after 48 h [29].

Important Considerations

The data for many of the special scenarios below is adapted from adult literature due to the scarcity of data among the pediatric trauma population and the relatively low incidence of VTE events. These following scenarios summarize recommendations for specific injury patterns. Unless contraindicated, children older than 13 years of age or those who are under 13 years of age and are post-pubertal, should be considered for chemical thromboprophylaxis under the following conditions.

- Postoperative Abdominal Surgery
  - Surgery has been associated with an increased rate of VTE in the adult and pediatric populations, especially among patients with other known risk factors [13].
  - In a review of thromboprophylaxis in the adult general surgery population, the authors showed a clear reduction in VTE events with UFH or LMWH administered preoperatively and continued postoperatively compared to no VTE prophylaxis [25].
  - The authors found that anticoagulation is safe and can be given up to 2 h preoperatively, or 10–12 h preoperatively in high-risk patients, without an increase in intraoperative bleeding [25].
- Orthopedic Injuries
  - Pediatric traumatic orthopedic injuries, particularly those due to lower extremity fractures or pelvic fractures, are at an increased risk for VTE events [16, 17].
  - Studies have also found that pediatric patients with renal, gastrointestinal, and hematologic comorbidities are at further increased risk and should receive VTE prophylaxis [31, 32].
  - Older adolescent children, children with more severe injuries, children with lower extremity, or pelvic fractures and those with other comorbidities leading to increased inflammation should be considered for chemical prophylaxis with Enoxaparin [25, 28, 31, 32].
- Solid Organ Injury
  - Patients with solid organ injury are at high risk for bleeding due to the nature of their injury. However, they are also at high risk for VTE events due to the severity of the associated trauma, duration of bed rest, and hypercoagulable status [33].
  - The most recent Western Trauma Associations algorithm for adults state that anticoagulation may be safely initiated within 24–48 h of admission for most patients. Special consideration should be given for patients with grade IV and V solid organ injuries which may require operative intervention [30, 34].
- Spinal Trauma
  - Spinal trauma patients are known to have a higher rate of VTE events compared to other trauma patients, and the VTE rate is notably increased if pharmacologic prophylaxis is withheld for 72 h [35].

  - Adult literature has found that there is no increase in post-operative complications when pharmacologic prophylaxis is initiated within 48 h and therefore do not recommend delaying for longer than 48 h to initiate prophylaxis [30].
- Traumatic brain injury
  - Patients with traumatic brain injury are known to be at increased risk for VTE events, particularly those with severe TBI who require medical coma and ICP monitoring [36].
  - In this population, mechanical DVT prophylaxis with sequential compression devices is recommended to reduce VTE events [37]. In the pediatric population this may be challenging due to the size limitations of sequential compression devices but should be considered in all ages in which a device can appropriately fit.
  - Pharmacological prophylaxis should be held until there is imaging evidence showing stability of the bleed. When no longer contraindicated, prophylaxis should be promptly started—preferably within 24–72 h of hospital admission [30, 37]. In pediatric traumatic brain injury patients, Enoxaparin may be superior to Unfractionated Heparin in preventing VTE [38].

Risk Stratification Tools: Classifying Between High and Low Risk Pediatric Patients (Table 11.1)

Using what we know about risk factors for VTE events, there has been an effort to develop scoring systems that help stratify patients of low, medium, and high risk for VTE events. In the setting of pediatric trauma, there are several risk stratification tools that have been developed and are summarized in Table 11.1: The Connelly et al. clinical tool [12], the Cunningham et al. prediction algorithm [16], the ROCKiT score [17], and the Injury Severity Score (ISS) [39–41]. The utility of the ISS in predicting risk for development of VTE is low as it is not easily calculated on admission and is generally calculated on discharge. The ROCKIT score and the Connelly et al. risk tools show promise for application in clinical practice; however, both must first undergo further prospective testing and validation studies. The Cunningham et al. study was designed to validate the Connelly et al. clinical tool. The authors made several calibration changes to the weight-based model, and although they showed the tool to fit well, further multi-institution validation studies will need to be performed. What we can apply now from these scores is that patients with increased age, lower GCS on admission, ICU admission, central venous access, blood transfusion, major surgery, and pelvic or lower extremity fractures are at the highest risk for VTE events.

Table 11.1 Published risk stratification tools for screening and research

Study	Population	Proposed risk assessment model	Predictive value	Proposed action	Strengths/limitations
Injury Severity Score (ISS) (1976)	All hospitalized trauma patients	3 most severely injured body areas	In pediatrics, ISS 25 associated with increased risk of VTE	ISS 25 should receive pharmacological VTE prophylaxis	Not designed as a triage tool prior to final diagnoses Does not take into account other risk factors associated with VTE
Connelly et al. Clinical Tool (2016)	NTDB data for hospitalized pediatric trauma patients from 2007 to 2012 0–17 years old	GCS, age, sex, intubation, ICU admission, central line, blood product transfusion, pelvic fracture, lower extremity fracture and major surgery	Low risk = 0–523 ≤ 1% risk of VTE Moderate risk = 524–688 = 1–5% risk High risk = 689–797 ≥ 5% risk as high risk	Low risk = no prophylaxis Moderate risk = mechanical prophylaxis High risk = Mechanical & Chemical prophylaxis	First clinical tool for the prediction of VTE in pediatric trauma patients Utilizes GCS rather than ISS, allows the prediction score to be calculated at admission
ROCKiT Score (2016)	Institutional data of hospitalized trauma patients from 1987 to 2011 <21 years old	Weighted multivariable logistic regression model Age, ISS, GCS, intubation, blood transfusion and major surgery	For model 1 a score of 17 out of 23 and for model 2 a score of 13 out of 19, was related to a VTE incidence of >2%	Suggests potential cut-offs for when to initiate VTE prophylaxis for model score = incidence of >2%	Absence of data regarding central line placement, preventing the incorporation of this important risk factor into their model Uses ISS
Cunningham et al. (2020)	NTDB data for hospitalized pediatric trauma patients from 2013–2016 0–17 years old	GCS, age, sex, intubation, ICU admission, central line, blood product transfusion, pelvic/lower extremity fracture and major surgery	Low risk = 0–565 ≤ 1% risk of VTE Moderate risk = 566–728 = 1–5% risk High risk = 729–826 ≥ 5% risk as high risk	Low risk = no prophylaxis Moderate risk = mechanical prophylaxis High risk = chemical prophylaxis & screening	First study to validate a clinical tool for use Should undergo further validation studies

Current Pediatric Trauma Society Recommendations

Due to the low prevalence of VTE events in the pediatric trauma population, the recommendations for VTE prophylaxis are based on low-quality evidence. The only formal practice management guidelines for pediatric trauma were published as a joint project with the Pediatric Trauma Society and the Eastern Association for the Surgery of Trauma (PTS/EAST) [1]. The guidelines set out to answer three questions:

1. Should pharmacologic VTE Prophylaxis be utilized?
   (a) Conditionally recommend pharmacological prophylaxis for children 15 years of age and older who are at low risk of bleeding.
   (b) Patients who are post-pubertal with an ISS of >25 but younger than 15 should also be considered for pharmacological prophylaxis due to the increased risk for VTE events.
   (c) For all other patients, conditionally recommend against the use of pharmacological prophylaxis due to the paucity of data showing safety in this group.
   (d) Specifically recommend for the use enoxaparin over unfractionated heparin.
2. Should mechanical VTE prophylaxis be utilized?
   (a) Mechanical prophylaxis does not have associated risks and is relatively well tolerated.
   (b) Conditionally recommended for the use of mechanical prophylaxis either alone or in conjunction with chemical prophylaxis for children >15 years old or post-pubertal with an ISS of >25.
3. Should pediatric trauma patients undergo routine screening ultrasounds?
   (a) One study that evaluated the use of screening ultrasound in this patient population utilized screening ultrasound for all patients admitted after trauma to the PICU on PICU day 7. Of the 6 patients who underwent screening ultrasound, 3 patients were found to have VTE. All were high risk for VTE and high risk for bleeding and did not receive VTE prophylaxis. All patients were asymptomatic at the time of detection [42].
   (b) Based on the available evidence, the risk of bleeding with therapeutic anticoagulation, and the unknown course for asymptomatic DVT in this population, the group recommended against the use of screening ultrasound for VTE surveillance.

Conclusions

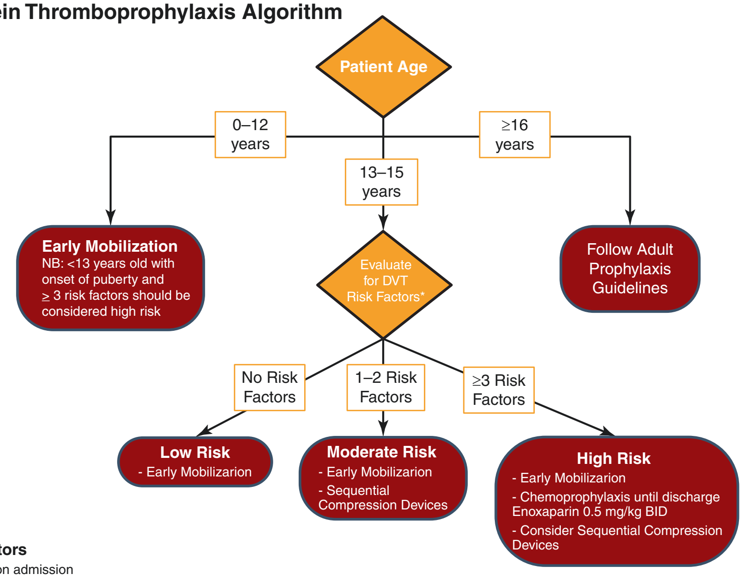
VTE events are considered never events which are associated with significant morbidity and mortality. While the overall risk is low in the pediatric population, there has been an increase in VTE events in hospitalized pediatric patients. Trauma remains an independent risk factor for the development of VTE, particularly in the adolescent age group. Our recommendations for the management of VTE prophylaxis are adapted from the Pediatric Trauma Society/EAST guidelines [1] above. Children over the age of 15 may be treated using adult VTE prophylaxis protocols. Children 13–15 years of age, and those with precocious puberty, require special consideration. Pre-pubertal children less than 13 years of age do not require chemical prophylaxis, and early ambulation alone should be sufficient.

Take Home Points
There are several important points to walk away from this discussion:

- When admitting a pediatric trauma patient to the hospital:
  - Consider chemical DVT prophylaxis in all patients over the age of 15 without contraindications (solid organ injury, traumatic brain injury, spinal injury, requiring major surgery within 24 h)
- For patients who are age 13–15 OR under the age of 13 and have reached puberty:
  - Low risk—may require no prophylaxis, early ambulation alone.
  - Moderate risk—early ambulation, should consider sequential compression devices.
  - High risk—early ambulation, should receive prophylactic anticoagulation, should consider the addition of sequential compression devices.
- For patients under the age of 13:
  - Most require no prophylaxis and early ambulation alone is sufficient.
  - Patients with three or more risk factors should be considered high risk and should be considered for the addition of sequential compression devices.
- You may use either Lovenox or Heparin for prophylaxis.
  - Lovenox is preferred as it has been shown to have some benefit over heparin in all trauma patients without increased risk of bleeding.
  - Dosing should be weight-based, 0.5 mg/kg BID, and adjustment based on anti-Xa levels may be considered for patients at very high risk for thrombosis.

- See algorithm at the end of the chapter for a concise flow diagram.

Deep Vein Thromboprophylaxis Algorithm



*** Risk Factors**

1. GCS <9 on admission
2. PICU Stay >24 hours
3. Central Line in place
4. Intubation
5. Pelvic or Lower Extremity Fracture
6. Transfusion of multiple blood products
7. Immobility for ≥48 hours

Special Considerations

1. Solid organ Injury – consider starting prophylactic anticoagulation within 48 hours of admission if Hgb is stable
2. TBI – Start prophylactic anticoagulation within 24 hours of stable imaging
3. Spinal trauma–consider prophylactic anticoagulation within 48 hours of admission or post-operatively

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Chapter 12
Surgical Nutrition

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Abstract Nutritional support after pediatric trauma is designed to provide adequate calories and protein to mitigate the effects of the catabolic injury response, preserve lean body mass through improved nitrogen balance, and decrease recovery time and morbidity. Estimation of energy and protein needs should take into consideration patient age, as well as severity and mechanism of injury. Provision of adequate protein is likely the most important intervention after trauma, as it leads to improved nitrogen balance. Enteral nutrition (EN) is the preferred route for feeding when oral feeding is inadequate and should be initiated early in the post-injury period after resuscitation is complete, typically within 24–48 h. Continuous intragastric tube feedings are started at a low rate and progressively advanced towards goal. Post-pyloric feedings are utilized for patients with high aspiration risk or in those who do not tolerate gastric feedings. Parenteral nutrition (PN) is indicated for patients in whom EN is contraindicated or inadequate. Because of concern for hyperglycemia and associated infection risk in the acute post-injury phase, PN initiation is typically delayed for 48–72 h. Patients with normal gastrointestinal (GI) function can receive standard, polymeric formulas, while those with impaired GI function benefit from peptide-based or elemental formulas that minimize intestinal work. A feeding protocol should be utilized to ensure that estimated energy and protein requirements are being met through the delivery of adequate nutrition. Necessary monitoring includes anthropometrics and biochemical markers, as well as clinical parameters of feeding tolerance, such as GI symptoms and abdominal examination findings. Feeding interruptions are a significant challenge to the delivery of optimal enteral nutrition that leads to delayed achievement of caloric goals

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and increased PN utilization. Surveillance and awareness of the preventable causes of these interruptions allow for targeted interventions to facilitate EN delivery.

Keywords Trauma · Catabolism · Energy expenditure · Nutritional support · Trauma nutrition protocol · Enteral nutrition · Protein balance · Underfeeding

Key Concepts/Clinical Pearls

- Children have a lower tolerance for protein loss during the injury response due to their smaller lean body mass relative to body size.
- Provision of adequate protein after injury, especially via the enteral route, improves nitrogen balance and leads to better clinical outcomes.
- Enteral nutrition (EN) is the preferred route for feeding pediatric trauma patients and should be initiated after resuscitation is complete, typically within 24–28 h of injury.
- Parenteral nutrition is utilized when EN is contraindicated or inadequate but is not generally initiated during the acute injury phase.
- Utilization of a nutrition protocol provides for monitoring of nutritional support and allows for assessment of adequate energy and protein delivery and feeding tolerance.
- Feeding interruptions impede optimal EN delivery. Targeted interventions may facilitate prevention.

Narrative

Physiologic Response to Trauma

The physiologic response to trauma is characterized by an initial ebb phase, during which there is decreased cardiac output, temperature, blood pressure and oxygen consumption. This is followed by the flow phase that is marked by increased cardiac output and hypermetabolism associated with increased levels of glucagon, cortisol and catecholamines. During this latter phase, endogenous sources of carbohydrate, fat and protein are broken down to fuel the inflammatory response and to provide substrate intermediates for tissue repair and wound healing. The catabolism of protein from skeletal muscle and the gut to release free amino acids can be particularly devastating in children, whose lean body mass is smaller relative to body size and could potentially lead to delayed healing, organ dysfunction and susceptibility to infection [1].

The intensity and duration of the hypermetabolic/catabolic response are proportional to the mechanism and severity of the injury. In this regard, injury mechanisms in pediatric patients who have sustained severe trauma can be broken down into three categories [2]:

– Blunt/penetrating torso trauma
– 20–30% TBSA burns
– CNS trauma, primarily traumatic brain injury

Young children are different than adolescents and adults in their response to trauma and their nutritional needs during recovery, and these differences influence nutritional strategy. In general, children [1]:

– Have higher energy expenditures per kg of body weight
– Have higher rates of protein turnover after injury
– Require more gut perfusion to absorb calories, potentially putting them at risk for mucosal ischemia

Nutritional Support

The goal of nutritional therapy after trauma is to provide adequate calories and protein to attenuate/mitigate the effects of the catabolic injury response, improve nitrogen balance, preserve lean body mass, decrease recovery time and avoid late complications [1].

Nutritional Assessment and Development of Feeding Protocol

Nutritional assessment should be undertaken in all pediatric trauma patients admitted to the hospital, especially those in the ICU, to determine baseline nutritional parameters and to identify potential underlying malnutrition within the first 48 h of admission. This includes measurements of weight, height (length) and head circumference for children <36 months of age. Admission *z* scores based on weight for age and BMI for age (or weight for length for children <2 years of age) can be used to screen for malnutrition and obesity [3].

An important part of initial planning is the development of a feeding protocol by a multidisciplinary team, including dietitians, nursing, pharmacy, respiratory therapy and physicians. This process has been reported to optimize nutrient delivery in multiple studies [3–5]. The protocol provides for standardization of multiple parameters, including nutrition screening, feeding advancement, fasting guidelines and definitions of feeding intolerance. All of this information is presented in a stepwise algorithm to allow all members of the treatment team to appreciate the “big picture” of nutritional support (Fig. 12.1).

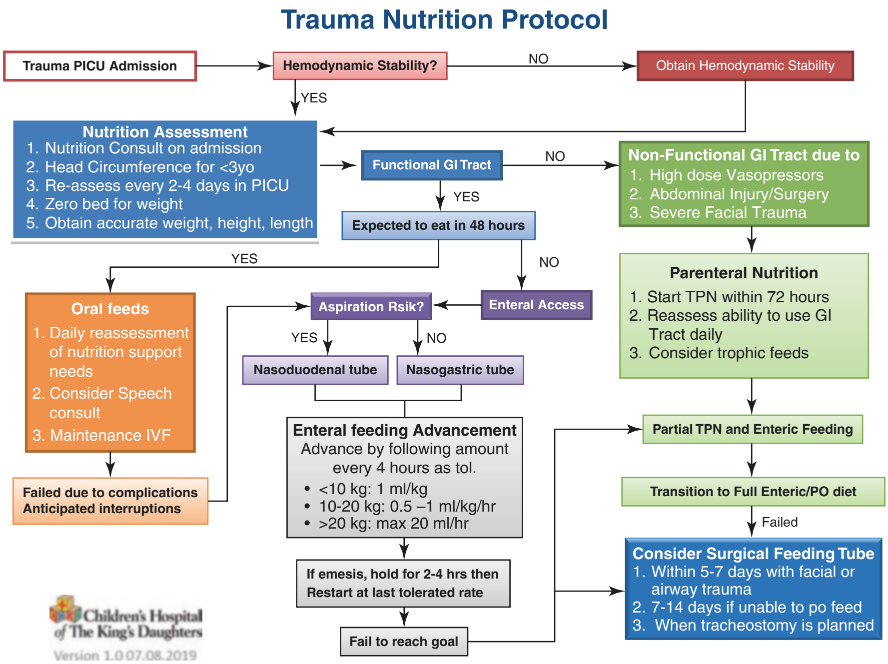

Fig. 12.1 Trauma nutrition protocol [6]

Estimation of Energy and Protein Needs

The "gold standard" for determining the caloric needs of injured patients is to measure their oxygen consumption (VO_2) and carbon dioxide production (VCO_2) with indirect calorimetry (IC) to allow calculation of their resting energy expenditure (REE) [1]. Use of IC helps to avoid under- or over-estimation of energy needs, particularly in complex trauma patients, such as those with large burns and traumatic brain injury (TBI). Serial calculations using IC help to guide appropriate modifications in nutritional support as energy requirements change during convalescence. In reality, most centers utilize standard predictive energy equations, such as the Schofield or World Health Organization, to estimate basal energy requirements. As these were developed for healthy patients, their accuracy wanes in the setting of trauma and critical illness.

The most important nutritional intervention following trauma is the provision of adequate protein [1]. The influence of enteral protein delivery may have a greater impact on clinical outcomes than total calories delivered [7, 8]. While it cannot reverse protein catabolism, it does improve nitrogen balance by facilitating protein synthesis.

Estimated protein requirements for injured children receiving EN are age-dependent. The American Society for Parenteral and Enteral Nutrition (A.S.P.E.N.) recommendations for various age groups are as follows [9]:

0–2 years = 2–3 g/kg/day
2–13 years = 1.5–2 g/kg/day
13–18 years = 1.5 g/kg/day

While meeting full, estimated energy and protein requirements is the target of nutritional support, clinical reports provide insight into the minimum requirements necessary to effect positive protein balance and favorable outcomes in critically ill pediatric patients (non-trauma). Based upon systematic literature review of nine studies of critically ill PICU patients requiring mechanical ventilation, it appears that positive protein balance can be achieved with a minimum energy intake of 57 kcal/kg/day (approximately two-thirds of prescribed energy) and protein intake of 1.5 g/kg/day during the first week of hospitalization [10]. Additionally, permissive underfeeding, delivering 60–70% of the estimated standard calorie requirements with non-protein calorie restriction and supplying complete protein needs, has been reported to meet metabolic demands and improve catabolism during the first phase of critical illness and to positively influence short- and long-term outcomes [11].

Route of Nutritional Support

Enteral Nutrition (EN)

EN is the preferred route for feeding pediatric trauma patients when oral feeding is unfeasible or inadequate. It allows for the delivery of nutrients directly into the gut lumen to nourish enterocytes [1]. Protein intake via the enteral route is more efficient in achieving a positive protein balance than similar protein intake via parenteral nutrition (PN) [7]. Early enteral feeding is associated with improved clinical outcomes, decreased infection rates, decreased length of stay and cost-effectiveness [4]. In addition to its nutritive benefits, EN also facilitates [12]:

1. Preservation of the barrier function of the GI tract (decreased bacterial translocation) through maintenance of GI structural integrity and mucosal perfusion and
2. Maintenance of immune function, including preservation of gastrointestinal-associated lymphatic tissue (GALT)

Based upon the patient's injuries, GI status and hemodynamic stability, there are multiple contraindications to EN (Table 12.1).

Table 12.1 Contraindications to enteral nutrition [12]

Absolute
Hemodynamic instability with ongoing volume resuscitation[a]
Escalating vasopressor/inotropic requirements[a]
Proximal gastrointestinal discontinuity
Bowel obstruction
Significant GI bleeding
Abdominal compartment syndrome
Relative
High output ostomy or fistula
– In the setting of unrepaired anastomotic leak, internal or external fistula, EN can be administered via feeding access distal to defect [13]
Intractable diarrhea
Open abdomen
– In the open abdomen without bowel injury, EN after resuscitation is associated with increased fascial closure rates, decreased complication and mortality rates [14]

[a]Low dose EN/trophic feeding can be considered after shock controlled with fluids and pressors/inotropes with close surveillance for signs of bowel ischemia [13]

Gastric Vs. Post-pyloric Feeding

Gastric feeding is preferred due to ease of administration and reduced costs. Post-pyloric feeding is appropriate for patients at high risk for aspiration, based upon the following risk factors [5]:

- Altered mental status with depressed gag and cough reflexes
- Persistent vomiting, 2 or more episodes/24 h
- Witnessed regurgitation or aspiration of gastric contents
- Delayed gastric emptying
- High gastric residual volumes (>3 mL/kg threshold on consecutive measurements)
- Noninvasive ventilation (escalating or high settings)

If intragastric feedings are not tolerated within 48 h, conversion to post-pyloric feedings is recommended. In comparison studies in critically ill PICU patients, a higher percentage of patients in the post-pyloric group achieved their daily calorie goals [15].

Trophic Feedings

In patients who are unable to absorb all of their nutrition from the gut, administration of trophic feedings can be considered. These are intended to provide a sufficient amount of nutrients into the bowel lumen to nourish the enterocytes. It is estimated that a minimum of 12% of the total estimated calories is sufficient for enterocyte nourishment [1]. Multiple studies in critically ill patients have demonstrated similar clinical outcomes between trophic feeding and standard enteral feeding protocols

[12]. Trophic feedings can be utilized effectively in combination with PN to meet nutritional goals in patients who are unable to tolerate full enteral feedings.

Initiation of trophic feedings may be particularly appropriate in patients who have recently completed volume resuscitation or who are weaning from pressor/inotropic support. These patients should be monitored for evidence of feeding intolerance from bowel ischemia, the symptoms of which may include abdominal distension, ileus and blood in the stool [1].

Parenteral Nutrition (PN)

PN is indicated when oral/EN is contraindicated or is inadequate to deliver sufficient nutrients to meet energy demands. Patients who fail to tolerate at least 50% of their goal enteral feedings by post-injury day 7 should be started on PN [2]. When PN is utilized as the sole source of nutrition, it is not typically started in the immediate post-injury period [16]. Initiation is delayed for 48–72 h to minimize potential metabolic complications (hyperglycemia). The exception to this is patients who have underlying malnutrition or who are at high nutrition risk, in whom PN should be started earlier.

Negative opinion surrounding PN use for nutritional support after trauma is associated with high rates of infection and septic complications related to hyperglycemia. Potential strategies for optimizing safety and efficacy of PN administration [17]

1. Minimize hyperglycemia and associated infection risk
   (a) Target blood glucose control to 150–180 mg/dL with insulin therapy to minimize hyperglycemia and associated infection risk.
   (b) Consider limitation of glucose infusion rate to 5 μg/kg/min, as rates in excess of this are not oxidized efficiently.
   (c) Initiate PN below goal rate and advance in the setting of pre-existent hyperglycemia.
2. Discriminate use of intravenous lipids
   (a) Potential deleterious effects include interference with platelet function, impairment of immune function and exacerbation of lung injury.
   (b) Intravenous lipid intake should be carefully monitored and limited to <30% of total kcal intake.
   (c) Intralipid may not be necessary for patients receiving propofol, as this contains a 10% soybean oil solution and, thus, provides essential fatty acids.
3. Optimize amino acid concentration
   (a) High amino acid content allows satisfaction of protein goal without excessive volume.

As tolerance to EN improves during convalescence from injury, PN support should be weaned and eventually discontinued once the patient is receiving >60% of target energy requirements from EN [16].

Considerations Based Upon Mechanism of Injury

Assessment of energy and protein requirements and implementation of nutritional support in pediatric trauma patients should be individualized based upon mechanism and severity of injury (Table 12.2).

Additional considerations for patients with burns:

- Estimation of calorie needs is most accurate with the utilization of IC.
  - Multiple predictive formulas are available that incorporate %TBSA
- The nutritional demands of small burns (<20% TBSA) not involving facial trauma or inhalation injury can usually be met with a high-calorie, high-protein oral diet [20].

Table 12.2 Specific considerations based upon mechanism of injury

	Blunt/penetrating torso trauma	20–30% TBSA burns	Traumatic brain injury (GCS ≤ 8)
Duration of response	Short-lived; measured in days; increases with age	Prolonged; weeks to months to potentially years [18]	Protein catabolism appears to peak 8–14 days post-injury [19]; increase in REE up to 5 days [1]
Energy expenditure	Typically less than adults as energy designated for "growth" diverted to hypermetabolic response [1]	Depends on TBSA involved; generally up to 175% predicted REE	Variable; up to 200% predicted REE [14]; dependent upon medical treatment interventions
Protein requirements	Age-dependent; typically 1.5–2 g/kg/day	2.4–4 g/kg/day	2–2.5 g/kg/day
Initiation of nutritional support	Intragastric feeding as soon as feasible after resuscitation	Intragastric feedings as soon as possible after admission	Post-pyloric feedings after resuscitation
Special considerations	At laparotomy, consider placement of direct small bowel access (NJ, GJ or feeding jejunostomy)	– Protein losses from open wounds – Consider continuing enteral feedings intraoperatively in patients that require frequent burn wound debridements	– High rate of delayed gastric emptying and dysfunction of LES [3] – Often difficult to meet high metabolic demands with oral or enteral feeding alone – Prolonged nutritional support usually required – Prior to initiation of oral diet, assess swallowing function to rule out aspiration

- Delayed enteral feeding (>18 h) results in a high rate of gastroparesis and potential increased need for PN [2]; early intragastric feedings can offset this need.
- The ability of the body to handle additional amounts of fat is significantly altered; consider specialty formula with a low fat content of 3–15% of total calories [18].

Additional considerations for patients with TBI:

- Estimation of calorie needs is most accurate with the utilization of IC.
- Metabolic rate depends on the level of consciousness, presence of other injuries, temperature and posturing responses [21].
  - Hypermetabolism, hyperventilation, seizures and posturing can elevate energy expenditure 200–250% [2].
- Medical treatment with barbiturates and neuromuscular blockade can each decrease energy expenditure by 40% [2].
  - Interventions such as hypothermia can have similar effects.
- Improved outcomes, including mortality, correlated with early nutrition therapy and provision of optimal energy and protein intake [16].
- Higher utilization of PN related to challenges that result in delayed initiation of EN [22]
  - Concurrent abdominal trauma with impaired gut function
  - Inotrope/pressor requirement to support cerebral perfusion pressure

Timing/Initiation of Nutritional Support

Initiation of nutritional support should occur as soon as the patient has been resuscitated and stabilized [1]. This will generally correspond to the first 24–48 h after injury. Because of the hypermetabolic state present immediately after injury and the propensity for hyperglycemia, as well as associated inefficient use of nutritional substrates, feedings should be initiated conservatively and advanced slowly. The presence of bowel sounds and evidence of bowel function (passing flatus or stool) are not prerequisites for initiation of EN [16]. Advancement to at least two-thirds of goal energy requirements should be targeted over the first week of hospitalization. In patients with a functioning GI tract, enteral nutrition is preferred. However, when contraindications to EN are present (Table 12.1), PN should be initiated within 72 h.

Nasogastric (NG) or nasoenteric feeding tube placement should be established and confirmed by x-ray. The latter may require fluoroscopic or endoscopic guidance for proper placement. Continuous feedings are initiated at 0.5–1 mL/kg/h (maximum 20 mL/h) and advanced by the same rate every 4–6 h until the goal feeding rate is achieved (Fig. 12.1). Once continuous NG feedings are tolerated at the goal rate, conversion to bolus feedings can begin. When appropriate based on clinical status, oral feedings can be introduced,, with the ultimate goal being a transition to goal oral feedings.

Choice of Formula

Standard formulas used for oral/enteral nutrition typically provide non-protein calories in a baseline ratio of carbohydrate 50–60% and lipid 30–40%. Fortification can be undertaken with additional powdered formula to increase kcal concentration or with the addition of specific macronutrients (carbohydrate, fat, protein). The choice of formulas for patients receiving EN is based upon the status of their gut function during recovery from trauma, as well as their overall physiologic status. For example, patients who have undergone intestinal surgery related to injuries sustained and those who have recently stabilized after resuscitation may suffer from GI tract dysfunction that interferes with the absorption of nutrients. For these patients, utilization of specialty formulas that are easier to absorb is recommended [23].

Patients with normal GI function can receive standard, polymeric formulas. For those with impaired GI function, both peptide-based (hydrolyzed protein) and elemental (free amino acids) formulas are utilized. In addition to improved protein absorption, these latter specialty formulas have the advantage of containing medium-chain triglycerides that are more easily absorbed by the intestine. These special formulas are available for a wide range of ages and can be concentrated up to 1.5 kcal/oz. Examples of commercially available formulas include:

- Infant formulas
  - Intact whey—Similac, Enfamil
  - Hydrolyzed casein—Pregestimil, Nutramigen
  - Free amino acids—Neocate
- Pediatric formulas
  - Intact whey—Pediasure
  - Hydrolyzed whey—Peptamen Junior
  - Free amino acids—Elecare

For babies, expressed human milk and donor human milk can generally be administered in the settings of both normal and impaired GI function.

Formula Supplementation

There is considerable scientific data in the adult trauma literature to support EN supplementation and the use of specialty enteral formulations that contain targeted functional ingredients designed to elicit anti-inflammatory, immune-modulating or GI tolerance-promoting effects [21]. This same information is not available for pediatric trauma patients, making standardization difficult and leading to considerable clinical practice variation based on individual institution preferences.

There is some general consensus regarding utilization of particular supplements for pediatric post-injury nutritional support:

Glutamine [1, 23]

– Acts as the primary fuel for enterocytes and lymphocytes
– Depletion occurs rapidly during injury
– Glutamine-supplemented EN is recommended for trauma and burn patients to support intestinal barrier function and immune responses during recovery.

Dietary antioxidants (vitamins A, C and E and selenium) [23]

– Function to reduce the potential for tissue damage by stabilizing free radicals
– Burn patients should receive daily supplementation of vitamins A, C, D and E and trace elements (including Fe, Cu, Se and Zn) to replace losses and facilitate optimal wound healing and immune function [18].

Omega-3 fatty acids (eicosapentaenoic acid (EPA) and docosohexaenoic acid (DHA)) [23]

– Less inflammatory and immune-enhancing
– Conversion from omega-6 to omega-3 fatty acids can modulate inflammatory and immune responses to injury

Monitoring of Nutritional Support

Delivery of adequate nutritional support and timely achievement of nutritional goals is enhanced with the utilization of standardized nutrition protocols. Routine monitoring of the adequacy of nutritional support should be standardized (Table 12.3). This assures that estimated energy and protein requirements are being met, allows assessment of the response to feeding and helps to detect potential complications [24].

Patients should also be monitored at least twice daily for tolerance of enteral nutrition based upon selected GI symptoms and abdominal examination findings [16]. Characteristic signs and symptoms of EN intolerance include [5]:

- Vomiting, 2 or more episodes/24 h
- Aspiration
- Abdominal discomfort
- Abdominal distension, 2 consecutive increases of abdominal girth in 24 h
- Diarrhea, 6 or more episodes of loose stools in 24 h

Table 12.3 Monitoring of adequacy of nutritional support [17]

Nutritional evaluation category	Assessment elements	Monitoring schedule	Considerations
Anthropometrics	Weight	Biweekly	– Trend to assess adequacy of nutrition delivery – Calculate new baseline dry weight after resuscitation
Biochemical markers	Pre-albumin	Biweekly	Gradual increase suggests resolution of acute injury response & delivery of adequate nutrition
	C-reactive protein	Biweekly	Decrease suggests resolution of acute injury response
	Urinary urea nitrogen	Weekly	– Surrogate measure of protein balance (nitrogen intake vs. nitrogen output) – Nitrogen losses should decrease over time as protein catabolism wanes – Trend can drive adjustment of protein delivery
	For patients with large burns: Serum copper, selenium & zinc	Weekly	Burns >20% TBSA associated with large exudative losses of these elements, often requiring iv repletion [24]
Estimated nutritional requirements & intake	Indirect calorimetry	Weekly	– Most accurate tool for defining energy needs during convalescence – Particularly helpful in patients with large burns or TBI
	Calorie & protein intakes/delivery	Daily	– Important for verifying actual delivery of prescribed nutrition

- High gastric residual volumes (GRV); the definition is variable: >3 mL/kg threshold on consecutive measurements, 4 h of feeding volume or 200 mL [25]
  - With regard to utilization of GRVs in assessing EN intolerance:

    GRV's do not correlate with the incidence of pneumonia, regurgitation or aspiration [16]

    Current evidence does not justify using GRV as a primary marker of EN intolerance in critically ill children [5, 24]; it is useful in the context of other signs and symptoms

Surveillance for potential complications of nutritional support is imperative.

Underfeeding

– Most commonly the result of the gap between prescribed vs. delivered nutrition; can also be due to inaccurate estimates of energy expenditure

– Clinically associated with weight loss, signs of malnutrition, prolonged ventilator dependence, nosocomial infection, increased length of hospital stay and increased mortality [3]

Refeeding Syndrome [24]

– More common in the setting of pre-existing malnutrition or prolonged starvation
– Typically manifests as hypophosphatemia 3–5 days after initiation of EN or PN as phosphate shifts from the extracellular to the intracellular compartment; magnesium and potassium levels follow a similar pattern
– Clinically associated with decreased cardiac function, arrhythmias, ventilatory insufficiency
– Phosphate level should be checked on ICU admission with values <0.6 mmol/L raising concern
– Risk can be minimized with aggressive electrolyte correction and/or feeding initiation with limited calories

Overfeeding [3]

- Providing calories and glucose in excess of energy required to meet the demands of the injury response (typically defined as 110% of needs)
- Clinical signs include hyperglycemia, hypertriglyceridemia and rapid or excessive weight gain
- Due to ease of administration, more likely to occur with PN use, especially when PN is used in combination with EN or oral diet
- Pathophysiology [20]:
  – Increased CO_2 production, causing increased ventilatory work and prolonged mechanical ventilation
  – Impaired liver function due to lipogenesis, steatosis and cholestasis
  – Increased risk of infection due to impaired immune function associated with hyperglycemia

Challenges to Delivering Adequate Nutrition

Feeding interruptions represent a significant barrier to delivering optimal EN to pediatric trauma patients (Table 12.4). Identifying patients at high risk for EN interruptions will allow targeted interventions to optimize EN delivery [8]. Avoidable EN interruptions have been associated with a three-fold increase in the use of PN and significant delay in reaching calorie goals [15].

Table 12.4 Causes of enteral nutrition (EN) interruptions [15]

Causes of EN interruptions and standard procedures for withholding feedings	Potential interventions and preventive measures
Feeding intolerance	Intervention based upon symptoms/signs: – For emesis/GE reflux, consider elevating HOB to semi-recumbent position (30–45°), medical therapy – For abdominal distension, suspected delayed gastric emptying, high GRV's, consider pro-motility agents – For patients receiving gastric feedings, consider conversion to post-pyloric feedings
Feeding tube malfunction, malposition or obstruction	– Strictly follow standard procedures – Consider nasal bridle placement to secure NG and NJ feeding tubes in place – Flush feeding tubes every 4–6 h during continuous feedings and before and after bolus feedings to prevent clogging
Endotracheal intubation or extubation—EN held for 4 h before elective intubation and extubation	– Strictly follow standard procedures – Timely restart of feedings after procedure – Consider increasing feeding rate at the restart to compensate for missed volume
Diagnostic tests and procedures in radiology—EN held for 6 h prior to sedation for tests/procedures	– Strictly follow standard procedures – Timely restart of feedings after the procedure – Increasing feeding rate at the restart to compensate for missed volume
Bedside procedures—EN held for 6 h prior to sedation for procedures	– Strictly follow standard procedures – Timely restart of feedings after the procedure – Consider increasing feeding rate at the restart to compensate for missed volume
Surgical procedures in the OR—EN held for 6 h prior to anesthesia for trauma surgery procedures	– Timely restart of feedings after the procedure, if appropriate and GI tract intact postoperatively – For patients with large burns receiving post-pyloric feedings, consider continuation of feedings during surgery

Feeding intolerance is the most common cause of enteral feeding interruptions, and, in some cases, may be unavoidable. If feeding intolerance does not improve with medical therapies or transition to post-pyloric feedings, it may be necessary to initiate PN as a sole nutrition source or as a supplement to suboptimal EN in the appropriate patients [15].

Conclusions

Early initiation of nutritional support in pediatric trauma patients helps to blunt the hypermetabolic/catabolic response to injury, preserve lean body mass, minimize complications and shorten recovery. Nutritional support monitoring is facilitated by the utilization of a standardized nutrition protocol. This allows for verification of delivery of adequate nutrition and provides for the assessment of the response to feeding. Feeding interruptions are a significant challenge to the delivery of prescribed EN that leads to delayed achievement of nutritional goals and increased PN usage. Surveillance and awareness of the preventable causes of these interruptions allow for targeted interventions to facilitate optimal EN delivery.

Take Home Points

- Enteral nutrition is the preferred route for feeding when oral feeding is inadequate and should be initiated early in the post-injury period after resuscitation is complete, typically within 24–48 h. Beyond its nutritive benefits, EN supports the barrier function of the GI tract and immune function. Provision of adequate protein via EN appears to have a greater clinical impact than total calories delivered. Positive nitrogen balance and favorable clinical outcomes have been reported with non-protein calorie restriction (60–70% prescribed energy) and provision of complete protein needs. Trophic feedings, alone or in combination with PN, have physiologic benefits similar to standard EN.
- PN is utilized when EN is contraindicated or is inadequate to deliver sufficient nutrients to meet energy and protein needs. Because of concerns for hyperglycemia and associated infection risk, PN is not typically started in the immediate post-injury period but is delayed 48–72 h. Safety of PN usage has improved with targeted blood glucose control (150–180 mg/dL) with insulin therapy and macronutrient restrictions/modifications. As tolerance to EN improves during convalescence, PN support should be weaned.
- The severity and mechanism of injury (blunt/penetrating torso trauma vs. 20–30% TBSA burns vs. TBI) have a significant impact on the intensity and duration of the injury response, as well as energy expenditure and protein requirements. Complex patients with these injuries, alone or in combination, may require individualization of nutritional strategies and close monitoring to ensure delivery of adequate nutritional support.

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Further Reading

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Chapter 13
Thromboelastography: An Overview

Joseph Lopez and David Juang

Abstract Trauma and its sequelae of coagulopathy account for the leading cause of mortality in children (Leeper et al., Surgery 163(4):827–31, 2018). Significant blood products and crystalloid transfusion can lead to substantial factor deficiencies and propagate further hemorrhage (Tapia et al., J Trauma Acute Care Surg 74(2):378–85, 2013). In addition to clotting factor depletion, fibrinolysis, endothelial injury/contributions and/or abnormal clot strength or kinetics play a part in trauma induced coagulopathy. Unfortunately, conventional laboratory studies of coagulation (INR, aPTT, and platelet count) lack in their ability to ascertain specific derangements in the factors of coagulation and subsequent transfusion guidance (Kahn et al., Monitoring in anesthesia and perioperative care, Cambridge University Press, Cambridge, p. 291–307, 2011; Govil and Pal, Indian J Crit Care Med Peer-Rev 23(Suppl 3):S202–6, 2019). Elevated INR is one of the strongest predictors of mortality in severely injured children, but it is unclear what drives this coagulopathy. Prior studies have demonstrated that abnormal INR levels do not correlate with coagulopathy in pediatric patients and may be elevated in both hyperfibrinolysis and fibrinolysis shutdown (Leeper et al., Surgery 163(4):827–31, 2018). Viscoelastic analysis, such as thromboelastrography (TEG), is an effective method of evaluating an individual patient's coagulation profile and tool to guide interventions surrounding coagulopathy in this population and preventing further morbidity associated with hemorrhage.

Keywords Thromboelastography · Coagulopathy · Trauma-induced coagulopathy · Pediatric trauma

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Learning Objectives

- Describe the principles and mechanics of thromboelastography (TEG) and what parameters are measured.
- Utilize a TEG tracing and parameter measurements to guide transfusion of blood products as well as potential reversal agents for pharmacologic anticoagulation.
- Be able to describe a patient's specific coagulation profile based on the TEG tracing morphology.

Initial Management of the Trauma Patient

A 14-year-old male is involved in a head-on motor vehicle collision. He has sustained a severe TBI with a GCS of 5. He also has sustained bilateral pulmonary contusions and a grade V liver injury. He has required massive transfusion. A thromboelastogram is obtained that shows an increased R time. What is the next appropriate management for this patient.

Introduction

Trauma and its sequelae of coagulopathy account for the leading cause of mortality in children [1]. Significant blood products and crystalloid transfusion can lead to substantial factor deficiencies and propagate further hemorrhage [2]. In addition to clotting factor depletion, fibrinolysis, endothelial injury/contributions and/or abnormal clot strength or kinetics play a part in trauma induced coagulopathy. Unfortunately, conventional laboratory studies of coagulation (INR, aPTT, and platelet count) lack in their ability to ascertain specific derangements in the factors of coagulation and subsequent transfusion guidance [3, 4]. Elevated INR is one of the strongest predictors of mortality in severely injured children, but it is unclear what drives this coagulopathy. Prior studies have demonstrated that abnormal INR levels do not correlate with coagulopathy in pediatric patients and may be elevated in both hyperfibrinolysis and fibrinolysis shutdown [1]. Viscoelastic analysis, such as thromboelastrography (TEG), is an effective method of evaluating an individual patient's coagulation profile and tool to guide interventions surrounding coagulopathy in this population and preventing further morbidity associated with hemorrhage.

Principles

In TEG, a sample of whole blood is placed in a small container and a pin is suspended in the sample. This is then rotated through 4° 45′, six rotations per minute to allow for clotting. A thin wire probe is used to measure this change in viscosity, around which the clot forms (Fig. 13.1). As clotting progresses, the increased viscosity of the blood is measured graphically. This graphic representation shows the interaction of platelets with the coagulation cascade (Fig. 13.2). It represents

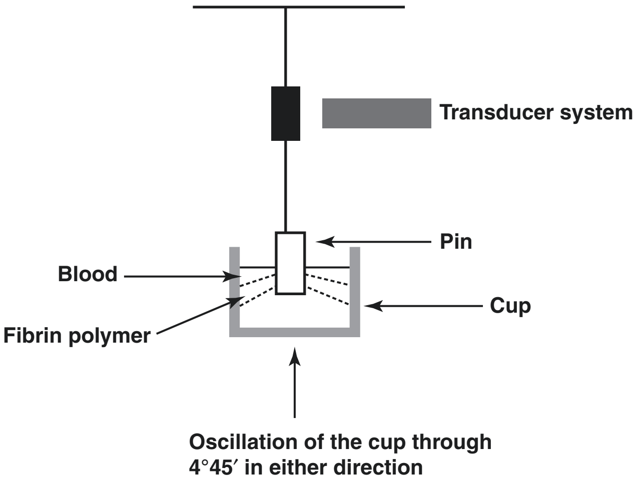

Fig. 13.1 Thromboelastography (TEG) concept and mechanics [3]

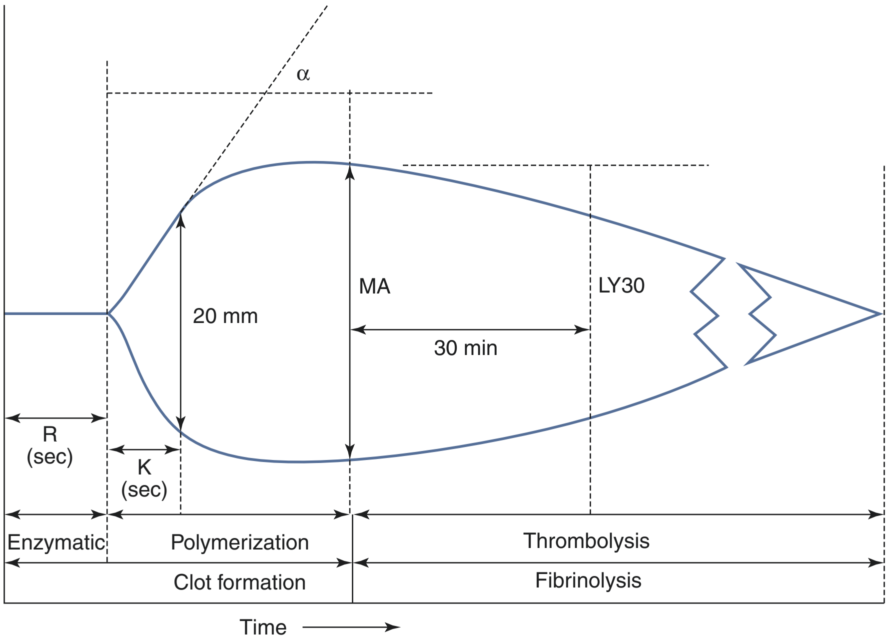

Fig. 13.2 Thromboelastography (TEG) tracing with the components of clot formation fibrinolysis noted [4]

aggregation, clot strengthening, fibrin cross linking and finally fibrinolysis. Despite the inherent complexities of the test which include daily required calibrations and its susceptibility to technical variations, overall improvements have allowed for its utilization in the point of care (POC).

Five values that represent clot formation and fibrinolysis are evaluated in this diagnostic modality: reaction time (R), clot formation time (K), Alpha angle (α), maximum amplitude (MA) and LY30 (Fig. 13.3, Table 13.1).

- **R value** represents the time until the first evidence of a clot is detected. It is the measure of the time from latency to initiation of fibrin formation. In other words, it reflects the level of clotting factors. *Prolonged R times are typically corrected with fresh frozen plasma transfusions*.

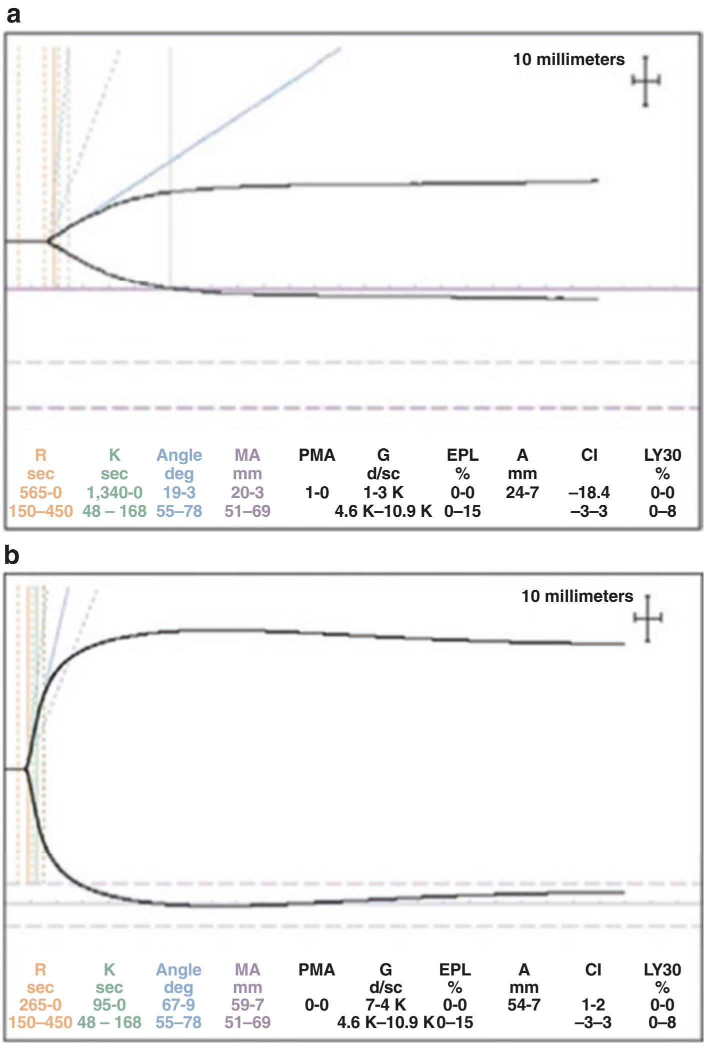

Fig. 13.3 Two examples of thromboelastogram (TEG) graphical tracings. (**a**) This tracing represents a normal coagulation profile. (**b**) This tracing represents a hypercoagulable state. Normal coagulation parameters include the following: R: 3.8–9.8 min, K: 0.7–3.4 min, alpha: 47.8–77.7°, MA: 49.7–72.7 mm, LY30: −2.3–5.77% [5]

Table 13.1 TEG parameters that aid in resuscitation decisions

TEG parameters	Clinical utility	Transfusion recommendation
R (Clotting time)	If prolonged, indicates presence of anticoagulation or deficiency of coagulation factors	FFP
K (Clot formation time)	Represents clot formation kinetics	Cryoprecipitate
α (Alpha angle)	If prolonged, may represent platelet/fibrinogen deficiencies. If angle is diminished, hypercoagulable state	Cryoprecipitate and/or platelets
MA (Maximal amplitude)	Clot strength	Platelets, DDAVP
LY30 (CL30)	Represents fibrinolysis. Consider antifibrinolytics	Tranexamic acid

- **K** is the time to a standardized clot firmness or the time to develop clot strength. K is affected by fibrinogen activation, fibrin accumulation, and cross-linking. *Abnormal K values reflect the need for cryoprecipitate due to an absence of fibrinogen.*
- **Alpha angle** represents the speed of fibrin build up and cross linking. *Abnormal values reflect the need for cryoprecipitate and/or platelets due to an absence of fibrinogen and/or a deficiency of platelets.*
- **MA** represents the properties of fibrin and platelet bonding. MA is the widest portion of the tracing and reflects the clot strength; MA is affected by platelets and fibrinogen. *Abnormal or suboptimal MA can be corrected by platelet transfusions. DDAVP may also be considered.*
- **LY30** is the amount of clot lysis 30 min after the MA has been reached. It represents the degree of fibrinolysis 30 min post maximal amplitude or fibrin and platelet bonding. *Abnormal LY30 representing hyperfibrinolysis has been treated with tranexamic acid (TXA) and Aminocaproic acid (ACA; Amicar)* [6].

Thromboelastography Assay Types

Four different assays utilized in thromboelastrography are the standard test, a rapid test utilizing tissue factor which decreases clotting time to allow for a faster assay result (rTEG), a heparinase test, and a platelet mapping test.

- The rapid TEG, or rTEG, employs the addition of tissue factor as well as Kaolin, a clay mineral, to initiate the coagulation cascade rapidly. Results are usually obtained within 20–30 min.
- The heparinase test provides insight into the differences of the pharmacologically anticoagulated patient in contrast to the non-anticoagulated patient. In patients where anticoagulation status is not known, this test can provide a rapid answer to clinicians guiding resuscitation and reversal of the pharmacologic anticoagulation in this patient subset.

- Platelet mapping tests can identify the presence of the pharmacologic activity of arachidonic acid (aspirin) and adenosine diphosphate (clopidogrel) as well as the levels of platelet inhibition that may be present.

The results of these assays can guide the resuscitation of the bleeding trauma patient with blood products and elucidate the administration of more directed reversal agents for pharmacologic anticoagulants/platelet inhibitors. One such agent, prothrombin complex concentrate (PCC) shows lifesaving promise in anticoagulated trauma patients experiencing active hemorrhage. PCC, also named factor IX complex, is a combination of blood clotting factors II, IX, and X which quickly reverse anticoagulant effects of warfarin and vitamin K antagonists upon intravenous administration. Advantages of this include rapid reconstitution, use, and action [7].

Clinical Utility

In children, abnormalities in fibrinolysis, clotting factor depletion/consumption, and variability in clot strength can all contribute to trauma-induced coagulopathy (TIC). An analysis of each of the factors as well as the overall graphical morphology measured by TEG can provide valuable guidance as to the next steps in the correction of coagulopathies (Fig. 13.4). These specific derangements and their graphic morphologies include:

1. Factor consumption/deficiency
2. Platelet inhibition/dysfunction

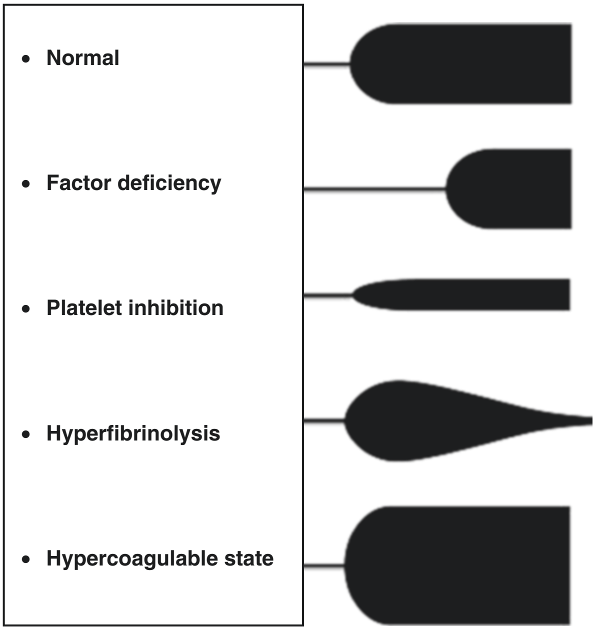

Fig. 13.4 Thromboelastographic representation of coagulation abnormalities

3. Hyperfibrinolysis
4. Hypercoagulable state

These different, but not mutually exclusive, etiologies of TIC highlight that coagulation is a multifactorial and dynamic process. Single time-point conventional coagulation studies, such as PT, PTT, and INR fail to capture the underlying derangement and, therefore, guide transfusion and treatment [1, 8]. With thromboelastography, each parameter measured, often quickly and in a point of care (POC) fashion, provides practitioners with a roadmap to correct these disorders. For example, a prolonged R time indicates the presence of anticoagulation or deficiency of coagulation factors could be treated with FFP. The alpha angle measures the thrombin breakdown and conversion of fibrinogen to fibrin. If prolonged, it may represent platelet/fibrinogen deficiencies. Thus, a depressed alpha angle could be treated with cryoprecipitate. Approximately 80% of the MA is derived from platelet function while 20% is accounted for fibrin function. Therefore, a significantly depressed MA could be treated with platelet transfusion or medications that rescue platelet function, such as desmopressin (DDAVP). Finally, an increased LY30 suggests a state of fibrinolysis. This can be treated with an antifibrinolytic like tranexamic acid. In our clinical question presented at the beginning of this chapter, the patient described has sustained a significant trauma with activation of a massive transfusion protocol. Thromboelastography can assist with the management and use of blood products to correct coagulopathy. In our example above, a prolonged R time would be consistent with factor deficiency best treated by FFP. Platelet therapy would be required when the TEG shows a decreased MA. Fibrinolysis can be seen on a TEG and would be an indication for tranexamic acid.

Conclusions and Future Directions

Thromboelastography (TEG) is a valuable tool in the resuscitation and care of the trauma patient, particularly in pediatric patients, who are vulnerable to coagulation factor derangements during massive transfusion. A better understanding of trauma induced coagulopathy will further improve the care of these patients.

Current research with whole blood in the massive transfusion of pediatric patients in the trauma setting has shown faster resolution of shock, and decreased component product transfusion, and interestingly a modest lower post-transfusion INR [8]. Unfortunately, the authors acknowledged that TEG was not routinely utilized until 2015 but the lower INR would suggest prevention or improved management of trauma induced coagulopathy.

Overall, further education, research, and implementation of thromboelastography can allow us to intervene on morbidity and mortality by enhancing our understanding of trauma induced coagulopathy and guiding resuscitative efforts with either whole blood, component therapy, and/or more directed reversal agents.

Take Home Points

- Elevated INR is one of the strongest predictors of mortality in severely injured children, but it is unclear what drives this coagulopathy.
- Viscoelastic analysis, such as thromboelastrography (TEG), is an effective method of evaluating an individual patient's coagulation profile and tool to guide interventions surrounding coagulopathy in this population and preventing further morbidity associated with hemorrhage.
- In children, abnormalities in fibrinolysis, clotting factor depletion/consumption, and variability in clot strength can all contribute to trauma-induced coagulopathy (TIC).
- TEG has been utilized to help characterize and provide management of coagulopathy in patients sustaining severe TBI.

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Chapter 14
Pediatric Traumatic Brain Injury

Christopher P. Carroll, Vijay M. Ravindra, and Mario J. Cardoso

Abstract Traumatic brain injury (TBI) is the leading cause of morbidity and mortality in children and adolescents. In the United States, pediatric TBI accounted for 18,000 hospitalizations and 1500 deaths in 2013 among patients 0–14 years of age. Validated clinical evaluation tools like the ACE, MACE, and Child SCAT-5 can guide injury history and neurologic examination of mild TBI patients. The CHALICE, PECARN, and CATCH studies yielded validated mild TBI decision tools that predict intracranial pathology, clinically significant head injury, and neurosurgical intervention. As general surgeons are more frequently called upon to manage "mild" TBI, the Brain Injury Guidelines and their pediatric modification were formulated in collaboration with neurosurgeons to guide triage decisions to higher echelons of care with neurosurgical capability. Moderate and severe TBI represent a minority of cases but overwhelmingly constitute the burden of inpatient, neurocritical care, and surgical TBI management. The medical and surgical management of pediatric TBI aims to minimize secondary brain injury and is based on the results of serial neurologic examination, radiographic

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evaluation, and, in severe TBI, invasive monitoring. Evidence-based guidelines for the clinical management of pediatric severe TBI provide a tiered, algorithmic approach to the neurocritical care of pediatric severe TBI patients absent conditions defined in the guidelines for surgical management of TBI that were published in 2012. Familiarity with the breadth of these topics will help facilitate the appropriate evaluation and management of this ubiquitous pathology in pediatric trauma care.

Keywords Traumatic brain injury · Concussion · Skull fracture · Intracranial hematoma · Intracranial pressure · MACE · Brain injury guidelines

Key Concepts
- Traumatic brain injury (TBI) is the leading cause of morbidity and mortality among children and adolescents.
- TBI is the most common injury seen in non-accidental trauma (NAT) and is associated with the greatest risk of NAT mortality.
- Mild TBI, as defined by Glasgow Coma Scale (GCS) score, is the majority of the injury burden.
- Clinical decision tools have been validated for the clinical evaluation, radiographic evaluation, and triage of pediatric TBI patients.
- Evidence-based consensus guidelines for the management of pediatric severe TBI were updated in 2019, providing an algorithmic approach to management with tiered therapies.

Initial Management of Traumatic Brain Injury
- Initial management of traumatic brain injury begins with Advanced Trauma Life Support (ATLS®) algorithms to prevent hypotension (SBP < 90 mmHg, mean arterial pressure (MAP) < 65 mmHg) and hypoxemia (SaO_2 < 90%, PaO_2 < 75 mmHg).
- Resuscitation of ABCs is followed by a focused neurologic assessment of mental status, cranial nerves, motor function, and sensory deficits with attention to any asymmetries on exam.
- In mild TBI patients, validated assessment tools like ACE, MACE-2, and Child SCAT-5 can guide diagnosis and track post-concussive symptoms.
- The Brain Injury Guidelines and its modifications can help guide decisions regarding neurosurgical consultation and transfer to higher echelons of care.
- In moderate and severe TBI patients, updated evidence based-guidelines for initial management are available and provide an algorithmic approach to management.
- Surgical intervention is indicated for decompression of mass lesions with cerebral compression or herniation; elevation of depressed skull fractures; repair of traumatic CSF leak; decompression of penetrating brain injury with salvageable examination and survivable wounding pattern; and treatment of refractory intracranial hypertension.

Initial Radiographic/Ancillary Evaluation of Traumatic Brain Injury

- Non-contrast computed tomography (CT) head is the imaging modality of choice for traumatic brain injury.
- In pediatric mild-TBI patients, there are several validated decision tools to indicate CT head.
- Repeat CT head is indicated in mild TBI patients with a decline in neurologic status.
- Electroencephalogram (EEG) and magnetic resonance imaging (MRI) are appropriate adjuncts in patients with persistent unexplained depression of neurologic examination discordant with CT findings.
- Laboratory evaluation in the initial management of TBI focuses on the identification of coagulopathy that can exacerbate intracranial hemorrhage and other metabolic derangements associated with worsened outcomes (hyponatremia, hyperglycemia).

Pediatric Traumatic Brain Injury

Epidemiology

Traumatic brain injury (TBI) has been identified as the leading cause of morbidity and mortality among children and adolescents. The majority of the 2.5 million TBI emergency department encounters annually are mild and uncomplicated, but TBI results in roughly 282,000 hospitalizations and approximately 56,000 deaths annually—2.2% of all deaths in the United States [1, 2]. Patients between 15–24 years of age are the largest age demographic for TBI-related emergency department evaluations by volume, accounting for 17.9% [2]. In 2013, TBI accounted for 640,000 emergency department visit, 18,000 hospitalizations, and 1500 deaths among children and adolescents 0–14 years of age. For survivors, the incidence of disability was 14% among mild TBI and 62% among moderate and severe TBI [3, 4]. In pediatric populations, traumatic injury remains a leading cause of death, and TBI is the injury type most frequently associated with death in the pediatric trauma population. The primary mechanisms of pediatric TBI vary by age group. Generally, as age increases, the rate for TBI from falls and non-firearm assault decreases while the rate of transportation- and firearm-related TBI increases [5, 6].

Classification of Pediatric TBI

As with adult trauma patients, TBI severity is typically stratified by the patient's clinical status at presentation, often defined by the Glasgow Coma Scale (GCS) [7]. The GCS has been shown to be reliable across examiners (i.e., kappa statistic >0.6), with a minority of studies suggesting moderate or low reliability. The GCS score and its components are strongly associated with outcomes and mortality in TBI [8]. However, assessment of GCS can be confounded by a variety of factors common in the injured patient (i.e., sedating drugs, hypothermia, hypotension, etc.). Accordingly, the post-resuscitation GCS may be a better representation of clinical status and injury severity than field or presentation GCS [9]. The GCS can be applied to patients 5 years of age and older; for patients 4 years of age and younger, the Children's Coma Scale Score is frequently used to account for verbal development (Table 14.1) [10]. The GCS is typically conveyed clinically as both the composite and subordinate scores—i.e., "The patient is GCS 9, E2-V2-M5". An alternative to the GCS, the Full Outline of Unresponsiveness (FOUR) score adds cranial nerve evaluation and assessment of respiratory status [11]. While this more fully conveys a patient's neurologic status, it is unclear whether the additional elements of FOUR improve upon the prognostic value of the properly assessed GCS.

The post-resuscitation GCS is often used to stratify TBI severity as mild (GCS 13–15), moderate (GCS 9–12), or severe (GCS 3–8). Among 729 emergency department encounters for pediatric TBI, 84.5% were mild, 13.2% were moderate, and 2.3% were severe by GCS criteria [12]. Mild TBI can be further considered complicated or uncomplicated based on the presence or absence of acute traumatic skull or

Table 14.1 The Children's Coma Scale and Glasgow Coma Scale scores for evaluation of pediatric TBI patients' neurologic status

		Children's Coma Scale (3–15) – age ≤ 4 years [10]		
		Best verbal response		
Points	**Best eye response**	**Pre-verbal**	**Verbal**	**Best motor response**
6	–	–		Spontaneous, purposeful Follows commands
5	–	Babbles	Oriented	Withdraws to touch Localizes to pain
4	Spontaneous	Crying, irritable	Disoriented/confused	Withdraws to pain
3	To verbal stimuli	Cries to pain	Incomprehensible words	Abnormal flexion
2	To painful stimuli	Moans to pain	Incomprehensible sounds	Abnormal extension
1	No response	No verbalizations/intubated		No response
Glasgow Coma Scale (3–15)–age ≥ 5 years [7]				
Points	**Best eye response**	**Best verbal response**		**Best motor response**
6	–	–		Follows commands
5	–	Oriented		Localizes to pain
4	Spontaneous	Disoriented/confused		Withdraws to pain
3	To verbal stimuli	Inappropriate speech		Abnormal flexion
2	To painful stimuli	Incomprehensible, guttural sounds		Abnormal extension
1	No response	No verbalizations/intubated		No response

intracranial abnormality on neuroimaging, respectively. Colloquially, "concussion" usually intends to imply an uncomplicated mild TBI. The phenotype of TBI is highly variable and can include skull fractures, cranial nerve injuries, intracranial hemorrhage, cortical contusions, diffuse axonal injury, or combinations thereof [5, 13]. The Marshall Classification scheme focuses on the overall radiographic phenotype of a given TBI to judge injury severity, specifically focusing on the status of basal cisterns; presence and degree of subfalcine herniation (aka "midline shift"); and presence and size of a traumatic mass lesion like a subdural hematoma. Marshall grade is significantly associated with mortality, clinical outcome, and surgical intervention in adults [14]. However, the utility of Marshall grade is limited to TBI with intracranial injuries, a small subset of the overall TBI patient burden. This shortcoming of our traditional classification systems has been buttressed with several pre-hospital and hospital decision tools to help triage pediatric TBI care.

Etiologies and Injury Patterns in Pediatric Traumatic Brain Injury

The majority of TBI patients present with a mild injury by GCS criteria. Among patients in the CHALICE (Children's Head injury Algorithm for the prediction of Important Clinical Events), PECARN (Pediatric Emergency Care Applied Research Network), and CATCH (Canadian Assessment of Tomography for Children Head injury) studies with available data, 96.4% (n = 69,050) were GCS 15 on presentation, 90.1% (n = 65,048) did not have a reported loss of consciousness, and the most common symptoms at presentation were headache and/or emesis [15–17]. As in adult TBI, blunt mechanisms of injury far outweigh penetrating injuries, with falls from standing height, athletic injuries, and head struck or hit by an object representing 79.1% of injury mechanisms in the pediatric population. While assault and penetrating brain injury represent a minority of injury mechanisms, both are significantly associated with intracranial injury [17].

In the PECARN study group, of 14,969 pediatric mild TBI patients who underwent CT of the head, 780 (5.2%) had demonstrable skull fracture or intracranial injury [16]. Unfortunately, PECARN did not report specifics of the injuries sustained in their cohort. In the CATCH cohort, 9.3% and 7.8% of patients undergoing CT head showed evidence of skull fracture and/or intracranial injury, respectively [17]. CHALICE and CATCH reported details of intracranial injuries in their cohorts. Epidural hematoma and cerebral contusion were the most common intracranial injuries in both studies. Linear morphology was present in 65.3% of skull fractures versus depressed pathology in only 17.6% (Fig. 14.1a–f) [15, 17]. Both blunt and penetrating mechanisms may produce a combination of skull fracture patterns and intracranial injuries in a single patient. Of the three study groups, only the CHALICE cohort included pediatric TBI patients of all severities. Of 22,772 patients in that cohort, only 193 patients were a moderate or severe TBI by

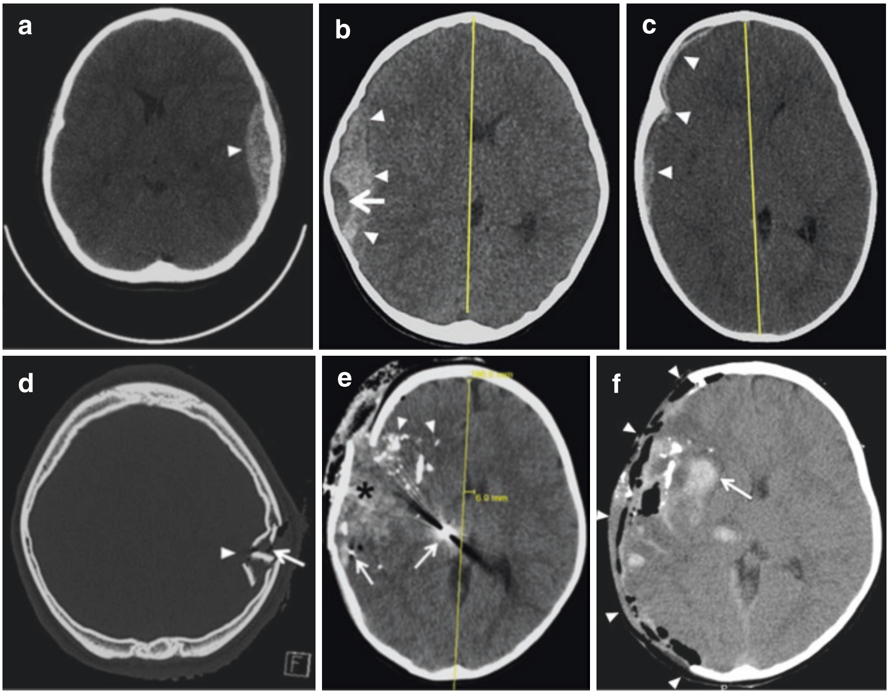

Fig. 14.1 Common injury patterns in pediatric TBI. (**a**) Acute epidural hematoma (*arrow head*). (**b**) Acute epidural hematoma (*arrow heads*) with hyperacute component (*arrow*). (**c**) Acute subdural hematoma (*arrow heads*) with midline shift. (**d**) Depressed skull fracture (*arrow head*) with pneumocephalus (*arrow*). (**e**) Penetrating brain injury with depressed skull fragments (*arrow heads*), retained projectile fragments (*arrows, note starburst artifact from metal*), and diffuse traumatic subarachnoid hemorrhage (asterisk); (**f**) PBI status post decompressive craniectomy (*arrow heads*) with blossoming subcortical hemorrhagic contusion (*arrow*). (Photos (**a**–**d**) courtesy of Dr. Libby K. Infinger, MD, Department of Neurosurgery, Medical University of South Carolina; photos (**e**–**f**) courtesy of Dr. Shawn M. Vuong, MD, Division of Neurosurgery, University of South Dakota Sanford School of Medicine)

presentation GCS, and the overall pediatric TBI mortality rate was less than 0.1% (n = 15) (Table 14.2) [15].

There are several injury mechanisms and injury patterns that are relatively unique to pediatric TBI. These include:

- *Non-Accidental Trauma (NAT):* NAT is a leading cause of trauma-related death in children. From 2007 to 2014, 19,149 admissions for pediatric trauma were due to NAT, and 95% were less than 5 years old [18]. In one study of 4623 pediatric trauma admissions, 12% of admissions were due to NAT, but NAT accounted for 46% of trauma mortality in the series. In that study, TBI was both the most common injury and also was associated with the greatest risk of death [19]. NAT patients may present with non-trauma complaints, show signs and symptoms of malnourishment or other neglect, and may have orthopedic and soft tissue inju-

Table 14.2 Demographics of pediatric TBI patients included in the CHALICE, PECARN, and CATCH studies

Clinical variable	CHALICE [15] n = 22,772	PECARN [16] n = 42,412[a]	CATCH [17] n = 3866
Loss of consciousness			
Any LOC	1185	4003/38,410	1267
LOC > 60 s	524	1274/38,410	NR
Glasgow Coma Scale evaluated	**3–15**	**14–15**	**13–15[b]**
15	21,996	41,071/42,412	3489
14	229	1341/42,412	282
≤13	266	969/43,904[c]	(95 = GCS 13)
NOS	281	NR	NR
Emesis			
Any vomiting	2498	5304/41,859	NR
≥2 episodes	1418	3216/41,859	1582
Headache	**4783**	**11,644/26,494**	**NR**
CT performed	**766**	**14,969**	**2043**
Injury identified	NR	780	NR
Skull fracture	421	NR	192
Acute intracranial injury	281	NR	159
Neurosurgical intervention	**137**	**60/42,412**	**20**
Mortality	**15**	**NR**	**0**

NR not reported
[a]PECARN dataset incomplete such that analysis was based on those with available data for the variable in question
[b]Patients were only eligible for CATCH if GCS 13–15 *and* LOC, amnesia, disorientation, vomiting, or irritability
[c]GCS ≤13 excluded in PECARN analysis reported in methods

ries of various ages. The common radiographic findings of NAT-related TBI include acute and/or chronic subdural hematomas; subdural hygromas; acute subarachnoid hemorrhage; and/or loss of grey-white differentiation on CT (Fig. 14.2a, b). Additionally, retinal hemorrhages may be apparent on fundoscopic examination.

- *Cephalohematoma (CPH):* Unique to neonates and infants, cephalohematoma is an extracranial hemorrhage due to sheering of epiploic veins running from the skull to the periosteum. CPH typically presents as a parietal swelling in the newborn, sometimes in association with diastasis. Though often asymptomatic and self-limited, large lesions may require evacuation, and calcified lesions often require neuro-plastic surgery (Fig. 14.2c, d) [20].
- *Green-stick, aka "Ping-Pong", Depressed Skull Fractures:* While depressed skull fractures are seen in both adults and children, so-called "ping-pong" fractures are unique to pediatric TBI. These are typically seen due to forceps delivery in the neonate, low-level fall (<1 m), or blunt strike to the head. Ping-pong frac-

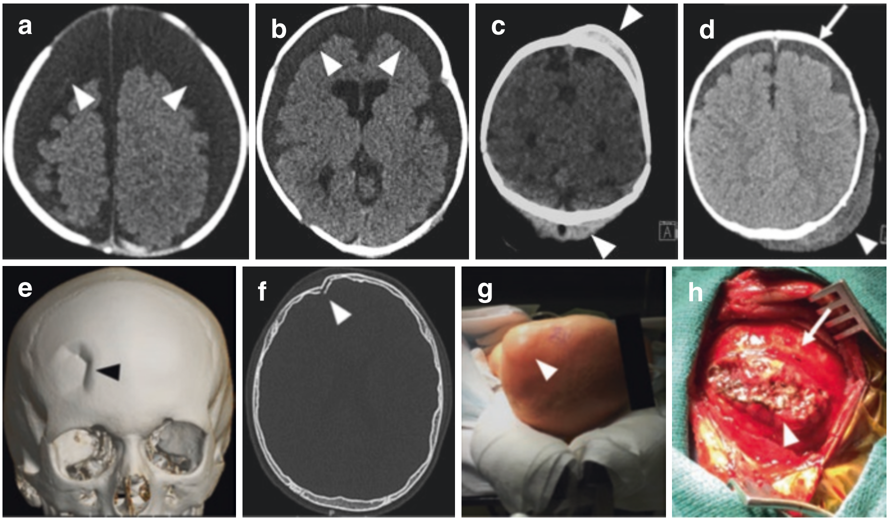

Fig. 14.2 Injury patterns relatively unique to pediatric TBI. (**a**, **b**) Chronic bilateral convexity subdural hematomas (*arrow heads*) characteristic of non-accidental trauma. (**c**) Acute coup-contrecoup cephalohematoma of frontal and occipital scalp. (**d**) Acute left cephalohematoma without underlying fracture (*arrow head*) with bifrontal chronic subdural hematomas (*arrow*). (**e**) 3D reconstruction and (**f**) axial CT of "ping-pong" depressed skull fracture (*arrow heads*) with ~1 cm depression from baseball, treated with elevation. (**g**) L parietal leptomeningeal cyst, aka growing skull fracture (*arrow head*); (**h**) intraoperative view showing periosteum (*arrow*) covering brain herniated through the skull defect (*arrow head*). (Photos (**a**–**c**, **g**–**h**) courtesy of Dr. Libby K. Infinger, MD, Department of Neurosurgery, Medical University of South Carolina)

tures entail a green-stick fracture of the inner table and diploe while the outer table remains in continuity. Many are small and remodel over time without intervention; larger fractures may require elevation utilizing open or vacuum-assisted techniques (Fig. 14.2e, f) [20, 21].

- *Leptomeningeal Cysts, aka Growing Skull Fractures:* A leptomeningeal cyst is a rare, late complication of linear skull fracture with associated dural laceration seen almost exclusively among pediatric TBI patients less than 3 years old. Over weeks to months, the patient presents with an enlarging, pulsatile soft tissue swelling at the site of the prior fracture. On imaging, the skull fracture will widen over time as the pressure and pulsation of the growing brain beneath causes the dural and bone defects to widen. The resulting subperiosteal cyst contains brain parenchyma and cerebrospinal fluid. Leptomeningeal cysts require reduction/resection of herniated brain, duraplasty, and cranioplasty to prevent recurrence (Fig. 14.2g, h) [22, 23].
- *Anemia, Hemorrhagic Shock Secondary to TBI:* Although rare, isolated traumatic brain injury can result in both anemia and/or hemorrhagic shock in pediatric patients, particularly in infants and neonates. Typically, this is seen with large cephalohematomas or epidural hematomas. Anticipation with blood products immediately available and prompt resuscitation is essential to prevent secondary injury [24, 25].

Initial Evaluation of Pediatric Traumatic Brain Injury

Prehospital and initial evaluation of all TBI patients begins with ATLS algorithms. Stabilization and optimization of airway, breathing, and circulation prevents secondary brain injury by preventing hypoxemia and hypotension, both of which are associated with worse outcomes in TBI [26, 27]. After initial stabilization, attention can turn to evaluation for disability including the trauma neurologic evaluation to identify any cranial or spinal injuries. This generally includes the following elements, as clinically indicated and feasible:

- Evaluation for outward signs and stigmata of neurotrauma
- Neurologic assessment of mental status, including pre- and post-resuscitation GCS
- Assessment of cranial nerve function
- Assessment of motor function for focal deficit and/or asymmetry
- Assessment of sensory function for focal deficit and/or asymmetry
- Assessment of deep tendon reflexes and any primitive reflexes

A detailed neurotrauma examination can be completed expeditiously, with a more detailed neurologic exam deferred to the secondary survey. Once the clinical examination has been completed, the evaluation typically turns to radiographic evaluation. The further evaluation of TBI patients can be more easily considered by TBI severity.

Mild Traumatic Brain Injury

The evaluation of mild traumatic brain injury patients primarily centers around the identification of risk factors for any significant intracranial injury that warrants imaging, neurosurgical consultation, and/or transfer to higher echelons of care. Part of the diagnostic challenge, particularly in resource-limited practice environments, is limiting unnecessary diagnostic studies and secondary over-triage.

There are several concussion/mild TBI diagnosis batteries that can be utilized in adolescents and will be encountered in the sideline, emergency department, and outpatient care of pediatric TBI patients. These were originally developed for different specific purposes, often building on elements of one another. Each has been utilized and validated in the acute assessment of TBI patients in the Emergency Department setting [28].

Acute Concussion Evaluation (ACE): The ACE is a four-component evaluation designed for outpatient clinical use that can be useful in the evaluation of outpatients in the trauma clinic or urgent care setting with mild TBI symptoms. Performance of the ACE includes the following four elements:

- Documentation of injury mechanism, amnesia, LOC, and seizures.
- A binary inventory of 22 physical, cognitive, emotional, and sleep symptoms as well as any symptom exacerbation with physical or cognitive activity.
  - Physical symptoms: headache, nausea, vomiting, balance problems, dizziness, visual problems, fatigue, sensitivity to light, and sensitivity to sound.

  – Cognitive symptoms: feeling of mental fog; feeling of cognitive slowing; difficulty concentrating; and difficulty remembering.
  – Emotional symptoms: irritability, sadness, emotional lability, and nervousness.
  – Sleep symptoms: drowsiness; sleeping less than usual; sleeping more than usual; trouble falling asleep.

- Assessment of four risk factors for prolonged recovery: concussion history; headache history; learning/developmental disorder history; and psychiatric history.
- Identification of red flags warranting transfer to the emergency department [29].

Military Acute Concussion Evaluation (MACE): The MACE is a two-component evaluation designed for the assessment of acute battlefield concussion/mild TBI in adult service members [30]. Performance of the MACE includes the following elements and has been utilized in civilian trauma populations [31]:

- Documentation injury mechanism, amnesia, LOC, and helmet use.
- An inventory of 7 physical and 2 cognitive symptoms similar to the ACE.
- Administration of the Standardized Assessment of Concussion (SAC), a 5-component evaluation of orientation, immediate memory, neurologic status, concentration, and delayed recall scored out of 30 points [32].
- The MACE was revised in 2012 (*MACE-2*) with the addition of Vestibular/Ocular-Motor Screening (VOMS) in which elicitation of headache, dizziness, nausea, and cognitive fog is assessed following pursuit, saccade, convergence, vestibular-ocular reflex, and visual motion sensitivity testing [33].

Sports Concussion Assessment Tool (SCAT): The SCAT was developed as a sideline concussion/mild TBI evaluation tool. The SCAT has been validated in athletes 13 years of age and older, while the pediatric version, Child SCAT-5, has been validated for children 5–12 years of age. The Child SCAT-5 includes the following elements:

- On-field assessment for red flag symptoms of more severe injury, signs of TBI, and determination of GCS.
- An inventory of 21 symptoms scored on 0–3 scale of severity by the child or the parent/teacher/coach.
- Administration of the SAC-Child Version.
- Neurologic screen and Modified Balance Error Scoring System (mBESS) Test [34].

After clinically diagnosing a mild TBI, the next decision concerns whether a radiographic evaluation is indicated, typically with a CT head. As previously discussed, the majority of mild TBI patients have negative imaging. Significant effort has been put into the development of imaging decision tools for pediatric mild TBI patients to help minimize unnecessary radiation exposure in these patients. Familiarization with one or several of these tools will guide evidence-based utilization of noncontrast CT in pediatric TBI patients.

- *Children's head injury algorithm for the prediction of important events (CHALICE):* Specifically developed for pediatric TBI patients of all severities, the CHALICE decision tool indicates non-contrast CT head if any of 14 history, mechanistic, or exam risk factors are present. CHALICE was highly sensitive (>97%) and specific (>86%) for clinically significant head injury, intracranial pathology on CT, and neurosurgical intervention [16].
- *Pediatric Emergency Care Applied Research Network (PECARN) Algorithm*: The PECARN CT algorithm is specifically stratified for mild TBI cohorts with GCS 14–15. It is further divided into decision tools for patients less than 2 years of age and children 2 years of age and older.
  - In patients <2 years old, CT head was indicated if GCS = 14, palpable skull fracture, or GCS = 15 with occipitoparietal scalp hematoma, history of LOC >5 s, severe mechanism of injury, or not acting appropriately per caregivers.
  - In patients 2 years of age and older, CT head was indicated for GCS = 14, signs of skull base fracture, history of LOC, vomiting, severe mechanism, or severe headache. In both derivation and validation cohorts, the PECARN algorithm was found to be highly sensitive (>95%) but not specific [17].
- *Canadian Assessment of Tomography for Childhood Head Injury (CATCH):* A modification of the Canadian CT Head Rule for adult mild TBI [35], CATCH indicates CT head with the presence of any one of 7 high-risk findings: GCS <15 at 2 h post-injury; suspected open or depressed skull fracture; worsening headache; irritability; stigmata of skull base fracture; large, boggy scalp hematoma; or dangerous mechanism. CATCH was found to be highly sensitive for neurosurgical intervention and intracranial injury on non-contrast CT but was not specific [18].

While CT head is the typical imaging modality for evaluation of cranial trauma, anterior-posterior and lateral skull X-rays can help diagnose skull fractures and be useful identifying radio-opaque foreign bodies in contaminated scalp wounds and penetrating trauma. Ultrasound can be a useful adjunct to evaluate cephalohematoma, epidural hematoma, and even intracranial blood in infants before the closure of the fontanelles. Magnetic resonance imaging (MRI) is not typically utilized for the evaluation of mild TBI. There is no consistent evidence that abnormalities on MRI correlated to risk for prolonged recovery or worsened neurocognitive outcomes [36].

Moderate Traumatic Brain Injury

Moderate TBI is relatively infrequent compared to mild and severe TBI. Unlike patients presenting with GCS 13–15, moderate TBI patients are much more likely to have a skull fracture or intracranial injury on CT. Accordingly, moderate TBI patients are at higher risk of both deterioration and the need for neurosurgical intervention. In adults, moderate TBI is often attributed to confounding factors, like alcohol intoxication. In children, unintentional intoxication, household exposures, and environmental exposure may similarly depress the GCS. As with all TBI patients, evaluation begins with ATLS algorithms to prevent hypoxemia and hypotension. Once stabilized, moderate TBI patients warrant prompt non-contrast CT head to evaluate for skull fracture or intracranial injury and neurosurgical consultation. If neurosurgery is not available at the facility, transfer to a neurosurgery-capable center is indicated in most cases. While pediatric data is limited in this cohort, CT head was negative for intracranial injury in 79.6% of adult moderate TBI patients. But, among those with intracranial injuries, progression was seen in 32% on serial imaging. In patients with negative initial CT who do not recover to GCS >12 within 2 h of injury or who decline on serial neurologic examination, a repeat CT head is indicated [37]. If the repeat CT head is also negative, adjunctive evaluation modalities include EEG to rule out subclinical seizures; CT angiogram to evaluate for blunt cerebrovascular injury, when suspected; and MRI for evaluation of diffuse axonal injuries [38].

Severe Traumatic Brain Injury

The initial evaluation and management of pediatric severe TBI centers upon ATLS algorithms. Patient's presenting with GCS <8 should have their airway secured, if not performed in the field. In severe TBI patients with outward signs of craniofacial trauma, the skull base should be assumed to be incompetent and appropriate care taken during intubation; nasogastric tubes should be avoided. Hypoxemia should be aggressively corrected to $SaO_2 > 90\%$, $PaO_2 > 75$ mmHg, and a target end-tidal CO_2 of mild hypocarbia (ET-CO_2 30–35 mmHg, correlating to $PaCO_2$ 30–40 mmHg). After fluid resuscitation and establishing adequate, redundant large-bore IV access fluid resuscitation should be pursued to maintain a systolic blood pressure strictly >90 mmHg and mean arterial pressure >65 mmHg as hypotension is associated with poor outcomes.

After addressing the ABCs, a focused neurologic assessment is indicated as previously described. Particular attention should be paid to localizing signs like asymmetry on motor and/or cranial nerve examination that may suggest an intracranial mass lesion. Prompt neurosurgical consultation or transfer to a neurosurgery-capable tertiary center is indicated.

If the patient is neurologically stable, i.e., not actively herniating or deteriorating where hyperosmolar therapy needs to be initiated, prompt radiographic evaluation is the next step in evaluation. In penetrating TBI, plan skull X-rays can identify skull fractures and retained projectiles, particularly if CT is unavailable or the patient is unstable. Otherwise, non-contrast CT head is the imaging modality of choice in severe TBI patients. Based on the CT findings, patient should be triaged to the operating room, ICU, and/or transfer to a higher echelon of care.

In all TBI patients, serial neurologic evaluation is the cornerstone of clinical evaluation and guides subsequent interventions. These are typically performed every 15 min for the first 2 h post-injury and hourly for the first 6–12 h after injury or until neurologically stable.

Clinical Management of the Pediatric TBI Patient

After initial stabilization and evaluation of the TBI patient, subsequent care depends on severity of injury; pattern of injury; and resources available.

Management of Pediatric Mild TBI

Mild TBI patients who are found to be GCS 15, neurologically intact, and with negative CT head (no intracranial injury or skull fracture, if performed) can often be discharged home with adult supervision. Patients with positive CT head, GCS <15, or any red-flag symptoms on ACE or MACE-2 should be observed with serial neurologic checks [3]. In mild TBI patients, repeat non-contrast CT head is indicated for decline on serial neurologic examination. There is growing literature that routine repeat CT head is not indicated for clinically stable mild TBI patients and may result in unindicated radiation [39, 40].

A second decision point in the management of mild TBI patients involves neurosurgical consultation and transfer to designated pediatric trauma centers. Evidence suggests those pediatric trauma patients treated at a designated pediatric trauma center or adult trauma centers with pediatric trauma qualifications have significantly better mortality rates than pediatric trauma patients treated at adult trauma centers. This was identified despite matched injury severity scores and presentation GCS [41, 42]. When feasible, transfer of complicated mild and most moderate or severe TBI patients to a designated pediatric trauma center may be both prudent and evidence-based. In many hospital systems, neurosurgical coverage may be lacking such that acute care surgeons are increasingly managing uncomplicated adult TBI patients without direct neurosurgical consultation. The Brain Injury Guidelines (BIG) were created as a collaboration between trauma and neurologic surgeons to guide neurosurgical consultation for mild to moderate adult TBI patients at a Level I Trauma Center (Table 14.3) [43]. The BIG were validated and updated at a Level III Trauma Center to aid triage decisions to the regional Level I center. In that study, the authors proposed that neurological consultation and transfer to a higher level of care should be considered for patients meeting BIG-II criteria and recommended for all patients meeting BIG-III criteria [44]. A similar adaptation of the BIG for pediatric TBI led to reduced repeat CT head and unnecessary neurosurgical consultations [45].

In most mild TBI patients, once appropriately imaged and triaged, management is supportive with a prescribed course of cognitive and physical recumbency until asymptomatic. Some mild TBI patients may require neurosurgical intervention for deterioration or elevation of depressed skull fractures, requiring neurosurgical consultation in accordance with the BIG. Patients with post-traumatic seizures should be treated with anti-epileptic pharmacotherapy; however, prophylactic antiepileptic drugs (AEDs) are not routinely recommended in mild TBI. AEDs may occasionally but prescribed prophylactically for 1 week course for depressed skull fracture or significant hemorrhagic contusions that represent a higher risk of early post-traumatic seizures.

Table 14.3 The brain injury guidelines for acute care surgeons managing traumatic brain injury [43]

Clinical variable	BIG-I	BIG-II	BIG-III
Loss of consciousness	±	±	±
Neurologic examination	Intact	Intact	Abnormal
Intoxication	–	±	±
Anticoagulation[a]	–	–	+
Non-contrast CT			
Skull fracture	None	Non-displaced	Displaced
Subdural hematoma	≤4 mm	5–7 mm	≥8 mm
Epidural hematoma	≤4 mm	5–7 mm	≥8 mm
Intraparenchymal hemorrhage	≤4 mm, solitary	3–7 mm, 2 lesions	≥8 mm, multifocal
Subarachnoid hemorrhage	Trace	Localized	Scattered/diffuse
Intraventricular hemorrhage	None	None	Present
Therapeutic plan			
Hospitalization	6 h observation	Yes	Yes
Repeat CT head	No	No	Yes
Neurosurgical consultation	No	No	Yes

[a]Anticoagulation with coumadin, aspirin, ibuprofen, or clopidogrel

Medical Management of Pediatric Moderate-Severe TBI

Moderate and severe TBI, thankfully, represent a minority of the pediatric TBI burden. But, TBI patients with GCS ≤12 overwhelmingly constitute the burden of inpatient, critical care, and surgical management. Evidence-based guidelines for the management of pediatric severe traumatic brain injury were updated in 2019 [46–48]. The third edition included 22 evidence-based recommendations with 3 level II and 19 level III guidelines—there is insufficient evidence to support any level I recommendations in the pediatric severe TBI literature. It is notable that of over 90 publications reviewed by the guidelines committee, 68 described a protocol used at the authors' institution to manage pediatric TBI, verifying the heterogeneity of treatments and treatment thresholds in the published literature [46–48]. The guideline authors published an evidenced base algorithm for baseline, first tier, and second-tier therapy [48] and an executive summary of the evidence-based recommendations [47].

The published treatment algorithm was divided into baseline care and pathway-specific recommendations for treatment of elevated intracranial pressure (ICP), clinical evidence of herniation, optimization of cerebral perfusion pressure (CPP), and optimization of Brain Tissue Partial Pressure of Oxygen ($PbrO_2$). As a baseline, the algorithm assumes the patient has had their airway definitively secured, is mechanically ventilated, on appropriate sedation and analgesia, non-contrast CT head has been completed to assess for a surgical lesion, and an ICP-monitor has been placed. Though not explicitly stated, elements of the protocol may require central venous access and invasive arterial pressure monitoring. The protocol also assumes neurosurgical consultation and surgical intervention as indicated.

Initial care of the severe TBI patient includes maintaining a clinical status conducive to frequent neurologic re-evaluation and optimizing physiology for cerebral perfusion and prevention of secondary brain injury.

- Patients are pharmacologically sedated with short-acting agents like midazolam and fentanyl. In our experience, an initial target Richmond Agitation Sedation Scale (RASS) of -2 is often reasonable in children and adolescents, while RASS -4 may be prudent for infants, young children, and patients intolerant of lighter sedation. Bolus doses of midazolam or fentanyl may cause cerebral hypoperfusion and should be avoided during ICP elevations (Level III) as this may jeopardize CPP. Continuous propofol infusion is not recommended for either sedation or management of refractory ICP.
- Mechanical ventilation should be optimized to maintain $SpO_2 > 92\%$ and PaO_2 of 90–100 mmHg. A target $PaCO_2$ of 35–40 mmHg is the consensus recommendation; prophylactic hyperventilation to $PaCO_2 < 30$ mmHg is *not* recommended (Level III).
- Temperature intervention should target normothermia (<38 °C). Prophylactic moderate hypothermia (32–33 °C) is *not* recommended to improve outcomes (Level II).
- Intravascular volume should target a euvolemic state and a neutral fluid balance with urine outputs of greater than 1 mL/kg/h. Several studies have suggested targeting a central venous pressure of between 4- and 12-mmHg, when such monitoring is available.
- Hemoglobin should be strictly maintained at greater than 7.0 g/dL in pediatric severe TBI patients such that a higher target may be needed to avoid dropping below that threshold for worsened outcomes.
- The patient's head should be positioned neutral with the head of the bed elevated to 30°.
- Antiepileptic drugs are suggested to reduce the incidence of early post-traumatic seizures within 7 days of injury (Level III). There is no evidence to support any single agent; though in our experience, levetiracetam may be easier to administer than phenytoin and its derivatives due to less effect on blood pressure. In comatose patients, continuous electroencephalography should be considered, particularly when paralytic agents are used.
- Enteral nutrition should be started within 72 h of injury to decrease mortality and improve overall outcomes, when feasible (Level III). Glucose control should target euglycemia with treatment indicated for glucose ≥180 mg/dL to avoid hyperglycemia. The consensus recommendation was to initially target eunatremia with $[Na^+]$ greater than 140 mEq/L though most protocols initially target anywhere from 135–150 mEq/L.

Invasive neuromonitoring of ICP is suggested in severe TBI patients (Level III); this can be accomplished with a number of bolt/ICP monitors or an extraventricular drain, though only the latter is both diagnostic and therapeutic. Multimodal neuromonitoring has become a more common practice in Level I trauma centers. This can entail monitoring ICP, $PbrO_2$, and brain temperature with a so-called triple lumen bolt or with the addition of a depth electrode for intracranial EEG via a quad lumen bolt. Additional monitors for perfusion and microdialysis also exist. However, there is currently insufficient evidence to recommend advanced neuromonitoring for the improvement of outcomes in pediatric severe TBI (Level III). When $PbrO_2$ monitoring is utilized, a threshold brain oxygenation of >10 mmHg is recommended (Level III). There is wide variation in published ICP parameters for intracranial hypertension, but a threshold of <20 mmHg is recommended as an initial target (Level III). Additionally, the consensus recommendation is for intervention when ICP is greater than 20 mmHg for more than 5 min barring a clear, reversible source of elevation (i.e., bronchoscopy, sedation off for examination, etc.). When monitoring ICP and MAP, a threshold CPP of at least 40 mmHg is recommended with a target of 40–50 mmHg to improve outcomes (Level III).

In those patients with intracranial hypertension (ICP > 20 mmHg × >5 min), a number of first-line therapies exist. The tiered algorithm suggested by the authors of the Pediatric severe TBI guidelines include:

1. CSF drainage via extraventricular drain, if present.
2. Hyperosmolar therapy with bolus hypertonic saline (3%: 1–3 mL/kg up to a maximum of 250 mL; 23.4%: 0.5 mL/kg up to a maximum of 30 mL) (Level II). Bolus dosing of mannitol 0.5–1 g/kg over 10 min as an alternative is noted in the consensus recommendation, but no studies of mannitol meeting inclusion criteria for pediatric TBI were identified. Serum sodium and osmolality should be monitored during hyperosmolar therapy. Serum osmolality typically should fall from 320 to 360 mOsm/L.
3. Increased sedation and/or analgesia.
4. Neuromuscular blockade. Continuous EEG should be considered in patients with paralytic infusion for refractory intracranial hypertension.
5. Additional hyperosmolar therapy with bolus hypertonic saline; continuous infusion of 3% hypertonic saline may be considered between 0.1–1 mL/kg/h using the lowest effective dose to maintain ICP < 20 mmHg (Level III).

If those first-tier therapies fail to control ICP, the guidelines recommend a repeat CT head to rule out the progression of intracranial injuries warranting surgical decompression. If no new or enlarging surgical lesion is identified, then second-tier therapies should be started. These include, in no particular order:

- Barbiturate infusion, typically pentobarbital at 2–4 mg/kg/h, in hemodynamically stable patients; barbiturate infusion will often cause hypotension, and cardiorespiratory instability is not uncommon. The therapeutic target is typically burst suppression on continuous EEG.
- Moderate hypocapnia by hyperventilating to target $PaCO_2$ of 28–34 mmHg.
- Further hyperosmolar therapy targeting serum $[Na^+]$ 155–160 mEq/L and osmolality 320–340 mOsm/L. Bolus 23.4% hypertonic saline is recommended for refractory intracranial hypertension (Level III). Care should be taken as sustained serum $[Na^+]$ > 160 mEq/L increases the risk of deep vein thrombosis while $[Na^+]$ > 170 mEq/L increases the risk of anemia and thrombocytopenia.

- For refractory intracranial hypertension, moderate hypothermia to 32–33 °C is suggested as an adjunct for ICP control (Level III). If used, rewarming at a rate of 0.5–1.0 °C over 12–24 h is recommended. As previously noted, prophylactic hypothermia is not supported by evidence in clinical trials.
- Additional neuromonitoring to optimize brain parameters, rule out subclinical status, and rule out cerebral ischemia is recommended.

Finally, for those patients with intracranial hypertension refractory to both first and second-tier therapies or with a new surgical lesion, surgical evacuation and/or decompression is recommended [46–48].

Surgical Management of Pediatric Traumatic Brain Injury

Guidelines for the surgical management of traumatic brain injury in adults have previously been published [49]. Surgery is recommended for mass lesions, neurologic deterioration, and/or clinical evidence of herniation. As previously stated, the foundation of all neurocritical care is serial neurologic examination. The neurologic examination is augmented by, not substituted with, CT and neuromonitoring. Specific clinical markers of deterioration or herniation include pupillary dilation, bradycardia with uncal and transtentorial herniation, hemiplegia with uncal and subfalcine herniation, and stereotyped responses to painful stimuli with brainstem compromise. Any new neurologic deficit or sign of herniation should be considered a neurologic emergency that warrants reevaluation for further medical or surgical intervention. Specific recommendations include emergent surgical intervention for:

- *Acute Epidural Hematoma (EDH)*: EDH >30 cm^3 regardless of GCS; consideration for decompression in patients with EDH ≥15 mm maximal axial thickness and ≥ 5 mm midline shift at the foramen of Monro with GCS <9. EDH <30 cm^3 and <15 mm thick with <5 mm midline shift can be managed nonoperatively in patients with GCS >8 absent focal neurologic deficit [49].
- *Acute Subdural Hematoma (SDH)*: SDH >10 mm maximal axial thickness or ≥5 mm midline shift at the foramen of Monro regardless of GCS. For SDH <10 mm thickness and <5 mm midline shift, surgery is indicated for a drop in GCS of 2 or more points on serial neurologic exams or new focal neurologic deficit [49].
- *Parenchymal Contusions and Intraparenchymal Hemorrhage (IPH)*: Patients with GCS <8 with moderate frontotemporal contusions >20 cm^3 and midline shift ≥5 mm or cisternal effacement, or any contusion >50 cm^3 should be considered for evacuation. Patients without signs of neurologic compromise or mass effect from their contusions and/or IPH can be managed nonoperatively with serial evaluation, ICP monitoring, and repeat imaging [49].
- *Mass Lesion of Posterior Fossa*: Any posterior fossa traumatic lesion (EDH, SDH, contusion, IPH) that causes compression or effacement of the fourth ventricle, compression or effacement of the posterior fossa CSF cisterns; or associated with obstructive hydrocephalus warrants surgical intervention regardless of

GCS. These patients can deteriorate exponentially from awake with minimal symptoms to obtunded and comatose [49].

- *Depressed skull fractures*: Depressed fractures resulting in compressed fragment(s) depressed past the inner table of the native skull warrant consideration for elevation. Open skull fractures with CSF leak, significant underlying hematoma, violation of the frontal sinuses, significant pneumocephalus, or frank contamination warrant surgical intervention to reduce the incidence of CSF leak and meningitis [49].
- *Penetrating Brain Injuries (PBI)*: Adult series would suggest prompt surgical decompression and/or debridement should be considered for severe PBI with post-resuscitation GCS >5 regardless of a mass lesion. Surgery can be considered for adult PBI patients with GCS 3–5 with mass lesion provided the missile trajectory does not cross the so-called "zona fatalis"—the thalamus, hypothalamus, and midbrain—or brainstem. However, surgery in the GCS 3–5 cohort may improve mortality but may not improve successful outcomes [50]. The St. Louis Scale for Pediatric Gunshot Wounds to the Head is a retrospectively validated decision tool scored 0–18 based on the presence of PBI risk factors for mortality. In 24 pediatric PBI patients, a score ≤4 had a positive predictive value for survival of 88.9%, while a score ≥5 had a negative predictive value for survival of 96.7%. Three variables were associated with 100% mortality in their pediatric PBI cohort: post-resuscitation bilaterally fixed pupils; missile injuries to the "zona fatalis" (though not termed as-such in the manuscript); and ICP >30 mmHg [51].
- *Intracranial Hypertension*: Surgical decompression should be considered to treat sustained intracranial hypertension >20 mmHg without surgical mass lesion as defined above refractory to first and second-tier therapies [46–49].

When patients normalize their ICP, CPP, and $PbrO_2$ and remain stable on neurologic examination for 12–24 h, a gradual, sequential wean from interventions can be started. This usually involves incrementally reversing second and then first-tier interventions [48]. Throughout both the acute and subacute phases of care, consideration must be given to plans for long-term care. Consideration for early tracheostomy and gastrostomy/jejunostomy may be appropriate in particularly severe TBI patients without contraindication. Once stabilized, many severe TBI patients will need disposition to long-term acute care or inpatient rehabilitation centers. While only 3.7% of hospitalized TBI patients are discharged to inpatient rehabilitation, this number is much higher among severe TBI patients [3, 4, 12]. At present, studies are lacking on the long-term sequelae of severe TBI in pediatric patients in early and late adulthood. Unfortunately, the National Institute on Disability, Independent Living, and Rehabilitation Research TBI Model Systems program, has been in place since 1987, and only captures patients 16 years of age or older. Similar initiatives for long-term monitoring of pediatric TBI health effects are ongoing [3].

Conclusions

Traumatic brain injury is a common primary and secondary injury among pediatric trauma patients with high morbidity and mortality. Familiarity with mild TBI clinical evaluation tools can focus the history and examination when evaluating mild TBI patients. Familiarity with the CHALICE, PECARN, and CATCH decision tools and the Brain Injury Guidelines, pediatric modification, can help guide imaging, disposition, and neurosurgical consultation decisions as well as triage at-risk patients to higher echelons of care. Unlike the management of mild TBI, the management of severe TBI is resource and time-intensive. The recent third edition of the guidelines for the management of pediatric severe TBI provides an evidence-based, algorithmic approach to the neurocritical care of these patients to augment existing guidelines for the surgical management of TBI. Overall, familiarity with the breadth of these topics will help facilitate the appropriate evaluation and management of this ubiquitous pathology in pediatric trauma care.

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Chapter 15
Pediatric Facial Trauma

Check for updates

Kerry Latham and Richard J. Redett III

Abstract Trauma is a leading cause of mortality in children (Lopez et al., Pediatrics 138(2):e20161569, 2016; Imahara et al., J Am Coll Surg 207(5):710–6, 2008). Facial Injury patterns vary with age due to growth and development that impacts bone quality, proportional relationship of structures, dentition, sinuses, and soft tissue (Lopez et al., Pediatrics 138(2):e20161569, 2016; Imahara et al., J Am Coll Surg 207(5):710–6, 2008; Totonchi et al., J Craniofac Surg 23(3):793–8, 2012; Ryan et al., J Craniofac Surg 22(4):1183–9, 2011; Meier and Tollefson, Curr Opin Otolaryngol Head Neck Surg 16(6):555–61, 2008; Kellman and Tatum, Facial Plast Surg Clin North Am 22(4):559–72, 2014). A newborn has a relatively large cranium to face ratio of 8:1, but by adulthood, the ratio is 2:1. Infants, toddlers, and children have softer. thinner bones of the facial skeleton. This bone type is more susceptible to greenstick fractures and faster healing. As children approach adulthood, the bone becomes more calcified, the sinuses enlarge and become aerated and permanent dentition erupts (Table 15.1). In the deciduous dentition phase, the permanent tooth buds fill the maxilla and mandible, and once erupted, the maxillary sinus develops more, and the mandible thickens and enlarges. The bones accomplish the majority of the growth in a top-down fashion with the mandible completing growth by age 18 in females and age 20 in males (Ryan et al., J Craniofac Surg 22(4):1183–9, 2011; Meier and Tollefson, Curr Opin Otolaryngol Head Neck Surg 16(6):555–61, 2008; Kellman and Tatum, Facial Plast Surg Clin North Am 22(4):559–72, 2014).

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Based on the growth and development, the mechanisms of injuries also vary as do the fracture patterns (Lopez et al., Pediatrics 138(2):e20161569, 2016; Imahara et al., J Am Coll Surg 207(5):710–6, 2008; Ryan et al., J Craniofac Surg 22(4):1183–9, 2011) (Table 15.2). Skull fractures are more common than facial fractures in infants, with mandible and nasal fractures being the most common in teenagers (Lopez et al., Plast Reconstr Surg 145(4):1012–23, 2020; Gordon et al., Pediatr Emerg Care 37(12):e1701–7, 2020; Coon et al., Plast Reconstr Surg 134(3):442e–8, 2014; Ryu et al., Pediatr Emerg Care 36(3):125–9, 2020; Choi et al., Pediatr Emerg Care 36(5):e268–73, 2020; Jenny et al., Plast Reconstr Surg 147(2):432–41, 2021). CT is the most sensitive and specific modality for imaging fractures (Gordon et al., Pediatr Emerg Care 37(12):e1701–7, 2020; Ryu et al., Pediatr Emerg Care 36(3):125–9, 2020; Choi et al., Pediatr Emerg Care 36(5):e268–73, 2020). C-spine fractures are less common in kids than adults with facial fractures (Xun et al., J Oral Maxillofac Surg 77(7):1423–32, 2019). Children have more facial injuries from dog bites that may have associated facial fractures than adults (Tu et al., Plast Reconstr Surg 109(4):1259–65, 2002; Saadi et al., Craniomaxillofac Trauma Reconstr 11(4):249–55, 2018). Non-accidental trauma should be considered for histories and injuries that don't align or for children with patterns of hospitalizations for injuries or injuries in various stages of healing. Although many facial fractures can be treated nonoperatively, it is important to follow a child through their growth and development as long-term sequelae to include soft tissue or bony growth disproportion can result.

Keywords Pediatric trauma · Face · Fracture · Dog bite

Key Concepts/Clinical Pearls

- Facial injury patterns in children vary based on age, growth, development due to anatomic proportions, soft tissue, bone and sinus development, and age-related abilities and interests.
- Facial fractures are rare in kids under 6.
- Children over 12 have facial fracture patterns more similar to adults.
- Computed tomography (CT) scan with 3D reconstruction is accurate in identifying facial and skull fractures in children.
- C-spine Injuries are less common in kids than adults with facial fractures.

Initial Management of the Pediatric Trauma Patient

The initial management of a pediatric trauma patient is best performed by a trauma team experienced in the care of pediatric patients. Advanced Trauma Life Support principles of Airway, Breathing, Circulation, Disability, and Exposure are important. The pediatric patient may be fearful and difficult to examine. The airway is smaller and any head, face, and/or neck trauma can increase the complexity of airway management. In addition, the larger head size may contribute to a natural flexion position when younger children are lying flat. Trauma is a leading cause of mortality in children [1, 2]. Facial injury patterns vary with age due to growth and development that impacts bone quality, proportional relationship of structures, dentition, sinuses, and soft tissue [1–6]. A newborn has a relatively large cranium to face ratio of 8:1, but by adulthood, the ratio is 2:1. Infants, toddlers, and children have softer, thinner bones of the facial skeleton. This bone type is more susceptible to greenstick fractures and faster healing. As children approach adulthood, the bone becomes more calcified, the sinuses enlarge and become aerated and permanent dentition erupts (Table 15.1). In the deciduous dentition phase, the permanent tooth buds fill the maxilla and mandible, and once erupted, the maxillary sinus develops more, and the mandible thickens and enlarges. The bones accomplish the majority of the growth in a top-down fashion with the mandible completing growth by age 18 in females and age 20 in males [4–6].

Based on the growth and development, the mechanisms of injuries also vary as do the fracture patterns [1, 2, 5] (Table 15.2). Skull fractures are more common than facial fractures in infants, with mandible and nasal fractures being the most common in teenagers [7–12]. CT is the most sensitive and specific modality for imaging fractures [7–9]. C-spine fractures are less common in kids than adults with facial fractures [13]. Children have more facial injuries from dog bites that may have associated facial fractures than adults [14, 15]. Non-accidental trauma should be considered for histories and injuries that don't align or for children with patterns of hospitalizations for injuries or injuries in various stages of healing. Although many facial fractures can be treated nonoperatively, it is important to follow a child through their growth and development as long-term sequelae to include soft tissue or bony growth disproportion can result.

Radiographic/Ancillary Studies

CT scan with 3D reconstruction is the standard for evaluation of facial and skull fractures in the pediatric trauma patient. If there is suspicion of severe head or face injury, then a CT scan is warranted to evaluate for fractures. Point of care ultrasound of the skull and face bones may identify fractures but does not equal or surpass CT scan in sensitivity or specificity, and it cannot be utilized to decide to perform surgery or manage the fractures non operatively [7–9]. Additionally, CT scans are helpful for the surgical team to reference before, during, and after surgery when operative intervention is required. Although C-spine injuries are less commonly associated with pediatric facial fractures compared to adult facial fractures, CT scan for bony injury or T2 MRI for ligamentous injury are preferred modalities [13].

Fig. 15.1 Growing skull fracture. 15-month-old child with pulsations visible on right scalp and history of fall at age 6 months

Pediatric Facial Trauma

Skull Fracture

Skull fractures can occur at any age. Infants and toddlers that are trauma victims are particularly susceptible as their heads are large for their body size [1, 7]. The skull to face ratio in a newborn is 8:1, and by adulthood, it is 2:1 [3, 4]. The skull is thin and the bone is softer in an infant. The head has a large surface area compared to the face and body [3]. Because of the plasticity of the skull in an infant, a minimally displaced skull fracture may have disrupted the dura and then, after pressure or force was relieved, resumed a relatively aligned appearance on CT scan. Intact dura facilitates growth in a growing skull. If the dura is disrupted in a child with a comminuted skull fracture during a period of rapid growth and expansion, they may be at risk of developing a leptomeningeal cyst, also known as a growing skull fracture (Fig. 15.1). In these children, the skull fracture enlarges over time due to the herniation of intracranial tissue through the defect, which can cause significant long-term neurologic impairment. Once a child is more than 24 months, the growth potential reduces and the skull and scalp thicken. By age 12, the skull is relatively fully grown and similar to an adult skull. Management of the fully grown skull is similar to adults. A skull defect of size will present itself as a palpable defect with visible pulsations. The pulsations are more visible in hairless areas such as the forehead.

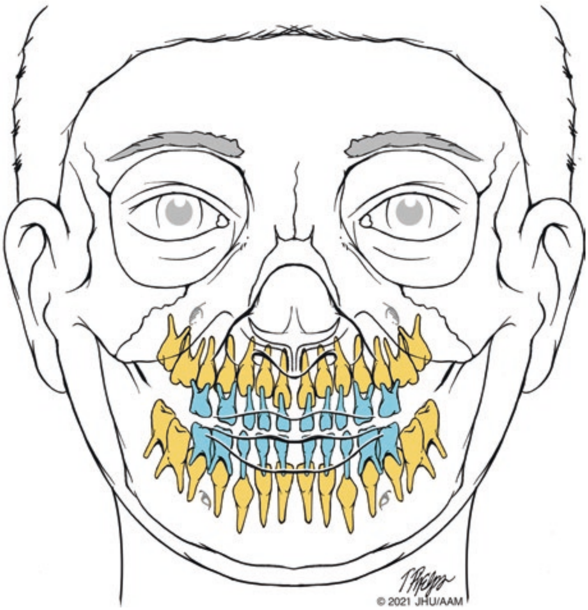

Fig. 15.2 Illustration of skull/teeth/sinus development at different ages. (Illustration by and with permission for publication from Timothy Phelps, M.S. of primary dentition and overlay of secondary dentition prior to eruption in bone and sinuses)

Orbital Roof

Skull fractures can extend into the orbital roof, also known as the anterior skull base. If the fracture is minimally displaced without dural injury or orbital volume changes, then the fracture most likely can be managed non-operatively. Operative management of these fractures almost always requires a small frontal craniotomy to access the orbital roof [10]. Although most of these can be managed conservatively in children, larger, comminuted fractures or those with significant inferior displacement of bone fragments are at higher risk of enlarging over time, resulting in an encephalocele which can cause inferior displacement of the globe or pulsatile exophthalmos [10]. Developing bone is less calcified, thinner, and more flexible allowing for greenstick fractures and incomplete fractures;thus a fewer number of fractures may require repair compared to adult bone.

Orbital Floor Fractures

The facial skeleton generally develops in a top-down fashion, with the skull and orbits growing rapidly in infancy and early childhood. As the deciduous teeth erupt and are replaced by permanent teeth between ages 6–14 years, the sinuses rapidly expand, increasing their projection and elongating the midface [16, 17] (Fig. 15.2). While the sinuses are small and the bone still soft, orbital floor fractures caused by blunt force to the orbit can open inferiorly and trap or pinch the inferior rectus muscle, and then bounce back to near original position leading to what is called a white-eye blow out fracture [16]. Patients with these types of fractures can have a normal-appearing CT scan but are unable to look op on the side with entrapment, and ocular cardiac reflexes can be stimulated, resulting in the triad of bradycardia, syncope, and nausea. Entrapped orbital muscles are at risk of necrosis and fibrosis and should be addressed urgently by surgically releasing the muscle and repairing the orbital floor [16].

As the maxillary, sphenoid, frontal, and ethmoid sinuses expand and aerate, the walls of the sinuses thin and calcify, making them more susceptible to fracture [17]. Once the sinuses develop, much of the strength of the facial skeleton comes from three vertical pillars called buttresses which include the nasomaxillary buttress, the zygomaticomaxillary buttress, and the pterygomaxillary buttress.

Nasal Fractures

Nasal fracture increases in frequency as the nose grows (projects) and as children engage in behaviors and sports that increase the likelihood of injury. Nasal injuries are very common in school-aged and teenaged children. These injuries can usually be diagnosed with a physical exam and do not always require a CT scan. Evaluation of a suspected nasal bone fracture should include close inspection of the nasal septum. A septal hematoma should be drained urgently as it may result in septal necrosis and long-term septal deformity. Only nasal bone fractures that are displaced enough to cause visible deformity require operative reduction. Oftentimes, a delay of 5–7 days is needed to allow swelling to subside before making a decision to perform surgery. Surgery for acute nasal bone fractures typically occurs within 14 days before the nasal bones heal and become fixed.

Midface

Midface fractures are more common in teens and children in later mixed dentition. Preserving permanent teeth and occlusion as well as facial height, width and projection are priorities in treatment [18]. Occlusion may be difficult to assess in children in mixed dentition due to missing teeth. Physical exam should involve facial nerve exam, assessment of extra-ocular movements, vision, pupil exam, palpation of structures for tenderness, crepitus, mobility, and stability [16]. The nose should be examined for the presence of septal hematoma and airway obstruction. Sensation in the V2 distribution should be assessed as numbness may be associated with injury to the nerve secondary to a LeFort or zygomatic maxillary complex fractures (Fig. 15.3) [18].

Fig. 15.3 Skull illustrating Le Fort's article. (Wellcome Collection. In copyright)

Mandible

In children, about one-third of all facial fractures involve the mandible [1]. The most common mechanisms of injury are falls and motor vehicle collisions in infants or small children, and assaults and motor vehicle collisions in adolescents [1]. Common subjective complaints include pain at the fractures site and malocclusion. Patients may also report difficulty opening their mouth (trismus), loose or fractured teeth, and lower lip numbness. Physical examination is often notable for malocclusion, swelling, ecchymosis, gingival or mucosal lacerations, and tenderness over the fracture site.

In children with mandible fractures associated with high force or multisystem trauma, airway stabilization can be difficult because of intraoral bleeding, avulsed or fractured teeth, and unstable mandibular bone segments. Although the risk of c-spine injury is lower in children compared to adults, patients with high-risk mechanisms should undergo cervical spine immobilization and evaluation [13].

All children with suspected a mandible fracture should undergo CT imaging of the entire facial skeleton. The most common type of mandible fracture in children less than 10 years of age is the condyle, and in adolescents, the angle [19]. In children, mandible fracture-related treatment is even more challenging than in adults, given the potential impact on subsequent bone, dental and occlusal development. Surgical or non-surgical management is dictated by the patient's

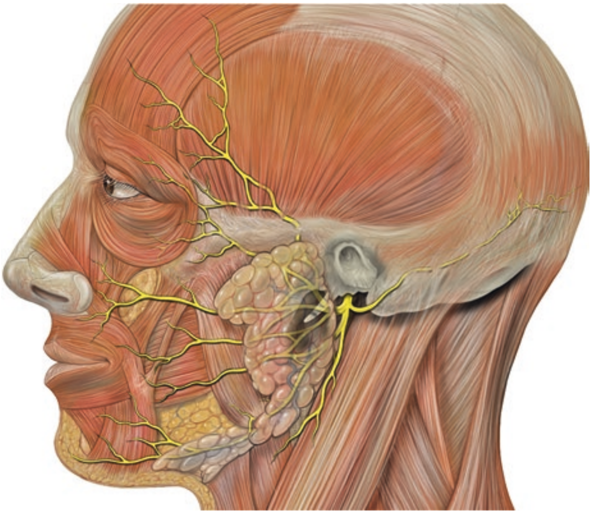

Fig. 15.4 The facial nerve and its branches. (Used with permission from Creative Commons. Created by Patrick J. Lynch, medical illustrator; C. Carl Jaffe, MD, cardiologist. https://creativecommons.org/licenses/by/2.5

age and dental development, and the location and displacement of the fracture(s) [19, 20].

Soft Tissue

The child's face has thicker fat pads and high turgor of the skin. Fat pads are protective for the facial skeleton and globes. They absorb injury and impact but can be damaged and atrophy if affected by hematoma. The skin is taught and has high turgor, so it tends to lacerate in stellate fashion with subcutaneous fat and fat pads herniating, leading the wound to look more challenging to close than it is. Consultation with a pediatric facial surgery specialist for the repair of periocular structures, nose, and lips (central face) is important for the best aesthetic and functional results. Long-term follow-up is recommended after significant bony and soft tissue injury to monitor for sequelae of trauma and to offer timely intervention if needed. Additionally, children benefit from social and mental health support after experiencing significant trauma and impacts many need to be assessed longitudinally.

Facial Nerve

The facial nerve has five major branches to the face: frontal, zygomatic, buccal, marginal, and cervical (Fig. 15.4) [21]. Facial palsy of one or more branches in association with lacerations warrant exploration and attempted repair of the nerve [21]. Nerve repair is more successful if there is a clean cheek laceration lateral to the lateral canthus [21]. Specialists who manage and treat facial palsy and reanimation should be consulted.

Dog Bite

Dog bites are common to the arms and legs as defensive wounds in children of all ages. Dog bites to the face occur at any age but are even more likely in small children. The central face, scalp and neck are commonly involved. Children with significant dog bites to the face should have a CT scan of the face as facial fractures can occur due to the soft bone of a child's face and the power of the canine jaw [14]. If the rabies vaccination status of the dog cannot be verified at the time of treatment, immunoglobulin should be injected in the wound after a thorough cleaning but prior to closure of the wound [22]. A short course of broad spectrum antibiotics is recommended after a dog bite [22]. Tooth puncture wounds may penetrate deeply and be difficult to wash out.

Burn

Children with burns to the face should be stabilized and transferred to a specialized center to manage burns. Protecting the airway is critical as children have small airways that are very reactive. Lips, eyelids, and nasal passageways swell impressively and quickly after a burn. Protecting the airways, cornea, regulating fluids, urine output, and body temperature are also important in transfer [23].

Psychosocial Care

The psychosocial impact of trauma should be addressed in the child's treatment plan. The parents may also require support. Parents may feel guilty or responsible for trauma or may have witnessed the trauma. Facial differences resulting from trauma can impact self-esteem and social interactions. Guided reintegration into school can be helpful. Children with significant trauma to the facial skeleton or soft tissues may have continued care requirements as they grow and develop as long-term sequelae of trauma may result from injury to growth centers. Further reconstructive surgery may be beneficial to improve form or function as the child grows, so follow-up with a pediatric craniofacial surgeon for monitoring and age-appropriate intervention is recommended. Since the Affordable Care Act, access to care has increased for some children, race has not been a contributing factor to trauma mortality in children with facial trauma, but uninsured kids have a lower odds ratio of fracture reduction [11]. Non-accidental trauma should be considered for histories and injuries that don't align or for children with patterns of hospitalizations for injuries or injuries in various stages of healing.

Tables

See Tables 15.1 and 15.2.

Table 15.1 Tooth eruption and shedding for deciduous teeth and eruption for permanent teeth by age (American Dental Association)

Tooth development	Primary eruption	Primary shed	Permanent eruption
Maxillary			
Central incisor	8–12 months	6–7 years	7–8 years
Lateral incisor	9–13 months	7–8 years	8–9 years
Canine	6–22 months	10–12 years	11–12 years
1st Premolar	n/a	n/a	10–11 years
2nd Premolar	n/a		10–12 years
1st Molar	13–19 months	9–11 years	6–7 years
2nd Molar	25–33 months	10–12 years	12–13 years
3rd Molar	n/a	n/a	17–21 years
Mandibular			
Central incisor	6–10 months	6–7 years	6–7 years
Lateral incisor	10–16 months	7–8 years	7–8 years
Canine	17–23 months	9–12 years	9–10 years
1st Premolar	n/a	n/a	10–12 years
2nd Premolar	n/a	n/a	11–12 years
1st Molar	14–18 months	9–11 years	6–7 years
2nd Molar	23–31 months	10–12 years	11–13 years
3rd Molar	n/a	n/a	17–21 years

Table 15.2 Facial fractures by age group: incidence, operative incidence, top 2 facial fracture locations and top mechanisms [1]

Age	% of NTDB trauma admissions with facial fracture	% of age group with facial fractures requiring surgery	#1 injury	#2 injury	Top mechanisms
0–4	2.4%	11%	Skull	Nasal and maxillary	MVC, Fall ,NAT (NAT >FALL in infant), MV-Ped for toddlers
5–9 years	Not available	19%	Nose	orbit	MVC, MV-bike/ MV-ped, Fall
10–14 years	Not available	23%	Nose	mandible	MVC, MV-Bike, Ped, sports/fall
15–18	6.9%	30%	mandible	nose	MVC, Violence

Conclusions

Trauma is a leading cause of mortality in children [1, 2]. Facial Injury patterns vary with age due to growth and development that impacts bone quality, proportional relationship of structures, dentition, sinuses, and soft tissue. Care is best accomplished in a team approach leveraging pediatric trauma specialists with the consideration of the child and the family as a whole and with future growth and development in mind.

Take Home Points

- Many facial fractures in children are non-operative
- Children should be followed after trauma through their growth and development as late sequelae are possible.
- Be mindful of Non-Accidental Trauma (NAT) and have a low threshold to notify Child Protective Services (CPS) for evaluation.
- Psycho-social impact of trauma should be addressed in the child's treatment plan. The parents may also require support. Facial differences resulting from trauma can impact self-esteem and social interactions. Guided reintegration into school can be helpful.

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Chapter 16
Neck Injuries

Edward B. Penn Jr., Charissa M. Lake, and Romeo C. Ignacio

Abstract Pediatric neck trauma is an uncommon entity in the United States. Whether the mechanism of injury is blunt or penetrating, there is a significant risk to the upper aerodigestive tract and the surrounding critical neurovascular structures. The National Trauma Data Bank between the years 2008–2012 for children less than 15 years old with penetrating neck trauma (Advances in pediatric neck trauma: What's New in assessment and management? In: Relias Media—Continuing Medical Education Publishing. https://www.reliasmedia.com/articles/146681-advances-in-pediatric-neck-trauma-whats-new-in-assessment-and-management. Accessed 5 Oct 2021). A total of 1238 pediatric patients were identified among 434,780 children. The most common mechanisms of injury within this group were stabbings and gunshot/firearm. Many blunt injuries are the result of sports participation and play activities. This chapter will focus on blunt and penetrating injuries to the neck, including injuries to the vasculature, digestive tract and larynx and airway management; cervical spine injuries will be addressed separately (Chapter 17).

Keywords Pediatric Neck Trauma · Pediatric Laryngeal trauma · Blunt Laryngeal Injury · laryngotracheal separation · McGovern Criteria · Denver Criteria · Blunt cerebrovascular injury · Penetrating neck injuries

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Key Concepts/Clinical Pearls (Learning Objectives)
Laryngeal Trauma

- The role of flexible fiberoptic laryngoscopy as an initial assessment in evaluation upper airway and endolaryngeal injuries.
- The difference in laryngeal cartilage pliability and calcification in the pediatric larynx in addition to the anatomic considerations.
- Role of CT imaging in a laryngeal trauma.
- The severity of laryngeal injuries and mucosal injuries despite unassuming radiologic findings.
- The role and importance of complete airway assessment with upper aerodigestive tract injury.

Vascular Trauma
- The role of CT imaging in blunt cerebrovascular trauma including utilization of the Denver criteria and McGovern scoring systems in pediatric trauma.
- The necessity and timing of operative exploration in penetrating vascular trauma based on the presence of hard and soft signs.
- The role for antithrombotic therapy.

Esophageal Trauma
- Radiographic workup of suspected esophageal injury.
- Techniques for repair of esophageal injuries.

Initial Management of the Trauma Patient

Initial management of neck trauma and, in particular, suspicion of laryngeal, vascular or upper aerodigestive injury must include a focused history on the velocity and mechanism of injury. Attention to urgent or impending signs of acute life-threatening airway obstruction are paramount with ever present awareness of possible concomitant cervical spine injury. In multisystem trauma, initial treatment consists of airway preservation, cardiac resuscitation, control of hemorrhage, stabilization of neural, and spinal injuries and systemic investigation for injuries to other organ systems [1].

The primary and secondary surveys may identify injuries that require immediate intervention. For critical injuries, imaging should be delayed until immediate airway, ventilation, oxygenation and hemorrhage control are obtained. Injury patterns and signs and symptoms requiring immediate management will be addressed later in this chapter.

Background and Incidence

Pediatric neck trauma is an uncommon entity in the United States. Whether the mechanism of injury is blunt or penetrating, there is a significant risk to the upper aerodigestive tract and the surrounding critical neurovascular structures. Stone et al. queried the National Trauma Data Bank between the years 2008 and 2012 for children less than 15 years old with penetrating neck trauma. A total of 1238 pediatric patients were identified among 434,780 children. The most common mechanisms of injury within this group were stabbings and gunshot/firearm [2]. Blunt injuries to the neck seem to be far more common than penetrating injuries in the pediatric population. Many of these blunt injuries are the result of sports participation and play activities and motor vehicle accidents [1, 3–7].

Clinical Considerations

Larynx

- The pediatric larynx has a higher position in the neck and is protected by the mandible from blunt trauma injuries owing to a lower likelihood of laryngeal fractures.
- Victims of major laryngotracheal blunt trauma may be unconscious or have other concomitant injuries that obscure airway injury [7].
- The potential for laryngeal fractures depends on the mechanism of injury and also the age of the patient. Increasing age influences the rising calcification of the thyroid cartilage and adjacent cartilages. The thyroid cartilage in children is more compliant, and fractures are less likely to occur, whereas in adolescents, this area is increasingly ossified and less compliant leading to a higher likelihood of thyroid fractures [1, 6]

Vascular

- Although both are rare, in blunt injuries, vertebral artery trauma is more commonly associated with cervical spinal fractures. Carotid artery injuries are more likely associated with skull base fractures.
- Intimal shearing is most likely to occur in the distal carotid and V1 and V2 portions of the vertebral artery due to associated rotational and extension forces.
- Risk of stroke with blunt cerebrovascular injury BCVI is 25–40% if the injury remains untreated [8]
- Operative management is typically reserved for penetrating injuries with hard signs of vascular compromise. Most commonly, it is a zone two lesion; however, zone one and three injuries can also require operative repair.

Esophagus

- Aerodigestive injuries are more common than vascular injuries and more likely to occur in younger children
- Primary repair should be the goal in esophageal injuries
- However, a delayed presentation can occur due to occult symptoms and may require more complex management strategies.

Mechanisms of Injury

Blunt Neck Trauma

Early diagnosis and high clinical suspicion of injury are crucial with a history of blunt neck trauma. While normally protected in the pediatric patient, the neck may be hyperextended and rotated during the event leading to exposure of the laryngotracheal complex with shear stress applied to the vasculature and subsequent injury. A rapid and focused history on the circumstances of the injury, mechanism and velocity are essential. While adolescents and older pediatric patients may be able to provide details of the injury, family members or other witnesses may be helpful in younger children and toddlers [6].

Laryngotracheal Injury

The increased pliability of the laryngeal cartilages in children reduces the incidence of laryngeal fractures. Blunt force on a pliable larynx splays the larynx and associated mucosa against the anterior vertebral body. This shearing effect of the upper airway mucosa produces many of the injuries seen endoscopically [1, 6]. Initially, the patient may present with the signs and symptoms of a stable airway and progress to airway embarrassment in several hours. Injuries include mucosal lacerations, supraglottic disruption, vocal cord hematomas, injury to the arytenoid cartilages, rupture of the vocal ligament [1, 3, 5, 7, 9].

Special note must be made of clothes-line injuries which involve high-velocity force an extended neck. This usually occurs when the neck of a young adult or adolescent riding a bike, motorcycle, snowmobile or all-terrain vehicle strikes a stationary object like a wire, rope or tree limb [1, 6]. This mechanism of injury can be especially associated with laryngeal crush injuries (see Fig. 16.1), cricothyroid separation, or cricotracheal disruption. Injuries of this type must be repaired

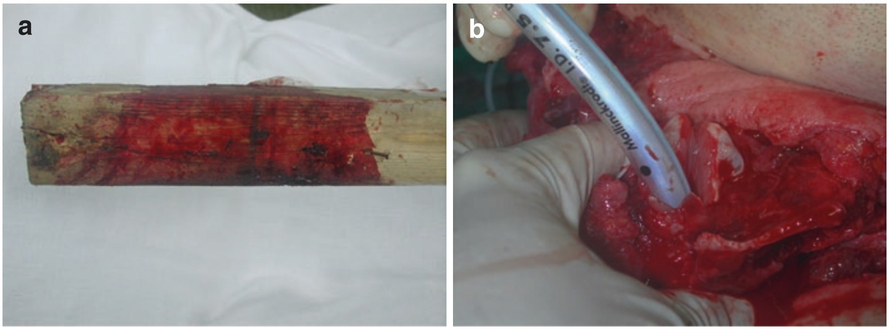

Fig. 16.1 (**a**) 17 year-old passenger of high speed motor vehicle accident into a fence where a wooden post directly struck him along the neck. (**b**) Direct blunt trauma to the neck causing complete division of hypopharynx (endotracheal tube placed into airway) and partial injury to thyroid cartilage. Portion of tongue is seen along the superior aspect of the picture

immediately via neck exploration in the operating room after the airway is secured via a ventilating bronchoscope or tracheostomy.

Vascular Injuries

Blunt cerebrovascular injury results from shear forces generated by extension or rotational forces of the child's proportionally larger head on their relatively weaker neck musculature [10]. Although rare, this injury may initiate and perpetuate an intimal flap resulting in a dissection. In adults, the most commonplace of injury is the carotid bifurcation. However, children are at risk in the distal portion of the carotid and the V1 and V2 portions of the vertebral artery [10]. The vertebral arteries are protected within the spinal column; however, cervical spine fractures can result in injuries to the posterior circulation [11]. Clinically relevant blunt cerebrovascular injury (BCVI) is a rare etiology; however, when present, stroke and resulting complications are potential risks. The diagnosis is typically made with CT angiography of the neck, and treatment consists of medical therapy.

Esophageal Injuries

The cervical esophagus is circumferentially tethered by soft tissue making blunt esophageal injuries uncommon. However, there remains a potential for a ruptured viscus in the neck resulting from associated fractures or barotrauma due to rapid compression and decompression that may require operative management.

Penetrating Neck Trauma

Penetrating neck trauma in pediatric patients is most commonly caused by either gunshot or stab wounds; however, the incidence is only 0.3% [2]. Evaluation and associated injuries have classically been based upon the zones of injury. The zones of the neck are classically divided into three zones:

Zone I: Area between the clavicles/sternum to the cricoid cartilage.
Zone II: Region between the cricoid cartilage to the angle of the mandible (see Fig. 16.2b).
Zone III: Area superior to the angle of the mandible to the skull area.

Symptoms may include subcutaneous crepitus, dyspnea, stridor, shock, expanding neck hematoma, hemoptysis or hematemesis and possible neurologic defects. [1, 2, 9, 12] Neurovascular injury is more commonly seen in penetrating neck trauma compared to blunt mechanisms. Trauma surgeons may estimate the course of injury based on entrance and exit wounds, thus determining which structures may be at risk for injury and require further evaluation; however, all penetrating wounds to the neck require a high index of suspicion for deeper associated injuries (see

Fig. 16.2 (**a** and **b**) 14 year-old sustains entrance and exit wounds (green arrows) along right cheek and left neck (Zone 2 injury). (**c**) Penetrating injury to the hypopharynx and excessive bleeding in the airway required an emergent airway

Fig. 16.2a–c). It may be difficult to determine the depth of injury with knife wounds. The timing of diagnostic and treatment modalities is dependent on the location of injuries, hemodynamic stability of the patient, and suspicion of deeper injuries to the aerodigestive tract or vasculature of the neck.

Laryngeal Trauma—Workup and Management

Clinical Presentation

Classic Symptoms

- Hoarseness
- Laryngeal pain
- Dyspnea
- Dysphagia

Classic Signs

- Dysphonia.
- Aphonia.
- Stridor (Inspiratory versus Expiratory versus Biphasic).
- Subcutaneous emphysema.
- Neck ecchymosis and tenderness.
- Drooling.
- Hemoptysis.

Flexible Fiberoptic Signs

- Vocal cord hematoma.
- Vocal cord immobility.
- Laryngeal edema/lacerations/hematoma.
- Arytenoid injury.

In a cooperative child or adolescent, minor laryngeal injury symptoms may range from hoarseness to complete aphonia [6]. Signs of increased work of breathing may only become apparent after several hours resulting from worsening edema. Flexible fiberoptic laryngoscopy is a crucial tool to assess for signs of a progressing laryngeal hematoma, impaired vocal cord mobility, upper airway mucosal injury, arytenoid dislocation, and glottic or supraglottic edema. Pediatric patients without acute airway symptoms can often be managed conservatively, provided that flexible fiberoptic laryngoscopy provides a safe airway [5]. This should be performed prior to imaging of the airway. Vigilance, keeping in mind the mechanism of injury, must be utilized as an initial unremarkable airway may progress to worsening upper airway obstruction due to hematoma, edema or laryngeal instability due to fracture [9]. Conservative management may include overnight observation versus close follow up with otolaryngology [5]. Bed rest with head of the bed elevation, voice rest, cool humidified room air, racemic epinephrine, and steroids may also be of use to treat minor laryngeal injuries in this group [1].

A conscious patient with severe laryngeal trauma may develop symptoms that can rapidly progress. Concerning symptoms may include tenderness over the laryngeal cartilages, neck ecchymosis, drooling, subcutaneous crepitus, dyspnea, and odynophagia. With this presentation, flexible fiberoptic laryngoscopy is initially utilized to assess and aid in determining more urgent securement of the airway prior to formal imaging. In regard to securing the airway, this is best done under direct visualization by the most experienced personnel with the smallest endotracheal tube in the operating room. Intubation in this setting is hazardous, and repeated attempts may traumatize the larynx and can lead to iatrogenic injury or loss of an already precarious airway [1]. Airway should be secured with the aid of a ventilating bronchoscope. An attempt should be made to perform a thorough inspection of the aerodigestive tract via direct laryngoscopy, bronchoscopy, and esophagoscopy prior to intubation or tracheostomy placement. Inhaled anesthesia via spontaneous ventilation is used to achieve endoscope evaluation prior to tracheostomy placement [1].

A patient with laryngeal trauma who has already been intubated or has had a tracheostomy placed in the field requires a full airway evaluation including direct laryngoscopy, bronchoscopy and esophagoscopy and immediate repair of laryngeal injuries via endoscopic or open neck approach.

Imaging

A stable airway must be assessed by flexible fiberoptic laryngoscopy in order to determine airway patency and rule out endolaryngeal disruption. Minor endolaryngeal injuries, which may include edema, hematomas, mucosal tears, and exposed cartilage seen on endoscopy, may be assessed by CT imaging prior to formal airway endoscopy and repair in the operating room. Signs and symptoms denoting impending airway collapse and instability should be urgently controlled in the operating room if possible, with full airway assessment prior to tracheostomy placement.

The imaging modality of choice is the computed tomography (CT) scan of the neck/larynx if the airway is stable. Imaging should only be performed if this influences the treatment of the patient [6, 9]. In the adult population, Schaefer discussed that imaging was beneficial in patients:

1. with a significant history of blunt force trauma to the anterior neck, with or without abnormal findings on physical examination, particularly with dysphonia or hemoptysis,
2. the condition of the endolarynx and trachea is not observable due to edema or hematoma,
3. the physician is uncertain of the extent of the injury,
4. Imaging can be performed under the supervision of a physician proficient at establishing an emergency airway [9].

It should be noted that due to the minimal calcification of the pediatric larynx, laryngeal fractures may not be seen in this age group. The absence of radiologic findings does not rule out significant laryngeal injury or mucosal trauma.

Management of Injuries

Goals

- Preserving and maintaining airway.
- Restoring function as judged by lack of dependence on a tracheostomy and voice quality [1].

Pediatric laryngeal injuries should be managed via a skilled endoscopist comfortable with endoscopic and open laryngeal reconstructive techniques and ideally evaluated in a tertiary hospital. In general, the earlier laryngeal/upper airway injuries can be reconstructed, the better the vocal outcome. Any surgical delay may lead to cicatricial airway stenosis, a non-functional larynx, bacterial superinfection and poor vocal outcomes, in addition to a potential failure of decannulation [1, 3, 5, 6].

Medical Therapy

- Overnight observation in a monitored unit.
- Bed rest with head of the bed elevation.
- Voice rest.
- Cool humidified room air aid with the prevention of crust formation with mucosal injury and mucociliary paralysis.
- Racemic epinephrine.
- Systemic steroids.
- Antibiotics in mucosal tears or lacerations as prophylaxis against infection.
- Control of Laryngopharyngeal reflux.

Surgical Therapy

- Endoscopic repair.
  - Arytenoid dislocation/avulsion.
  - Small mucosal tears requiring closure.
- Open repair.
  - Thyroid cartilage fractures, laryngeal fractures.
    - Open reduction internal fixation (ORIF).
  - Severe Supraglottic Disruption.
  - Laryngotracheal separation.
    - Laryngotracheal reconstruction with or without stent placement.

Vascular Trauma—Workup and Management

Clinical Presentation

Hard Signs and Symptoms

- Active bleeding.
- Expanding neck hematoma.
- Bruit/thrill.

- Altered mental status/reduced GCS.
- Shock.
- Stridor.
- Neurologic changes—cerebellar ataxia, TIA, sensorimotor deficits, Horner's syndrome, anisocoria, visual deficits.
- Massive epistaxis.

Soft Signs and Symptoms

- Small hematoma.
- Minor bleeding.
- Dizziness.
- Vomiting.
- Loss of consciousness.
- Dysphagia.
- Changing neck exam.

Initial assessment of blunt neck injuries should focus on ABC's to rule out the major airway issues delineated above. Obvious neck trauma with hard signs of vascular compromise on the initial or secondary survey will require operative exploration. If the patient does not have hard signs of injury, but clinical suspicion remains high, imaging can be obtained. In blunt cerebrovascular trauma, scoring systems are used, as noted below, to decide which patients should receive further imaging. The goal is to minimize radiation exposure while also identifying any vascular injuries present due to the risk of stroke. Pediatric neck trauma with vascular injury is rare, so incidence values are derived from a small number of patients. However, if a BCVI is unrecognized, the risk of stroke in adults is reported at 50 and 64% for vertebral and carotid artery BCVI, respectively. In children, this rate is reported between 25 and 40% for all BCVI injuries [8]. Delayed presentation of strokes can occur up to two weeks following an occult missed injury. A thorough physical exam, including neurologic assessment, is key to avoiding a missed lesion.

In penetrating trauma, a physical exam will identify the hard signs of vascular injury. In addition, if there is a violation of the platysma muscle or the patient is hemodynamically unstable, operative exploration should be pursued to rule out a vascular compromise. Imaging may be obtained if clinical suspicion remains in a hemodynamically stable patient with negative findings on the initial physical exam.

Imaging

In BCVI, imaging criterion has been evolving. There is an attempt to balance the risk of radiation in children with the potential complications of a missed vascular injury. If imaging is determined to be required, CT angiography of the head and neck to evaluate the anterior and posterior circulation is necessary.

Originally developed in 1996, the Denver criteria have undergone many revisions but remains a standard to determine when a CTA should be obtained. It should be noted that the Denver criteria were originally developed for adults and subsequently applied to children. If the child has any one of the following signs or symptoms: arterial hemorrhage, cervical bruit, expanding hematoma, focal neurologic deficit, a neurologic exam that does not match CT or findings of a stroke on CT, it is an indication for imaging. In addition, if the patient has risk factors associated with a high-energy mechanism, they should undergo CT imaging including Le Fort II/III, mandibular fracture, complex or basilar skull fracture, severe TBI (GCS <6), near hanging with anoxic brain injury, TBI with thoracic injury, thoracic vascular injury, blunt cardiac rupture, upper rib fractures, scalp degloving, any level of cervical spine fracture, subluxation or ligamentous injury or a seat belt abrasion with significant pain, swelling or altered mental status. Interestingly, recent literature has looked at multivariate analyses in pediatric patients, which have demonstrated the isolated presence of a seatbelt sign, in particular, has not reached significance for association with BCVI when other variables are accounted for in the multivariate analyses [13].

Additionally, the modified McGovern score has been used to specifically screen pediatric patients for BCVI. It was based on the initial Utah Scoring system, which was developed specifically for the pediatric population and assigned points to certain risk factors and signs and symptoms to determine if CTA should be obtained. A score greater than or equal to three indicates imaging is necessary. The Utah scoring system assigns points for GCS less than or equal to 8 (1), focal neurologic deficits (2), carotid canal fracture (2), petrous temporal bone fracture (3), and cerebral infarction on CT (3). The modified McGovern score uses these variables but also assigns two points to high-velocity mechanisms of injury. In short, if the patient has any of the risk factors identified in the Utah score and a high-velocity mechanism, a CTA is warranted to assess for injuries [14].

Management of Injuries

Goals

- Control hemorrhage.
- Preserve antegrade flow and reduce stroke risk.

Medical Therapy

- Dependent on the severity of injury and the presence of cerebral ischemia or signs of stroke.
- If BCVI is diagnosed, it should be treated with antithrombotic therapy.
- Type of preferred agent (antiplatelets and anticoagulant) as well as the duration of therapy has not been well established [8].

- Antiplatelet therapy has been implemented for lower grade lesions, whereas either anticoagulants and antiplatelet medications are used for more severe lesions [8].
- Follow-up imaging is required to determine progression or resolution, as well as determine the duration of antithrombotic course; in adults, it is recommended to obtain interval imaging at seven days and three months. At least three months has been used as a benchmark duration of antithrombotic therapy [13].

Surgical Therapy

- A collar incision is utilized for bilateral injuries requiring exploration; unilateral injuries can bed exposure through an incision anterior to the sternocleidomastoid.
- In addition to the vasculature, attention should be given to the hypoglossal, vagus and recurrent laryngeal nerves during a zone 2 dissection.
- Zone 3 injuries may require a superior extension of excision and are difficult to visualize in small children as access is limited due to smaller, more compressed anatomy.
- Zone 1 injuries may require median sternotomy with or without extended clavicular incisions. Special attention should be paid to the locations of the phrenic, vagus and recurrent laryngeal nerves as well as the brachial plexus.
- Utilization of patch versus primary repair of the carotid artery is determined by the extent of vessel injury and the resultant narrowing. If the vessel is significantly narrowed, patch repair should be undertaken, especially in small children.
- In damage control scenarios, the external carotid or common carotid may be ligated as the internal carotid should receive collateral flow.
- Unilateral internal jugular vein injuries may be ligated. Bilateral injuries require primary repair of one side for adequate cerebral drainage.
- Vasospasm is a potential complicating factor, especially in smaller pediatric patients that could lead to more difficulty with repair and risk of hypoperfusion.
- Shunts and endovascular interventions are not advised in children due to small vessel size and ongoing growth potential.
- Recent studies have indicated that providers continue anticoagulation following operative repair: for arterial injuries, aspirin was most commonly used while Lovenox was used for venous injuries [15].

Esophageal Trauma—Workup and Management

Clinical Presentation

Hard Signs and Symptoms

- Hemoptysis.
- Hematemesis.
- Bubbling the wound.

Soft Signs and Symptoms

- Dysphagia.
- Odynophagia.
- Dysphonia.
- Drooling.
- Subcutaneous emphysema.

Subcutaneous emphysema or bubbling from the wound indicate a connection with the aerodigestive tract. Airway injuries should be ruled out first prior to evaluating for esophageal defects. Additionally, signs of significant intraluminal bleeding from the aerodigestive tract should prompt thorough evaluation. However, many esophageal injuries can be missed due to their insidious presentation with either mild soft signs of injury or no signs at all. If clinical suspicion exists, especially in penetrating trauma, further investigation should occur.

Imaging

Chest and neck X-rays can demonstrate subcutaneous air that may not be clinically evident on exam raising the suspicion of an esophageal injury. If the patient is stable, an esophagogram with water-soluble contrast can be obtained to visualize an injury with evidence of contrast extravasation from the esophagus. Additionally, an esophagoscopy can be considered to evaluate for presence and location of the traumatic defect and is more sensitive than an esophagogram. Under direct visualization, a nasogastric tube can be placed past the defect which may allow for enteral nutrition access. It is important to distinguish between injuries in the cervical and thoracic esophagus. Thoracic esophageal injuries have an inferior prognosis due to the risk and severity of mediastinitis, while cervical injuries have a decreased associated morbidity and mortality.

Esophageal injuries can have a delayed presentation due to a lack of immediate symptoms. Fluid collection of the region of the cervical esophagus on a CT scan with a history of localized injury to the neck—either penetrating or blunt—should raise suspicion of a traumatic esophageal injury.

Management of Injuries

Goals

- Maintain digestive continuity.

Medical Therapy

- Blunt esophageal injury without perforation will be managed conservatively with NPO status and time to allow improvement in swelling and edema.
- A nasogastric tube is placed under direct visualization with endoscopy or TPN for parenteral nutrition while the patient is NPO.

Surgical Therapy

- Endoscopy may be attempted if there is a clinical suspicion without clear evidence of injury and for placement of nasogastric tube—however, it can be difficult in small children and may have a low yield and potential for missed injuries.
- A surgical approach is through a left-sided anterior sternocleidomastoid incision.
- Preference is primary closure—debridement to viable tissue with one or two-layered closure using absorbable sutures.
- If unable to close primarily, especially in cases of delayed recognition of injuries, plan for wide drainage.
- Esophageal diversion should be avoided. In adults, creating a controlled fistula with a T-tube has been described [16].
- Buttressing of esophageal injuries can be attempted with muscle flaps from the sternocleidomastoid or infrahyoid muscles (omohyoid in particular).

Conclusions and Take Home Points

Although uncommon, pediatric blunt and penetrating neck injuries do occur. Laryngeal and tracheal injuries can result in emergent airway issues. While radiologic imaging can aid in managing of neck/laryngeal injury, Otolaryngology consultation and flexible fiberoptic laryngoscopy should be an initial assessment tool to assess and ensure airway patency and mucosal injury. Management of identified injuries, endoscopically or via neck exploration must be initiated immediately in order to provide an optimal outcome. Pediatric vascular trauma is also rare. However, using proven scales, such as the McGovern screening score, can identify patients at risk for blunt cerebrovascular injury who should receive a screening CTA of the neck. Carotid injuries are more commonly associated with basilar skull fractures, while vertebral injuries co-exist with cervical spine fractures. Once identified, these patients can be appropriately treated to avoid the risk of stroke. Penetrating injuries to the neck should be monitored for hard signs of vascular injury which require immediate operative exploration. Exposure and repair may be more difficult in the pediatric neck due to patient size. Esophageal injury is also uncommon and, due to occult symptoms, can be diagnosed in a delayed fashion. Prompt identification allows for immediate evaluation with esophagogram and/or endoscopy facilitating primary repair.

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Chapter 17
Traumatic Spinal Injuries in Children

Gretchen Floan, Romeo C. Ignacio, and David Mooney

Abstract The most common mechanisms of spinal cord injury include motor vehicle collisions, sports, falls, and child abuse. The pediatric spine is more mobile, deformable, and underdeveloped when it comes to spinal muscular strength and ligament integrity. These predisposing factors contribute to spinal trauma in pediatric patients and result in a higher frequency of spinal cord injury without spinal column fracture, which is unique to pediatric patients <8 years old. The older the patient (>8 years old), the more mature the spine becomes and the more similar the injury patterns become to the adult patient.

Initial management starts with the primary resuscitation as defined by Advanced Trauma Life Support protocols. Vital signs should be monitored, and the spine protected using an appropriately sized cervical collar and log roll precautions. If there is a concern for spinal injury, radiographic studies should be obtained to include plain films, along with CT and MRI scans if indicated. It is important to also keep in mind that spinal column injuries may have multilevel injuries or involve concomitant thoracoabdominal injuries that may require more urgent intervention.

Pediatric patients can suffer certain fracture patterns, including compression, flexion-distraction, burst, apophysis, spinous process and transverse process fractures, slow vehicle crush injuries and spondylolisthesis/spondylolysis. If the fracture is unstable and/or there are neurologic deficits present, these fractures will

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often undergo operative intervention. Neurologic injuries can also occur either with or without spinal fractures. These neurologic injuries can affect the anterior, posterior, and central spinal cord regions. Other neurologic injuries include Brown-Séquard syndrome, Cauda equina syndrome, and Spinal cord injury without radiographic abnormality (i.e., SCIWORA) which is unique to pediatric patients. There is a risk of progressive spinal deformity, so patients should be followed through skeletal development to monitor for worsening deformities.

Keywords Pediatric spine injury · Cervical Spine · SCIWORA · Thoracic spine · Lumbar spine · Pediatric trauma · Spinal cord injury · Fracture

Key Concepts/Clinical Pearls (Learning Objectives)

- Understand the risk factors and mechanisms that predispose pediatric patients to spinal trauma.
- Understand the initial evaluation and imaging modalities for pediatric trauma patients at risk for spine injury.
- Understand indications for operative management of pediatric patients as well as nonoperative options.
- Understand cervical spine injuries as well as spinal cord injury without radiographic abnormality (SCIWORA) in pediatric patients.
- Understand thoracolumbar fracture patterns that can take place in pediatric patients.
- Understand the neurologic injuries that can be associated with thoracolumbar spinal trauma in pediatric patients.

Initial Management of Trauma Patient

Initial management starts with the primary survey as defined by Advanced Trauma Life Support protocols. The ABCDE's include airway management, breathing and ventilation, hemorrhage control and circulation, neurologic exam and disability, and exposure with environmental control. Vital signs should be monitored, and the spine protected using an appropriately sized cervical collar and log roll precautions [1]. An accurate history and secondary physical exam should be obtained. Radiographic studies should be obtained if there is a concern for spinal injury. The cervical collar should remain in place until both radiographic and clinical clearance have been performed. If a thoracolumbar injury is found and there is any concern for unstable injury, presence of spinal cord compression or neurologic deficit, or poor chance for long-term healing potential, operative management should be pursued. It is important to also keep in mind that spinal column injuries may have multilevel injuries or involve concomitant thoracoabdominal injuries that may require more urgent intervention.

Initial Radiographic/Ancillary Studies

The primary diagnostic studies for injuries to vertebral bodies are radiographic imaging. Currently, consensus recommendations are the main source of available guidelines to determine appropriate imaging modalities. Imaging often begins with AP (anterior posterior) and lateral x-rays of the entire spine as the initial screening modality. Due to poor technique or body habits, plain films may fail to detect the number of spinal fractures that may better be detected on a CT scan. A CT scan may assist with the diagnosis of osseous and soft tissue injuries but risks exposing the pediatric population to radiation [2, 3]. MRI scans can be obtained in place of CT scans to spare the patient radiation exposure. MRI scans may be necessary to detect injuries to the spinal cord and ligamentous structures and should be obtained if a patient presents with neurologic deficits on exam [4]. Consideration of sedation may be required depending on the age of the patient. In addition, pediatric protocols should be in place to minimize radiation exposure while obtaining adequate imaging quality.

Epidemiology

Spine injuries are relatively common, but spinal cord injuries are rare. Despite their rarity, the life-long effect of a missed spinal cord injury, along with liability concerns, give these injuries an outsized level of concern and cause providers to do much more than necessary to rule them out. Clinicians need some basic strategy to identify children with a realistic risk of having a spine injury to save the bulk of children unnecessary imaging and yet diagnose children with injuries promptly. If unable to rule out an injury, patients may be left safely immobilized while more urgent issues are addressed. No strategy is perfect and clinical suspicion must remain high at all times.

It's difficult to ascertain an exact number of how many children suffer a spine and/or spinal cord injury per year. An unknown number of children who suffer high cervical spine injuries die at the scene from respiratory insufficiency, and others die at the scene, en route, or soon after arrival to a hospital from a traumatic brain injury or other high energy injuries, and their spine injuries remain undiagnosed. Brennan et al. reported that 85% of the children under 2 that died from an abusive head injury in the city of Philadelphia were found on autopsy to have cervical spinal cord injuries, none of whom had cervical spine fractures [5].

Every year over eight million children under 18 present to an emergency department for the treatment of an injury [6]. Approximately 1 in every 1000 of these children are found to have a spine injury, and 1 in 3600 are found to have a spinal cord injury [7]. Of 1372 high-risk children brought to one of 4 trauma centers immobilized by prehospital providers or as a trauma activation, 25 (1.8%) were found to have a cervical spine injury [8]. In a review of hospitalized children under 18 years of age, Piaf et al. reported an incidence of 7800 spine injuries per year [7]. Fifteen percent of those children, or 2200, suffered a spinal cord injury. Nearly 2/3, or 1400 of the spinal cord injuries occurred in teenagers from 15 to 18 years of age, and only 800 occurred in children 14 years of age and younger. Injuries are even more unusual in very young children. Pieretti-Vanmarcke gathered retrospective data from 22 large trauma centers over 10 years, including 12,537 hospitalized trauma patients under 3 years of age [9]. Only 8 children, or 0.06%, suffered a cervical spinal cord injury, fewer than 1 child per center for every 27 years.

Etiology

Motor vehicle collisions are the dominant injury mechanism of cervical spine injury reported by Piaff with falls second (see Table 17.1). Spine injuries have decreased nearly half from 1997 to 2012, in parallel with the decrease noted in overall adolescent injury rates [7]. Much of this decrease has been ascribed to decreased motor vehicle collisions and greater passenger restraint use [10].

Surprisingly, the most common spinal level injured was the lumbosacral spine, likely secondary to inappropriate use of a lap belt. In younger children, upper cervical spine injuries were next, closely followed by thoracic spine injuries. In adolescents, the remainder of non-lumbosacral spine injuries were nearly evenly distributed (see Table 17.2). One in 7 patients had multiple levels of spinal injury [7].

The distribution of injuries to the upper cervical spine in younger children is secondary to differences in anatomy. Children's heads are larger and heavier per body surface area than adults. In addition, their neck muscles and ligaments are

Table 17.1 Mechanisms of injury of children with a spine injury

Mechanism	Children 0–14	Adolescents 15–18
Motor vehicle crash	31.9	50.0
Fall	18.3	10.0
Pedestrian	6.8	3.0
Penetrating	1.2	3.4
Sport	2.0	1.8
Bicycle	1.8	0.9
Abuse	1.7	0.0
Unknown	36.3	30.9

Table 17.2 Percentages of children injured in various spine levels

Spinal Level	Children 0–14	Adolescents 15–18
Upper Cervical	21.0	10.9
Lower Cervical	8.3	11.4
Thoracic	18.8	18.0
Lumbosacral	36.0	43.1
Multiple	11.5	14.4
Unknown	4.3	2.2

Table 17.3 Differences between Pediatric and Adult Spine Injuries

Injury Feature	Pediatric	Adult
Spinal injury level	Craniocervical junction to C3	C5-T1
Fulcrum level	C2-C3	C5-C6
Injury type	More likely ligamentous or soft tissue	More likely osseous
Longitudinal distractibility	Susceptible to longitudinal distraction SCIWORA	Less susceptible SCIWORA rare
Trauma-associated cord infarct	Infarction may be delayed	Delayed infarction rare

Adapted from: McAllister AS, Nagaraj U and Radhakrishnan R. Emergent Imaging of Pediatric Cervical Spine Trauma. Radiographics 39 (2019). 1126–1142 [14]

weaker, and the anterior cervical vertebral bodies are wedged, making hyperflexion injuries more likely [11–13]. Children are more likely than adults to suffer ligamentous injuries and less likely to suffer a fracture. The anatomic differences of cervical spines between adults and children go away by the age of 9 years. Beyond that age, a child's cervical spine anatomy and injury patterns are anatomically similar to adult patients (see Table 17.3). These differences may help guide the choice of imaging studies.

Pediatric Spine

The pediatric spinal vertebra is more mobile and deformable compared to the adult spine. The vertebrae are cartilaginous and incompletely ossified, and the spinal structure is maintained by lax ligaments and underdeveloped spinal muscles leading to less protection of the cervical spine. The facet joints are also oriented more horizontally allowing for more mobility. For these reasons, younger children tend to have spinal cord and ligamentous injuries without vertebral fractures. Young children have a disproportionate head size in relation to their body, creating an innate instability in the cervical spine. This larger head leads to a higher fulcrum which translates to a higher level of cervical spine injury. As the child ages, the fulcrum point is changed to a lower spot on the cervical spine. The expected fulcrum spot based upon age is as follows: [11–13, 15].

Infants—C2 to C3.
Toddlers—C3 to C4.
Adolescents—C4 to C5.
Adults—C5 to C6.

The spinal cord in pediatric patients is less protected as the spinal column elasticity allows it to withstand compression from outside forces and transfer this energy to the underlying neural structures. The spinal column is also more mobile than the underlying spinal cord and dura, resulting in a higher incidence of neurologic injury in younger children when compared to adults [11–13, 15].

Between the ages of 8–10, the spine matures to the point of resembling an adult spine with similar biomechanics. As such, spinal injuries such as vertebral fractures and ligamentous rupture are more common in older children and adolescence. Cervical spinal injury is more common in younger patients for reasons already mentioned, but as the child ages (>8 years old), injuries in the thoracolumbar region are more commonly seen [11–13, 16, 17].

Clinical Features

Midline cervical tenderness is the most common presentation of a cervical spine injury [17]. This can be difficult to elicit in a child who is non-verbal or who has trouble localizing the tenderness to the midline versus the paraspinal region. A high index of suspicion is therefore warranted. If midline cervical tenderness is present, a cervical collar must be in place, and range of motion testing should be avoided until radiographic and neurologic examinations are performed. Cervical spine injuries may also present with a triad of neck symptoms, including cervical pain, muscle spasm and decreased range of motion. The absence of symptoms in the setting of a high-risk injury should not preclude further radiographic imaging as 18% of pediatric patients were found in one study to be asymptomatic despite a cervical spine injury [17].

On initial examination, midline tenderness and ecchymosis have a 87% sensitivity and 75% specificity for thoracolumbar fractures [18]. “Breathlessness” at the time of injury can be used as another marker suggestive of underlying injury despite negative radiographs [19, 20]. Thoracolumbar spinal fractures can involve multiple levels 11–35% of the time, so the diagnosis of one fracture requires a thorough evaluation of the rest of the spine [18, 21]. It is also important to be aware of other associated intra-abdominal and intra-thoracic injuries that can occur in relation to spinal fractures, in particular the association with Chance fractures and injuries to the small bowel, mesentery, and pancreas (see Fig. 17.1). This is important to be mindful of as these abdominal injuries can sometimes have a delayed presentation and cause significant morbidity to the patient. Thoracic fractures can also be associated with lung contusion or injury, pneumothorax, hemothorax or aortic injury. These concomitant injuries occur in up to 40–50% of thoracolumbar spinal injuries [16, 20].

In pediatric patients, there are four patterns of injury that can describe spinal column trauma. These patterns are based on whether or not there is a fracture, subluxation, or spinal cord injury. Younger patients typically have (1) ligamentous injury from subluxation or dislocation without a fracture or (2) spinal cord injury without radiographic evidence of fracture based on their spinal mobility and ligament laxity. The other two injury patterns include (3) fractures with subluxation and (4) fractures without subluxation. The adolescent population (10–17 years old)

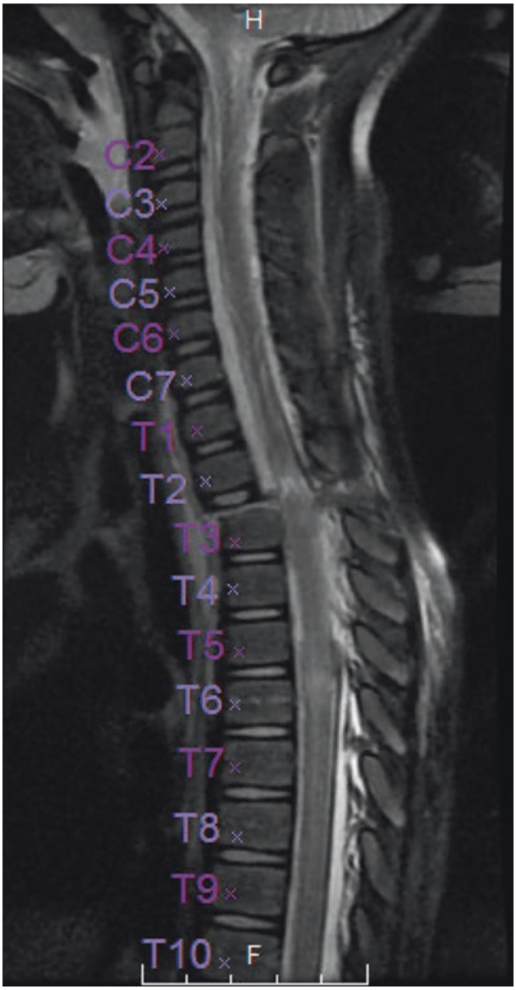

Fig. 17.1 MRI of the spine of a 7-year-old restrained passenger involved in a high-speed motor vehicle accident was diagnosed with an osteoligamentous Chance Fracture at T2–T3

more commonly displays these latter injury patterns given the development and maturation of their spine [20].

Diagnosis

History & Physical

In the process of diagnosing a spinal column injury, history, physical exam, and radiographic studies each play an important role. Mechanism of injury is important along with a history of head trauma or loss of consciousness. Screening for midline pain and paresthesias can also be helpful in older children, along with a reported history of bowel or bladder incontinence [17].

Examination should first start with an evaluation of the Glasgow coma scale. Next, an attempt should be made to perform a spinal and neurologic exam, including anogenital reflexes if concerned for spinal cord injury. The neurologic exam should be performed serially to evaluate for worsening or improvement in symptoms [17].

Imaging Guidelines

While consideration of the frequency of spine injuries may help inform policy and clearance guidelines, it will not help you determine if the child in front of you has a spine injury. Methods used to split patients into high-risk and low-risk groups may be useful for directing concern and imaging to those with a realistic risk of injury. A variety of scoring systems have been developed to help with that process and maybe most helpful to determine which patients do not need imaging (see Table 17.4).

Four groups have developed consensus-based risk stratification systems. Similar key elements are present in each, and a comparison of the various scoring systems: NEXUS (National Emergency X-Radiography Utilization Study) [22], Canadian [23], PECARN (Pediatric Emergency Care Applied Research Network) [24], and PCSCWG (Pediatric Cervical Spine Clearance Working Group) [25].

Table 17.4 Comparison of available scoring systems

	NEXUS-2001	Canadian-2001	PECARN-2011	PCSCWG-2019
Deficits	Focal deficit	Paresthesias	Focal deficit	Focal deficit
Phyiscial exam	Midline tenderness	Midline tenderness, abnormal neck rotation	Torticollis	Posterior midline tenderness, torticollis, limited rom
Mental status	Altered mental status/ intoxication	Not sitting in ed and not ambulatory	Altered mental status	GCS < 14
Distracting injuries	Distracting injuries		Substantial torso injury	Not able to focus because of other injuries
Mechanism		Dangerous mechanism, rear end collision	High risk mvc, diving	Stronger consideration for some
Neck pain		No delay in neck pain onset	Complaint of neck pain	Pain or parent report
Predisposing condition			Predisposing condition	
% of patients imaged [12]	44.2	48.4	68.1	–

Criteria for high risk of cervical spine injury that are consistent across the different scoring systems include neurological deficits, cervical spine tenderness or abnormal neck rotation, distracting injuries, high-risk mechanisms, and neck pain. In addition, the PECARN criteria include children with medical conditions such as connective tissue diseases and Down Syndrome [24]. Mannix et al. conducted a decision tree analysis of cervical spine clearance in children and concluded that cervical spine clearance is a clinical event and that the best outcomes were associated with clinical clearance for the majority of children with imaging reserved for those with positive screening [26]. In a single-institution series of 973 children who presented to a pediatric ED in Australia immobilized by prehospital providers, having neck pain or otherwise considered high risk for cervical injury, there were 5 children (0.5%) who had cervical spine injuries, and all were captured by each of the scoring systems, but each system was found to have a low specificity and would have still resulted in imaging for 44.2 to 68.1% of patients [27].

Screening Imaging Studies

Using imaging to screen the broad range of children who present to an emergency department in order to identify spine injuries is strongly discouraged, as the number of children with an injury is very low, and the number harmed by the radiation necessary to obtain the images is not trivial. Once the decision to image has been made, children cared for at pediatric trauma centers were shown to be more likely to undergo plain radiographs and MRI and less likely to undergo CT scan than children cared for at adult level 1 trauma centers [28]. The American College of Radiology has released consensus-based national guidelines for which imaging modality, if any, to select (see Table 17.5) [29].

Table 17.5 ACR appropriateness criteria for imaging studies in suspected child spine trauma

Age	Screening tool	Imaging	Comments
<3 years	Negative	None	Pieretti-Vanmarcke weighted score <2
	Positive	Plain films	Usually appropriate
		MR	May be appropriate
		CT	Usually not appropriate
3 to 16 years	Negative	None	NEXUS or PECARN as screening tool
	Positive	Plain films	Usually appropriate
		MR	May be appropriate (disagreement)
		CT	May be appropriate (disagreement)

There is scant data on cervical spine injuries in young, preverbal children. Pieretti-Vanmarcke created a weighted score: GCS < 14, GCSEYE = 1, MVC, and aged 2. A score of <2 had a sensitivity of 92.9%, as 5 of the 83 spine injuries would have been missed, and over 30% of children would have still undergone imaging [9]. Anderson et al. were able to clear the majority of such young children through the use of physical exam and plain films without cross-sectional imaging and felt that it was much less likely that a CT scan would be helpful given that ligamentous injury was more common in this age group [30].

A single lateral cervical spine radiograph is a common component of trauma resuscitation. Silva et al. reviewed the value of a single lateral view and multiple view cervical spine radiographs in 234 children who subsequently underwent CT scan [31]. The single plain film had a sensitivity of 73% for identifying injuries later seen on CT scan with no improvement in sensitivity when multiple views were obtained [31]. In a similar study, Nigrovic et al. found that plain films had a 90% sensitivity for identifying injuries noted on CT scan in a group of 186 children with cervical spine injuries [32]. Quality odontoid views may be difficult to obtain in younger patients and are less helpful [33].

Putting it all together, many pediatric trauma centers have created algorithms to guide their clinicians in evaluating the cervical spine. Algorithms have been shown to reduce the time required to remove the cervical collar, while decreasing radiation exposure, especially CT radiation [34, 35]. Arbuthnot analyzed the use of a cervical spine evaluation algorithm in 1023 children who presented to a pediatric trauma center in a cervical collar. She found that 23.2% were cleared without any spine imaging, 67.3% underwent plain films, and only 0.5% underwent CT only. The negative predictive value of the algorithm was 99.9%, and there were no significant missed injuries [36].

The Pediatric Cervical Spine Clearance Working Group, a multidisciplinary group of national experts in pediatric cervical spine injuries, was gathered by the Pediatric Orthopedic Society of North America, created a complex, but reasonable consensus-based evaluation management algorithm using a Delphi process (see Fig. 17.2) [25].

Use of protocol based on that algorithm was reported to increase the percentage of children cleared without radiographs while decreasing the number who underwent CT scan and MRI, with no missed injuries [37]. Adopting a ‘Next Day’ examination policy to assist in clearing the spine in children without neurological findings decreased the amount of radiation exposure without compromising the diagnosis in one pediatric center [38].

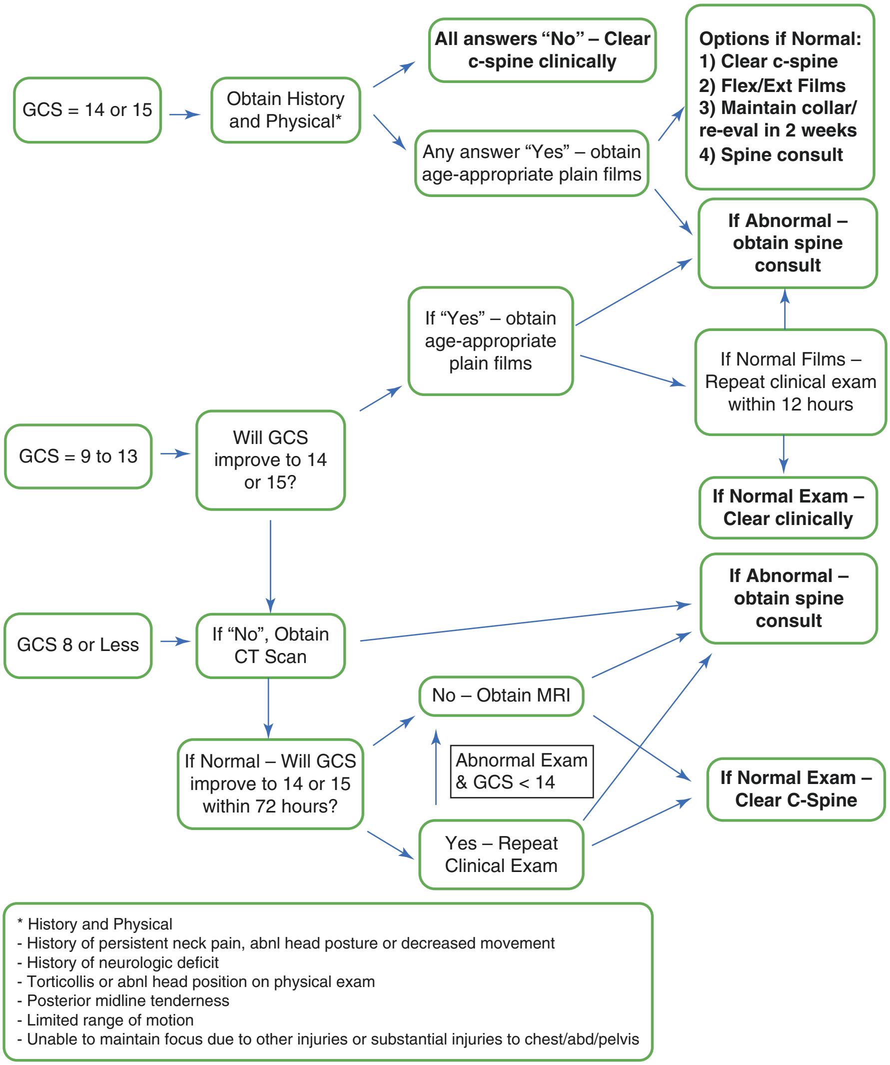

Fig. 17.2 Proposed Pediatric Cervical Spine Clearance Algorithm (adapted from Herman MJ, Brown KO, Sponseller PD, et al. Pediatric Cervical Spine Clearance. A Consensus Statement and Algorithm from the Pediatric Cervical Spine Clearance Working Group. J Bone and Joint Surg Am. 2019 101-a:e1(1–9) [25])

Initial Management

While the details of management are beyond the scope of this chapter, there are some broad principles that govern management. Immobilization of the cervical spine must be maintained until an injury is ruled in our out. If ruled in, management is focused on sustaining perfusion of the cervical spinal cord while maintaining immobilization in order to prevent additional injury to the cord. More permanent stabilization may be required through the use of a halo or by internal fixation. Epidural hematomas that compress the spinal cord and require prompt evacuation are rare. There is no evidence that steroid administration is helpful in patients with spinal cord injuries, while there is good evidence that it may be harmful [39]. Neurogenic shock may occur in up to 19% of patients with a cervical spinal cord injury and should be considered in any patient with a spinal cord injury higher than T 10 [40].

Initial management starts with securing the ABCDE's and beginning resuscitation. Vital signs should be monitored, and the spine protected using log roll precautions and cervical spine immobilization [1]. It is also important to be mindful that patients with cervical or high thoracic spine injuries may display neurogenic shock or develop respiratory failure [17]. **Immediate consultation to either neurosurgery or orthopedic surgery, depending upon institutional practice guidelines, is warranted**.

If a spinal column injury is diagnosed, management depends on the (1) stability of the spine, (2) spinal cord compression and underlying neurologic deficits, and (3) potential for long-term healing. Approximately 7–30% of thoracolumbar spinal fractures require operative intervention with the goals of achieving fracture reduction, stabilization, and spinal cord decompression [19, 20]. Surgeons are becoming more comfortable with thoracolumbar instrumentation in pediatric populations as it has shown good outcomes regarding injury correction and kyphosis deformities; however, others feel the extent of instrumentation should be minimized given the possible risk for long-term deformities and growth deficits [18, 20].

Several injury classification systems exist in order to describe and guide management for spinal column injury. A three-column system exists dividing the spine into anterior, middle and posterior columns. Disruption of 2 or more columns is thought to cause instability to the spine. This classification system is commonly employed but has not been well validated scientifically. Another classification system commonly used outside the United States classifies by fracture type such as burst, compression, flexion-distraction, flexion-compression. Certain fracture patterns have a higher likelihood of operative management (i.e., burst fractures), and some are better suited for nonoperative management (i.e., compression fractures) [16, 18, 20].

A reliable and more comprehensive classification method is the Thoracolumbar Injury Classification and Severity Score (TLICS) (see Table 17.6), which guides management for patients that may need operative intervention versus conservative management. This classification system includes morphology, disruption of

Table 17.6 Thoracolumbar Injury Classification and Severity Score [41]

Parameter	Points
Injury Morphology	
Compression Fracture	1
Burst Fracture	2
Translational/Rotational	3
Distraction	4
Posterior Ligamentous Complex	
Intact	0
Injury Suspected/Indeterminate	2
Injured	3
Neurologic Involvement	
Intact	0
Nerve Root Involvement	2
Cord/Conus Medullaris Injury	
Incomplete	3
Complete	2
Cauda Equina Syndrome	3

posterior ligamentous complex, and neurologic involvement. Each one of these components is given a score based on objective findings, and a score > 4 leads to a surgical recommendation. A score equal to 0–3 leads to conservative or nonoperative management, and a score equal to 4 is left to surgeon experience and choice of either operative or nonoperative intervention [16, 19, 20, 41].

When there is a stable fracture pattern and an absence of neurologic injury, nonoperative management can be safely undertaken. Nonoperative management consists of external bracing or body casting. This method of management can be pursued in some unstable fractures as long as no neurologic deficit exists and there is a high potential for healing with nonoperative treatment [20]. The treatment of children with unstable cervical fractures utilizes the placement of a halo-vest immobilization with fluoroscopic guidance to ensure appropriate reduction [42].

Fracture Patterns and Radiographic Abnormalities

Atlanto-Occipital Dissociation

Atlanto-occipital dissociation (AOD) (see Fig. 17.3) is a rare condition, although it is increasingly recognized, and autopsy studies have shown that it is one of the most common causes of death following high-impact motor vehicle collisions. Due to the high mortality associated with this condition, it is rare to see this clinically. The

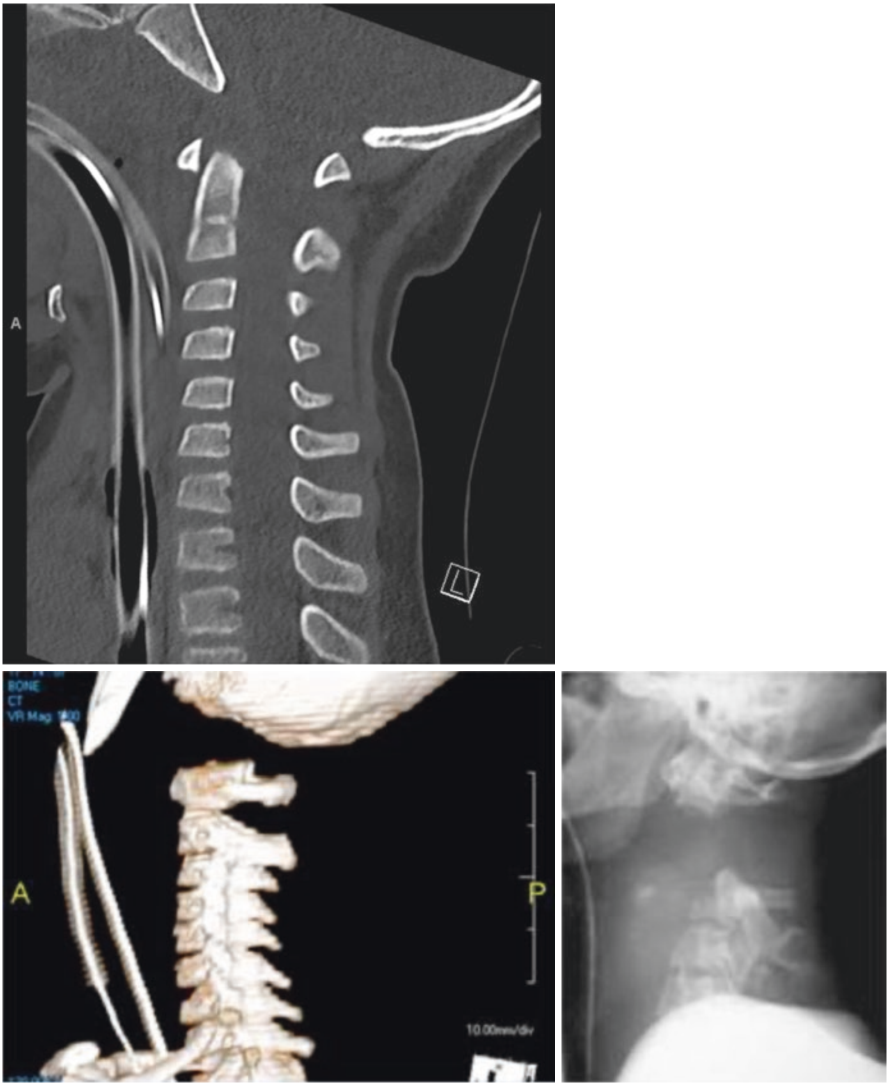

Fig. 17.3 Images of Atlanto-occipital dislocation in a 6-year-old unrestrained front seat passenger struck by an airbag

most common neurological injury associated with AOD is spinal cord injury of the brainstem with associated cardiopulmonary arrest. Diagnosis is made with plain films of the cervical spine with the lateral view, most often demonstrating the pathologic findings. There are no general recommendations for definitive stabilization in the pediatric population, and thus, a halo-orthosis is the most common initial management [12, 13, 42].

Odontoid Fracture

The typical mechanism of injury resulting in an odontoid fracture is a high-speed motor vehicle collision. Neurologic impairment in the setting of an isolated odontoid fracture is exceedingly rare. The diagnosis is typically made on plain radiographs that show an anteriorly dislocated odontoid process. Nonoperative management is the typical treatment strategy that results in excellent radiologic and functional outcomes [12].

Atlanto-Axial Rotatory Fixation

The most common form of pediatric cervical spine injury is atlantoaxial rotatory fixation (AARF). AARF is a condition in which the first and second vertebrae of the cervical spine become interlocked in a rotated position. This condition can be diagnosed when the facet joint is covered by the lateral mass of C1 in the odontoid view or when the lateral mass is projected anteriorly to the odontoid on the lateral view. Most authors recommend closed reduction with external immobilization. Spontaneous reduction is frequent, and there are outstanding functional outcomes reported with conservative management [12, 43].

Subaxial Cervical Spine Injuries

As noted previously, the injury pattern in older children is that of a lower cervical spine injury. Once a child is over 8 years of age, the injury pattern seen in cervical spine injuries is more consistent with an adult pattern. The most common location of a subaxial CSI is at the level of C5 to C7. The neurologic deficit seen is consistent with the level of injury, and thus, a thorough neurological assessment is required. Plain radiographs are the recommended initial diagnostic test as bony abnormalities predominantly occur. In up to one-third of cases, an injury involving more than one vertebral level may be seen. The mortality rate is significantly less than injuries of the upper cervical spine. Treatment guidelines are similar to adult management guidelines due to the completely developed cervical spine [12].

Compression Fractures

Of the fractures in the thoracolumbar region, compression fractures are the most common in patients younger than 18 years old, most often occurring near the thoracolumbar junction and involving multiple spinal levels [18]. The increased

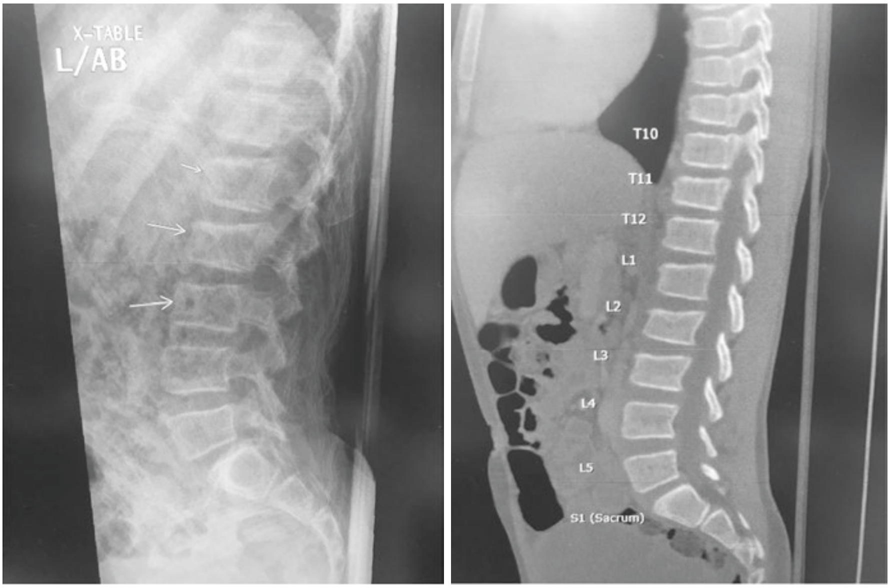

Fig. 17.4 Images of anterior compression fractures of the lumbar vertebrae in an adolescent who was a restrained back seat passenger in a motor vehicle collision

incidence of this fracture is due in part to the natural wedge shape of the pediatric vertebral body as well as the kyphosis of the pediatric spine (see Fig. 17.4). These fractures involve low energy mechanisms such as falls or sports injuries that cause axial loading and spinal flexion causing collapse of the anterior vertebral body. Usually, these fractures have a height loss of <30%, but a height loss >/= 50% should raise suspicion for a posterior ligamentous injury and prompt MRI. Often these compression fractures can be managed conservatively with or without bracing and activity modification. Bracing typically consists of thoracolumbosacral orthosis (TLSO) for 6–8 weeks with good results [16, 19].

Flexion-Distraction Fractures (i.e., Chance Fractures)

Flexion-distraction fractures, also known as Chance fractures or seat belt injuries, occur with sudden deceleration, and the seat belt migrates toward the spine resulting in direct compression of viscera against the spine. The flexion fulcrum is directed onto the anterior vertebral body. These fractures most often involve L2 and L3 levels and pose a risk for intra-abdominal injuries (i.e., small bowel, mesentery, and pancreas) [18]. If the fracture involves the thoracic region, there can also be an injury to thoracic structures involving the lung and aorta (i.e., hemothorax, pneumothorax, lung contusion, and aortic injury) [16, 20]. Because of the elasticity of the pediatric spine, there is also a risk for spinal cord and dura injury. These patients may need to be taken emergently to the operating room for concomitant injuries, but an isolated flexion-distraction fracture can be managed nonoperatively with TLSO bracing for 8 weeks if the brace provides adequate correction and alignment [19]. Surgical correction may be necessary if the alignment cannot be achieved or maintained. Any ligamentous injury may also require surgical correction.

Burst Fractures

Burst fractures are often caused by high-energy mechanisms the cause axial loading and drive the nucleus pulposus into the vertebral body causing fractures of the anterior and middle columns. With this mechanism, there can be retropulsion of the fragments of the vertebral body involving compression and injury to the spinal cord and dura. These fractures are considered unstable and are more often associated with neurologic injury requiring operative intervention for decompression and stabilization [19]. Stable burst fractures without neurologic injury can be managed nonoperatively with either hyperextension casting or TLSO bracing for 8–12 weeks [15].

Vertebral Apophysis Fractures

Children 10–14 years old are most susceptible to apophyseal fractures occurring as a separation of the vertebral apophysis from the vertebral body. These fractures most often occur L4 or L5 and can result in posterior herniation of the apophysis into the spinal canal or neural foramen [19]. This injury is comparable to intervertebral disk herniation in adults and produces similar symptoms to include radicular pain after strenuous activity or low back pain. This fracture may not be as readily seen on plain films. CT is a better imaging modality if this fracture is suspected but not identified on plain films. An MRI would also help identify fracture location and extent of herniation. The fracture may reduce spontaneously and be managed nonoperatively with TLSO bracing for 8 weeks; however, any evidence of neurologic injury needs to be managed surgically [15].

Slow Vehicle Crush Fractures

Children under 5 years of age are susceptible to slow vehicle crush injuries that occur when a vehicle is backing out slowly, and either pins the child against the vehicle bumper and/or another object causing spinal hyperextension. These injuries can also occur with the child getting run over by a car tire at slow speeds. These fractures can have concomitant and potentially major intra-abdominal and thoracic injuries [15].

Spondylolisthesis/Spondylolysis

Spondylolisthesis/Spondylolysis occurs as a traumatic injury, particularly in pediatric athletes that sustain repeated spinal loading and hyperextension. The effect of these biomechanics on an immature spine result in fatigue and fracture of the lower lumbar pars. Sports such as gymnastics, weightlifting, and football are contributors to the development of this fracture. Treatment can be operative for incapacitating or unresolved pain for >6 months or if there is the presence of neurologic injury or high-grade listhesis. Most often, this fracture is managed non-operatively with activity modification [15].

Spinous Process or Transverse Process Fractures

Blunt trauma can result in fractures to spinous or transverse processes. There may be other associated injuries, but a pure injury to these spinal components is managed conservatively with pain control and activity as tolerated [16].

C2–C3 Psuedosubluxation

C2–3 pseudosubluxation is a common, benign finding in children that may be confused with an injury [44]. The anterior portion of the posterior arch of C2 should be within 1 or 2 mm of a line drawn from the anterior portion of the posterior arches of C1 and C3, Swischuk's line. Less than a 2 mm distance between C2 and Swischuk's line is consistent with a pseudosubluxation. In a series of 91 children with a C2–3 pseudosubluxation Farr et al. found that no child under 8 with this radiographic finding had a cervical spine injury but that 11% of children 8 and older did, and that further evaluation should be limited to older children [45].

Neurologic Injuries

Patients can also present with neurologic deficits if there is an injury to the underlying neural structures. The American Spinal Injury Association (ASIA) describes spinal cord injuries as compete and incomplete and classifies the level of injury impairment into five categories A–E, A being complete and E being normal. Complete spinal cord injury, or ASIA grade A, complete lack of all motor and sensory function below the level of the injury. Incomplete spinal cord injury retains some motor and or sensory function below the level of injury. The initial spinal cord exam may not represent the true level of deficit as spinal shock may be present wherein patients lose reflexes below the level of injury. Once spinal shock resolves, a more accurate examination and description of spinal cord injury can be determined [21].

Anterior Spinal Cord Syndrome

This syndrome results in damage to the anterior 2/3rd[s] of the spinal cord involving the corticospinal and spinothalamic tracts but sparing the dorsal columns. The mechanism involves hyperflexion and axial loading resulting in injury to the anterior spinal artery and/or injury to the spinal cord from a retropulsed disk or boney fragments. Symptoms include loss of pain and temperature sensation along with motor paralysis, sparing proprioception and vibration sensations. This injury has a poor prognosis and potential for functional recovery [21].

Posterior Spinal Cord Syndrome

Posterior spinal cord syndrome is the opposite of anterior spinal cord syndrome and involves in loss of the posterior 1/3[rd] of the spinal cord involving the dorsal columns. The dorsal columns are responsible for proprioception and vibration sensations which are lost, but motor function as well as pain and temperature sensations remain intact. The mechanism involves hyperextension of the spine, particularly the neck, and/or direct injury to the posterior spinal cord or disruption of the posterior spinal artery [21].

Central Spinal Cord Syndrome

Central spinal cord syndrome represents the most common incomplete spinal cord injury, usually resulting from hyperextension. The injury involves mainly the central portion of the spinal cord resulting in a motor impartment in the upper and lower extremities. There is a disproportionately greater impartment in the upper extremities motor function as the corticospinal tract layers are organized lateral to medial, advancing from the feet to the arms, the arms being more centrally located along the spinal cord. This syndrome can also involve varying degrees of sensory loss as well as bladder dysfunction [21].

Brown-Séquard Syndrome

Brown-Séquard syndrome is frequently seen in the cervical spine and is caused by penetrating injury and hemisection of the spinal cord. The lateral half of the spinal cord is injured, disrupting the descending corticospinal tracts and ascending dorsal columns. As such, symptoms include ipsilateral loss of motor and proprioception and contralateral loss of pain and temperature sensations [21].

Cauda Equina Syndrome

This syndrome is caused by injury to the cauda equina which is the sac of lumbar, sacral, and coccygeal nerve roots. This syndrome may present with several clinical feathers, including bowel/bladder dysfunction, sensory loss and weakness in lower extremities, saddle anesthesia, and decreased lower extremity reflexes and rectal tone. This syndrome is an emergency and requires emergent surgical intervention once diagnosed [21].

Spinal Cord Injury Without Radiographic Abnormality (i.e., SCIWORA)

SCIWORA occurs in 6–19% of pediatric patients and is associated with high-speed MVC's, flexion-distraction injures, and slow vehicle crush injuries. Incidence along with poor prognosis is highest among children <8 years old secondary to predisposing factors including heavy head, weak musculature, and flexible spinal column. SCIWORA commonly affects the cervical spine, but the upper thoracic spine can also be affected if the watershed vascular supply is disrupted. Despite there being no fracture, SCIWORA is considered an unstable injury due to concern for ligamentous disruption. With this injury, there is also the potential to develop delayed neurologic deterioration 30 min to 4 days after the injury as well as recurrent SCIWORA. These risks are reduced with timely bracing for 12 weeks and spinal precautions [15, 16, 46].

Special Considerations

Unconscious Patients

Children who have a GCS < 8 and a mechanism concerning for spinal cord injury should undergo some form of imaging. Plain films may identify from 70 to 90% of spine injuries [31, 32]. CT scan can see more fractures but can't rule out a ligamentous injury. In patients who are not expected to become GCS 14–15 and examinable within 72 h, plain radiographs and MRI may be used to evaluate their cervical spine. Many centers use MRI to follow up from initial brain CT scans, making obtaining an MRI of the cervical spine logistically easier.

Child Abuse

Given a 69% rate of accompanying cervical spine injury, victims of suspected abusive head trauma who have a demonstrated brain injury should undergo cervical spine MRI [47].

Persistent Pain with Exam and Radiographs

Patients with a GCS of 15 may have a normal neurological exam and normal radiographs, but lingering physical findings, such as posterior cervical spine tenderness. Institutions have devised various methods to manage these children, but one reasonable option is to send a reliable patient home in a collar with scheduled follow in 2 to 3 weeks as an outpatient. Dorney et al. looked at this practice and found that it was safe, follow up was good, and that no injuries were missed [48].

Outcomes

Outcomes following traumatic cervical spine injury are dependent upon rapid diagnosis and stabilization of the cervical spine with a semi-rigid collar. Mortality is greatest with upper cervical spine injuries, especially seen in children with AOD, many of whom may succumb to this devastating injury in the field [13]. Prompt recognition of associated neurologic deficits and evaluation by pediatric neurosurgery or orthopedic surgery is paramount to ensuring the most optimal outcome.

After a traumatic thoracolumbar spinal injury, the biggest concern for long-term outcomes is scoliotic or kyphotic spinal deformities. These deformities can progress as a result of injury to the growth plate or before an adolescent growth spurt. If the growth plate is not involved in the fracture; however, the probability of developing spinal deformities is unclear. The biggest factor in determining the long-term outcome is the presence of a neurologic deficit at the time of injury [16].

Given the risk of progressive deformity, patients who suffered thoracolumbar spinal injuries should be followed through skeletal development to monitor for deformity development. Those who suffered a spinal cord injury may also develop late syringomyelia and should also be monitored for progression of neurologic symptoms. The deformities can be controlled with bracing, but any progressive deformity or neurologic deficit is an indication for surgical intervention [15, 16].

Conclusions and Take Home Points

Pediatric spinal injury is uncommon when compared to adults. Despite the rarity of this injury, the long-term consequences of unrecognized or inappropriately managed spinal injuries can be devastating. Initial management of any trauma patient begins with the primary and secondary survey of Advanced Trauma Life Support. Placement of a cervical collar for immobilization in children with high-risk mechanisms is paramount. No validated guidelines exist to determine which patients will benefit from imaging of the spine. Children who have tenderness in the midline over the spine, ecchymosis, decreased range of motion or neurologic deficits must undergo radiographic assessment. Initial imaging includes plain films of the affected region with CT scan and MRI reserved for inadequate imaging or further assessment of the spinal cord such as spinal cord injury without radiographic abnormality (SCIWORA). Initial management is with immobilization and prompt neurosurgical or orthopedic consultation. Nonoperative management is sufficient in many cases of spinal cord injury with good long-term outcomes. Further management is dependent upon the location and type of spinal cord injury.

1. The initial evaluation and workup of a pediatric spinal trauma patient involve a good neurologic exam and appropriate imaging. However, spine clearance in a child is a clinical event, not a radiologic event.
2. No validated imaging guidelines exist for children with suspected cervical spine injuries. Utilization of the PECARN risk factors along with a high degree of clinical suspicion may identify those children who will benefit from further imaging.
3. Initial management of any cervical spine injury includes maintenance of stabilization in a semi-rigid collar and immediate consultation to neurosurgery or orthopedic surgery. Spine clearance is rarely an emergency, and the spine may be left immobilized until more urgent issues are addressed.
4. Thoracolumbar spinal trauma is uncommon in pediatric patients when compared to adults, and pediatric patients have particular risk factors and mechanisms that predispose them to spinal trauma.
5. Management of thoracolumbar injuries can be operative or nonoperative and depends on the stability of the spine, spinal cord compression, underlying neurologic deficits, and potential for long-term healing.
6. There are a variety of fracture patterns that can occur in the spinal column along with neurologic injuries, and it is important to be mindful that some of these injuries can be associated with injuries to other intra-abdominal and thoracic structures.
7. Ligamentous injuries are more common in children and spine injuries cannot be ruled out using radiographs or CT scans. Anatomically the spine becomes mature around age 9 years.

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Chapter 18
Thoracic and Chest Wall Injuries

Jonathan L. Halbach and Romeo C. Ignacio

Abstract Pediatric thoracic and chest wall trauma are uncommon injuries; however, such injuries can result in significant morbidity and mortality. Most thoracic injuries in children result from blunt trauma and are associated with abdominal and head injuries. Relative to adults, children under the age of 14 have a more compliant chest wall due to decreased or incomplete ossification of the ribs. This difference results in a greater transmission of energy to the underlying organs and injury patterns that present differently than in adults (Sartorelli et al. Semin Pediatr Surg. 13:98–105, 2004). Additionally, a child's mediastinum is more mobile allowing for greater shift and potential for cardiovascular collapse in the setting of space-occupying fluid or air. The most common injuries in children are rib fractures, pulmonary contusions, pneumothorax, and hemothorax. Less frequent injuries include flail chest, esophageal, and diaphragm injury. This chapter focuses on the assessment and management of thoracic trauma in pediatric patients.

Keywords Thoracic trauma · Pneumothorax · Hemothorax · Pulmonary contusion · Rib fractures · Flail chest · Esophageal injury · Diaphragm injury

Key Concepts/Clinical Pearls (Learning Objectives)
After reading this chapter, the reader should understand:

- Initial assessment and diagnostic evaluation of thoracic trauma.
- Initial management of thoracic injuries.
- Indications for surgery in thoracic injuries.
- Procedural and operative techniques and considerations.
- Complications, common pitfalls, and sequela after thoracic injuries.

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Initial Assessment and Management of the Trauma Patient

Thoracic injuries can be immediately life-threatening. The successful treatment of thoracic injuries requires efficient assessment and intervention. Trauma team members should have pre-assigned roles and responsibilities. The team should be familiar with the trauma environment, the equipment and supplies, ancillary services and understand the limitations of their facilities in managing pediatric trauma patients.

The initial assessment and management of the trauma patient begin with a prompt evaluation of airway, breathing, and circulation as outlined by the Advanced Trauma Life Support (ATLS®) program. Efficient placement of monitors to assess heart rate, blood pressure, pulse oximetry, and the application of supplemental oxygen is critical. Intravenous (or intraosseous) access should be obtained immediately. Severe thoracic injuries identified during the primary survey that results in impaired gas exchange require immediate intervention. Once the primary survey is completed, a chest radiograph is critical to discern the nature of the injury and often will guide initial interventions or subsequent imaging if not evident on the initial survey. The trauma bay environment should be organized in a manner to allow for prompt procedural intervention such as needle decompression, tube thoracostomy, or if necessary, thoracotomy.

Radiographic/Ancillary Studies

Chest Radiograph

Patients with suspected thoracic injuries should undergo a chest radiograph as soon as it can be safely obtained as part of the secondary survey performed in the trauma bay. Upright plan radiographs are more sensitive for pneumothorax and hemothorax; however, supine films are frequently required secondary to suspected spinal injuries requiring the patient to be in spinal precautions.

The interpretation of the pediatric chest radiograph requires an understanding of anatomic differences from adults. The mediastinum in children may appear wider due to a larger thymus resulting in a prominent mediastinal shadow. This effect is variable and gradually decreases before eight years of age [1]. When evaluating bony structures of the thoracic cage, the decreased ossification in pediatric patients should be noted. Additionally, the pediatric patient is frequently distressed from the trauma and foreign environment and may demonstrate insufficient inspiration or motion artifact. Efforts should be made to distract and direct the child using age-appropriate language to optimize the images.

Ultrasound

Adult literature suggests that ultrasound can be useful in the rapid detection of pneumothorax or hemothorax with a reported sensitivity greater than 95% [2–4]. While this might suggest that ultrasound can be translated to the pediatric patient, the literature indicates it may not be as reliable for rapid evaluation in the pediatric trauma population with a reported sensitivity as low as 45% [5]. Due to variable reliability, use of ultrasound in the initial evaluation of the pediatric patient with thoracic trauma is provider and institution dependent.

Computed Tomography (CT) Scan

Computed Tomography is an important tool for the evaluation of thoracic trauma; however, the impact of radiation exposure requires selective use. Asymptomatic pediatric patients, even with a suspicious mechanism of injury, should not undergo routine CT scan [6]. CT scan use should be based on clinical exam, findings on chest radiograph, mechanism, or associated injury. CT should be used if there is a high suspicion of a great vessel injury such as a widened mediastinum on chest radiograph. A normal chest radiograph rarely warrants further imaging especially for blunt trauma.

Frequently, occult thoracic findings not visualized on chest radiograph are identified when a child undergoes CT looking at another area of the body—i.e., C-spine (occult apical pneumothorax) or abdominal (occult hemothorax). These findings should not routinely prompt additional CT images of the chest and can be followed appropriately with serial chest radiographs.

Management of Specific Injuries

Rib Fractures

Due to increased compliance of the chest wall in children, blunt thoracic trauma resulting in rib fractures implies a significant mechanism of injury, and it can be a marker for severe trauma [7]. Injury to underlying organs, such as the lungs, spleen, and liver, should be suspected in all children with rib fractures. Isolated rib fractures without associated injury are found in under 6% of patients, less than half compared to adult patients [8]. Associated head and abdominal injuries are higher in children with thoracic trauma. Rib fractures paired with head injury have a higher mortality rate [9]. The number of ribs fractured correlates directly with injury severity, the likelihood of underlying injury, extra-thoracic injury, and overall mortality [10].

Given the significant mechanism needed for a child's rib to fracture, pediatric rib fractures are less common in accidental trauma relative to adults [11]. Motor vehicle crashes remain the most common overall cause of rib fractures in all children; however, for children under the age of four, non-accidental trauma accounts for most rib fractures. While it should generally be considered a possible mechanism for children of all ages, non-accidental trauma should be suspected in younger children with rib fractures especially in infants. The number and location of ribs fractured can be a clue pointing to non-accidental trauma as the mechanism (i.e., multiple fractures on different ribs in different locations/sides of the body, fractures in different stages of healing, injuries that do not match the reported history).

Management

The treatment of rib fractures is centered on optimizing effective pulmonary gas exchange. Gas exchange should be optimized with supplemental oxygen if necessary and effective pulmonary toilet. If the child cannot effectively use an incentive spirometer, blowing bubbles or pinwheel toys are an effective alternative for the young pediatric patient. Pain control is essential to avoid splinting, subsequent underlying atelectasis, and potential for pneumonia. A multimodal systemic analgesia approach should be used, and careful consideration of the safety, side effects, and effectiveness of pain modalities are necessary. For severe cases, consultation with pain specialists is an option to ensure adequate pain relief, allowing better pulmonary mechanics, mobility, and clearance of pulmonary secretions. Regional pain techniques such as epidurals, rib blocks, or erector spinae blocks can reduce the use of opioids and their unwanted side effects and allow for improved pulmonary toilet.

Although utilized more frequently in adult trauma patients, no current evidence supports operative fixation of isolated rib fractures in children.

Other chest wall injuries commonly associated with rib fractures, such as sternal or clavicle fractures, can result in vascular compression and/or injury—especially when associated with a posterior sternoclavicular dislocation. Significant bleeding from these injuries, while rare, can result and manifest after reduction and fixation; therefore, a pediatric surgeon should be available at the time of reduction.

Flail Chest

Flail chest is defined as multiple (usually at least three) ribs with two or more fracture/dislocation sites. This results in paradoxical movement of the flail segment, increasing the effort needed to fully aerate the lung resulting in impaired mechanics and gas exchange. Due to increased chest wall compliance, flail chest is extremely rare in children.

Management

Operative fixation of flail chest in adults can reduce required ventilator support [12]. While this has not been adequately evaluated in children, it can be considered on a case-by-case basis. The key principle of managing flail chest in children remains optimization of gas exchange through pain control and pulmonary toilet.

Pulmonary Contusion

The severity of blunt thoracic trauma in children confers the extent of underlying pulmonary contusion. As mentioned, rib fractures require a more violent mechanism in children than in adults. Because of this, one should still suspect significant underlying injury despite the absence of fractures.

Management

The treatment of pulmonary contusion is supportive. Pulmonary toilet methods such as incentive spirometry, pin-wheel toys, and bubbles are effective tools to encourage good aeration to minimize sequela from pulmonary contusion such as pneumonia. Ventilator support is rarely indicated in children with pulmonary contusion and is often only utilized in patients with associated brain or abdominal injuries requiring ventilator support.

Pneumothorax

A pneumothorax from blunt trauma is usually secondary to small injuries to the parenchyma (Fig. 18.1). Rarely in severe blunt trauma, a pneumothorax can be secondary to displaced boney fracture. The timely identification of pneumothorax

Fig. 18.1 Large pneumothorax after blunt thoracic trauma

during the trauma evaluation is essential since a large pneumothorax can result in tension physiology and be fatal. A child's mediastinum is more mobile than an adult allowing a greater shift and potential for cardiovascular collapse from pneumothorax.

Management

Rapid thoracostomy should be performed in the form of needle decompression, finger thoracostomy, or a chest tube for the unstable patient with pneumothorax.

Needle decompression is a temporary treatment for tension pneumothorax. It can be safely performed with a large angiocatheter at the second intercostal space in the mid-clavicular line or the fourth intercostal space in the mid-axillary line. ATLS recommends the use of a 5 cm, 14–16 gauge needle for pneumothorax decompression. This size is adequate for most children <13 years of age unless they are morbidly obese [13]. The angiocatheter with the needle is inserted until air is returned, at which point the needle is removed, and the catheter is left in place. A saline-filled syringe on the angiocatheter can be drawn back during insertion to aid in the detection of air return. This is a temporary but potentially lifesaving technique that can be employed during the primary trauma evaluation.

Pediatric trauma patients with moderate to large pneumothorax will require tube thoracostomy to re-expand the lung, create pleural apposition, and heal the injured parenchyma. The type, size, and location should be determined based on the size and habitus of the child and if hemothorax is suspected. Small pigtail catheters (8-12F) are effectively used as chest tubes when only air needs evacuation. When hemothorax is suspected, or if the injury is from a penetrating mechanism, it remains prudent to utilize a conventional chest tube. A Broselow tape or chart should be used to aid in the selection of the correct chest tube size (Fig. 18.2).

Most pneumothoraxes in pediatric trauma will resolve with a chest tube. Application of suction and duration is determined based on the resolution of

Fig. 18.2 Weight based selection of chest tube size

Chest Tube Size Selection		
Small Infant	6-7 kg	10-12F
Infant	8-9 kg	10-12F
Toddler	10-11 kg	16-20F
Small Child	12-14 kg	20-24F
Child	15-18 kg	20-24F
Child	19-23 kg	24-32F
Large Child	24-29 kg	28-32F
Adult Sized	30-36 kg	32-38F

pneumothorax, expansion of the affected lung, and clinical improvement. Other factors to consider are the nature of the injury, the presence and quality of an air leak, associated injuries, and the presence of associated hemothorax. Bronchial injuries with ongoing air leak or a large volume of air loss will require surgical intervention.

Patients with very small pneumothorax or those occult on a chest radiograph but discovered on axial imaging can be safely observed, even if the patient requires positive pressure or ventilator support [14].

Hemothorax

The accumulation of blood in the pleural cavity from a traumatic injury implies a significant injury. Due to the low-pressure pulmonary circulation, bleeding from minor injuries to lung parenchyma is usually self-limited. Large pulmonary lacerations, injury to intercostal arteries, hilar vessels, or mediastinal vessels can result in exsanguination.

A plain chest radiograph performed during the initial trauma bay resuscitation will detect moderate to large hemothorax but can miss low volume hemothorax. Ultrasound by an experienced technician is more sensitive than plain radiograph in the detection of hemothorax with a sensitivity of 92%, specificity of 100%, and positive predictive value to 100% [15]. Occult or low volume hemothorax is often identified on abdominal CT scans capturing views of the lower thoracic cavity. Blood in the thorax has an attenuation of 35–70 Hounsfield Units (HU). Measurement of fluid attenuation by HU is important in the setting of pediatric trauma.

Management

Low volume hemothorax detected only on CT has been reported to be safely observed without chest tube or intervention and without risk of empyema or fibrothorax [16]. Early drainage of moderate to large hemothorax is essential and allows the trauma surgeon to quantify bleeding and directs further intervention. Early drainage also minimizes the risk of sequelae such as empyema or fibrothorax. Conventional chest tubes are recommended over pig-tail catheters for drainage of hemothorax in the setting of trauma.

Massive hemothorax is the result of continued hemorrhage, usually from an intercostal or hilar vessel. Signs of large volume hemothorax include decreased breath sounds and hemodynamic instability, both of which should be detected during the primary survey. A large-bore chest tube should be placed. The volume of blood returned after chest tube placement, as well as the hemodynamic impact of this intervention, should direct further management. Massive transfusion protocols should be implemented when large volume hemothorax is recognized. Thoracotomy should be considered when the initial blood volume return is greater than 30% of the

Fig. 18.3 Blood volume estimation in children

Estimated Blood Volume in Children:	
– Premature infants	100 cc/kg
– Less than 3 months	85 cc/kg
– Children > than 3 months	75 cc/kg
– Adolescents	70 cc/kg

estimated blood volume (approximately 15 cm^3/kg) (Fig. 18.3) or when the continued chest tube output exceeds 3 cm^3/kg/h over the subsequent 6 h [17]. While these volume limits are useful tools, patient physiology and response to resuscitation should be the primary guide for intervention in massive hemothorax.

Thoracotomy for massive continued thoracic bleeding should be performed in the operating suite when possible. Intercostal bleeding can usually be controlled with simple ligation. Bleeding from hilar vessels or deep pulmonary lacerations requires more complex techniques. Hilar bleeding carries extremely high morbidity and mortality, and damage control principles should be applied. Mobilization of the inferior pulmonary ligament with twisting of the hilum can temporize bleeding and increase exposure. Pulmonary resection in trauma is rare and carries a very high morbidity. In penetrating trauma, tractotomy—firing a GIA stapler through the missile tract to open and thus better expose the area of concern—can allow the surgeon to over-sew involved airways or vessels.

Emergency department thoracotomy (EDT), or thoracotomy performed in the trauma bay due to loss of a pulse forgoing dangerous and time-consuming transport to the operative suite, is uncommonly performed in pediatric trauma patients and carries a mortality in excess of 90%. For adult patients, the Eastern Association for the Surgery of Trauma recommends EDT for pulseless patients after penetrating thoracic trauma with or without signs of life on arrival. EDT is not recommended for patients without signs of life on arrival after blunt trauma [18]. No pediatric specific guidelines exist for EDT. After noting that only patients with signs of life on arrival survive after EDT, recent pediatric specific literature supports foregoing EDT for any patient without signs of life or pulse on arrival to the trauma bay [19].

Retained Hemothorax

When a hemothorax persists on a chest X-ray despite the placement of a chest tube, there is a risk of empyema and fibrothorax. If the patient is stable, video-assisted thoracoscopic surgery (VATS) can be considered to evacuate the retained hemothorax. While little supporting literature exists for pediatric patients, adult trauma recommendations can be considered. In 2011, the EAST guidelines supported early VATS (within 3–7 days) for retained hemothorax over a second tube thoracostomy [20].

Esophageal Injury

Traumatic esophageal injury or rupture is very rare in children. A review of 193 pediatric trauma patients with pneumomediastinum after trauma found only one patient with esophageal injury [21]. Iatrogenic/endoscopic esophageal rupture is far more common. Although rare, failure to recognize esophageal injury after trauma can result in significant morbidity and mortality [22]. Traumatic esophageal rupture from blunt trauma requires significant force and is frequently associated with other thoracic injuries.

A significant mechanism in a patient complaining of chest pain, abdominal pain, nausea, vomiting, fever, shortness of breath, and subcutaneous emphysema raises suspicion for esophageal injury. Pneumomediastinum and pleural effusion on chest radiograph warrant a water-soluble esophagram to confirm the diagnosis and characterize the location and size of the injury. In patients with associated injuries with an indication for chest tube placement, elevated amylase in pleural fluid is highly suggestive of esophageal injury.

Management

When large esophageal rupture is identified early, primary repair of the esophagus is usually possible. This should be performed in hemodynamically stable patients after intravenous resuscitation and antibiotic administration. The surgical approach depends on the location of the injury. The distal esophagus is approached via left thoracotomy and the proximal thoracic esophagus via right thoracotomy. It is important to identify and close the full extent of mucosal injury during repair, which may require debridement or extension of the muscular injury. Wide drainage of the chest and mediastinum is recommended after repair.

Small contained esophageal injuries can be managed non-operatively. This requires prolonged nil per os status, resuscitation, and antibiotics. Non-operative management of these injuries requires close monitoring for signs of sepsis and continual re-evaluation for the need for operation or drainage.

When the diagnosis of esophageal rupture is delayed resulting in mediastinitis, durable primary repair may not be possible. The goals of treatment should be to control the source of sepsis with wide drainage and, if necessary, operative washing of the mediastinum. In severe cases, an exclusion procedure with esophagostomy or T-tube is required [23].

Diaphragm Rupture

Traumatic rupture of the diaphragm typically results from abdominal structures transmitting force to the diaphragm resulting in rupture. This requires tremendous force in blunt trauma and is most common in the left posterolateral position—an area of natural weakness. The resulting herniation can cause respiratory embarrassment, and these injuries are often managed in the context of other severe thoracoabdominal injuries.

When a chest radiograph is obtained as part of the workup for thoracic trauma, attention should be given to the contours of the diaphragm and the presence of abnormal gas patterns in the chest. Uncertainty or irregularities on chest radiograph may prompt axial imaging with CT. The sensitivity of CT for diaphragm injury is reported to be 77% in blunt trauma and 47% in penetrating trauma [24]. Smaller injuries can go undiagnosed and present delayed with symptoms of intestinal obstruction.

Management

Diaphragmatic rupture requires operative repair. Repair of diaphragmatic rupture is most frequently approached through the abdomen, given the association with injury to abdominal viscera. Repair may be performed via thoracotomy when there are associated thoracic injuries. In cases of large right-sided diaphragm rupture with associated liver injury, a thoracic approach may be required to avoid excessive manipulation of the liver for exposure. The majority of traumatic diaphragm ruptures can be repaired primarily with pledgeted sutures. The use of a prosthetic patch should be avoided in a contaminated field.

Thoracoscopy and laparoscopy have been well described in the adult literature and serve as a useful adjunct given the poor sensitivity of CT for small diaphragm injuries. Minimally invasive approaches to diagnose and treat diaphragm injuries are reserved for the hemodynamically stable patient [25].

Conclusions

Pediatric thoracic and chest wall trauma are uncommon injuries; however, such injuries can result in significant morbidity and mortality. Initial management of the child with chest trauma includes a primary and secondary survey with chest radiograph. CT should be used if there is a high suspicion of a great vessel injury such as a widened mediastinum on chest radiograph. A normal chest radiograph rarely warrants further imaging especially for blunt trauma. Most patients who sustain thoracic trauma can be managed with adequate pulmonary toilet, pain control and tube thoracostomy for pneumo- or hemothorax. Patients with massive hemothorax or diaphragmatic injuries or esophageal injuries require operative intervention and the pediatric surgeon must be prepared to address these issues in the operating room.

Take Home Points

- Prompt recognition of injuries and intervention in pediatric thoracic trauma is life-saving.
- When assessing, diagnosing, and managing thoracic trauma in pediatric patients, it is essential to remember the physiologic and anatomic differences in children.
- The successful treatment of pediatric thoracic trauma requires a team with assigned roles, familiarity with equipment, and an understanding of capabilities and limitations.

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Chapter 19
Penetrating Abdominal Injury

Tara Loux and Christopher P. Coppola

Abstract Penetrating trauma is less frequent than blunt trauma in children and has higher mortality (Cunningham et al. N Engl J Med. 379:2468–2475, 2018). Injured children must be stabilized and transferred to a pediatric trauma center for Advanced Trauma Life Support (ATLS) resuscitation.

Primary and Secondary Survey are a search for life- or limb-threatening injury. They rapidly identify correctable processes such as impaired airway, tension pneumothorax, pericardial tamponade, or hemorrhagic shock. Focused abdominal sonography for trauma (FAST) in the trauma bay detects peritoneal fluid, but not the specific source.

Penetrating abdominal trauma usually requires operative treatment. This must occur immediately if the child is hemodynamically abnormal. If they respond to resuscitation, a more detailed diagnosis can be pursued with computed tomography. Often the initial operative approach is damage-control surgery: rapidly identifying and stabilizing organ injury then delaying definitive until the child has been fully resuscitated and stabilized.

Operative interventions for penetrating trauma are laparotomy, thoracotomy, laparoscopy and thoracoscopy. Adjuncts to operative therapy are transfusion (including whole blood transfusion), thromboelastogram (TEG), tranexamic acid (TXA), catheter-based embolization, extracorporeal membrane oxygenation (ECMO), and Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA).

Keywords Trauma · Penetrating · Pediatric · Child · ATLS · Abdomen · Chest · Gunshot · Stab

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Key Concepts/Clinical Pearls (Learning Objectives)

- Trauma is the most common cause of death in children. Penetrating trauma is less common, but more lethal, than blunt trauma.
- The Advanced Trauma Life Support (ATLS) algorithm, which is designed to rapidly identify and treat injuries after trauma, also ensures no life- or limb-threatening injuries are missed.
- Immediate threats to life after penetrating trauma are airway compromise, tension pneumothorax, pericardial tamponade, and hemorrhage with hemodynamic instability.
- Most penetrating trauma of the chest or abdomen in children will require operative intervention to rule out and/or repair injuries. Penetrating trauma can affect multiple body cavities from one injury.
- Emerging therapies for penetrating trauma, such as embolization, laparoscopy, thoracoscopy, tranexamic acid, Extra Corporeal Membrane Oxygenation (ECMO) and Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA), have a place in the triage and resuscitation of the severely injured child.

Initial Management of Trauma Patient

When a child presents with penetrating trauma, particularly to the chest and the abdomen, there is a high likelihood that operative intervention will be needed. Penetrating trauma is less frequent than blunt trauma in children and has higher mortality [1]. Initial assessment and management should be directed at rapid preparation for the operating room, unless this assessment can definitively rule out that an operation is needed.

Care starts in the field, not just with Emergency Medical Services (EMS) and pre-hospital providers but also with bystander care. The American College of Surgeons convened the "Hartford Consensus" and instituted the "Stop the Bleed" campaign as a response to the Sandy Hook School shooting in 2012 [2, 3]. Widespread training of civilians as well as pre-positioning of hemostatic dressings enables immediate delivery of care to attempt hemostasis and reduce shock after penetrating trauma. Tourniquets are made available to slow life-threatening hemorrhage from extremity trauma. Interagency communication between law enforcement, EMS, and Trauma Center hospital personnel facilitates rapid triage and transportation of children in need of lifesaving care. Some children with penetrating trauma will be best served by immediate stabilization at the closest medical facility with subsequent hospital-to-hospital transfer to a Pediatric Trauma Center. Pediatric Trauma Centers are particularly suited for the care of injured children, and even adolescents with penetrating trauma achieve improved mortality when treated at specialized pediatric centers, when compared with Adult Trauma Centers [4].

After arrival at the Trauma Center, the resuscitation and evaluation of a child with penetrating trauma follows ATLS protocols. Pre-hospital personnel deliver a report which includes known history of injury, course of vital signs, and interventions administered. When available from a guardian, the "AMPLE" past medical history is collected: Allergies, Medications, Pertinent medical history, Last meal, Events before presentation. Deteriorating and sedated children may not be able to participate in neurologic examination, so the best neurological examination since injury should be communicated, and the current Glasgow Coma Score (GCS) calculated. If injury to the cervical spine cannot be ruled out, a cervical spine collar is placed.

Initial assessment focuses on detecting and treating the correctable causes of shock, as well as determining the details of the injury sustained. Assessment starts with the primary survey of ABC (Airway, Breathing, Circulation) with attention to D, E (Disability sustained from neurologic injury and Exposure of the entire child to search for injuries with prevention of hypothermia by limiting full exposure/ covering with warm blankets.)

It is important to remember that when projectiles or stabbing objects enter the body, it is difficult to know their path. For this reason, abdominal penetrating injuries can involve both abdominal and thoracic injuries. This is discussed in more detail in the chapter on thoracic trauma. Rapidly lethal injuries are possible with penetrating trauma and include compromised airway, tension pneumothorax/hemothorax, pericardial tamponade and hemorrhagic shock. One thoracic injury that can occur when a when a penetrating abdominal object traverses the chest is pericardial tamponade. The Beck's Triad of pericardial tamponade (hypotension, jugular venous distention, and muffled heart sounds) is often not present. Pericardial tamponade is treated with pericardiocentesis or sub-xiphoid pericardial window. Penetrating trauma with loss of vital signs up to ten minutes prior to the child's arrival is an indication for resuscitative thoracotomy in the Emergency Department. Hemorrhagic shock is treated with one bolus of warmed isotonic fluid such as Ringer's lactate or normal saline, 20 mL/kg body weight. If shock does not respond or only transiently responds to one fluid bolus this is followed by blood transfusion, 10 mL/kg body weight, and this usually means an operation is rapidly needed. In trauma centers where whole blood is available it can used to treat hemorrhagic shock [18]. Otherwise packed red blood cell transfusion should be paired with matched component therapy that includes fresh frozen plasma and platelets. For a patient in shock, uncrossmatched blood should be used; therapy should not be delayed to type and cross a specimen. Some experts consider that blood products should be first-line treatment for hemorrhagic shock, though crystalloid solutions can be a lifesaving temporizing measure if blood is not immediately available.

The Secondary Survey is a head-to-toe examination of the body, searching for injuries and signs of shock. After penetrating trauma, care is taken to find all entry and exit wounds of piercing objects or projectiles. Careful inspection of the back, extremities, axillae, groins, buttocks, and perineum for wounds must be conducted during the primary survey. All wounds must be marked with radiopaque markers for imaging. Projectiles do not necessarily travel in a straight path within the body; they can have unexpected trajectories and fragment into multiple pieces. Careful examination of the neck is made to detect hematoma that will require operative exploration. Neck and chest are also examined for crepitus from subcutaneous air leaking from injured lungs, bronchi, or esophagus. The abdomen is observed and palpated for signs of distention or peritonitis. Rectal examination is imperative to evaluate for presence of gross blood and rectal tone. Extremities are examined for presence and character of distal pulses. If pulses seem diminished or unequal, ankle-brachial indices should be calculated. A brief but thorough neurologic examination should be conducted to assess for evidence of spinal cord injury.

Vital signs, including temperature are repeated frequently during the initial assessment to detect deterioration in condition as well as response to initial resuscitation. Children who become hypothermic while in shock suffer worse mortality due to impairment in clotting and perfusion of vital organs. Initial assessment should be conducted with constant forethought towards disposition of the child upon leaving the trauma bay. In most penetrating abdominal trauma, the destination is the operating room. Delaying an operation for more radiographic studies is at best a delay in definitive therapy, and at worst lost time during the post-trauma “golden hour”.

Loss of vital signs within 10 min of arrival to the trauma bay is an indication for resuscitative thoracotomy in the emergency department in patients with penetrating trauma. Though prognosis remains grim, the aim of this intervention is to rapidly open the pericardium, provide open cardiac massage, repair overt cardiac injury, clamp or compress the descending thoracic aorta to prevent ongoing abdominal hemorrhage and clamp or compress the left pulmonary hilum if there is lung hemorrhage. If central venous access has not been achieved, an introducer can be placed in the right atrial appendage and tied in with a purse string suture for rapid and direct intracardiac administration of blood products. Clamshell extension across the sternum can be performed to address hemorrhage in the right thorax. If the patient survives resuscitative thoracotomy, they must be taken immediately to the operating room for definitive hemorrhage control.

Initial Radiographic/Ancillary Studies

Laboratory Studies

1. Type and cross, consider initiating Massive Transfusion Protocol.
2. CBC.
3. PT/INR/PTT, consider TEG.
4. Electrolytes, liver function studies, amylase/lipase.
5. ETOH, drugs of abuse.
6. Urinalysis.
7. β-hCG for females who have reached 12-years-old or Tanner stage 3.

Radiographic Studies

1. Plain film X-rays of chest/abdomen/pelvis to enumerate projectiles, with radiopaque markers on all skin wounds to help determine trajectory.

2. Focused abdominal sonography in trauma (FAST-occasionally useful for blunt trauma, perhaps less for penetrating).
   (a) Sensitive for pericardial tamponade.
   (b) e-FAST (extended FAST—bilateral anterior chest windows can detect pneumothorax).
3. Computed tomography (CT) may be necessary to rule out spine or other bony injury or to help determine trajectory of projectile, but should be done ONLY in a hemodynamically NORMAL patient, or delayed until operative therapy is complete.
4. Consider need for intraoperative arteriogram, venogram, cholangiogram or cystogram, and endoscopic visualization of rectum and vagina, pharynx/esophagus and laryngotracheobronchial tree, depending upon trajectory of projectiles.
5. Diagnostic peritoneal lavage (DPL) has no role in evaluation or management of penetrating trauma.

Epidemiology

In 2016, 7.6% of pediatric trauma cases were penetrating. Firearm trauma had a case fatality rate of 11.2% and cutting or piercing trauma had a case fatality rate of 1.5% [5]. Most firearm trauma was intentional (attempted or actual homicide or suicide), with less than 1% deemed unintentional or undetermined [1]. This is an underappreciated type of non-accidental trauma. All penetrating mechanisms are stable in incidence up to age 13 and increase in frequency throughout adolescence. Males make up roughly 5 times as many firearm injuries as females and 50% more cut/pierce injuries, though the case fatality rates are similar between sexes.

Etiology

Firearm Injury

Firearm injury accounts for the great majority of pediatric penetrating trauma in the United States [6]. Knowledge of the types of weapons and projectiles can help an astute trauma surgeon anticipate and regulate injuries. A concise yet thorough review of weapons, projectiles, and demographics of injury common in the United States is provided by Rhee, et al. [7] In summary, the amount and type of injury caused is determined by a multitude of factors, the least of which is bullet diameter. Other important factors include the projectile length, amount of propellant, whether fully or partially jacketed, muzzle velocity, distance of shooter from target, presence of powder burns, the type of tissue penetrated, fragmentation of the bullet, and many others. High muzzle velocity (>2000 ft./s) is the most significant factor in determining traumatic energy delivered to tissue because kinetic energy = ½ mass × velocity

[2]. Unfortunately, most of this information will not be available to the trauma surgeon upon presentation of the patient with penetrating injury. External wounds should be described and documented according to their location, shape, size, and depth, and should NEVER be documented in the medical record as entry and exit sites, as most trauma surgeons are not trained in ballistics, physics, and forensic pathology to make such determinations.

Active shooter/mass casualty incidents (defined as having four or more mortalities or injuries) appear to be slowly increasing in incidence over the past two decades, with a dramatic increase just after the onset of the coronavirus pandemic [8]. Children under 18-years-old make up significant percentages of both mortalities and injuries in mass shootings (44% and 46% respectively in domestic events, 10% and 2% in public events) [9]. Therefore, both pediatric and adult trauma surgeons can expect to see more such injured children.

A full discussion of warzone trauma is beyond the scope of this chapter; however, suffice to say that children can be injured both as combatants and bystanders and the mechanism depends on the weapons available. Military-grade weapons are high-energy and leave behind a cone of injury from the blast wave. They can combine penetrating trauma with blunt/shockwave and heat/burn injuries, not to mention the possibilities of concomitant chemical and biological agents at play. Blast injury is often concomitant with warzone penetrating injury and may result in externally imperceptible damage to the brain, lungs, auditory system, and hollow viscus abdominal organs. Open wounds from blast injuries may be contaminated with dirt, toxic chemicals, and organic fragments from other victims. An excellent primer on this topic has been published by the Centers for Disease Control Injury Prevention Task Force [10]. Children injured in war zones tend to be cared for in military hospitals whose practitioners are often adult-trained specialists with little or no pediatric experience.

Cut/Pierce Injury

Children are active, curious, and relatively uninhibited; thus, unintentional cut/pierce injuries can be accumulated from a variety of sharp objects or can occur combined with blunt trauma mechanisms such as motor vehicle collision or pedestrian versus motor vehicle. Projectiles such as shattered window glass, metal or plastic parts of cars, or objects along roadsides can cause piercing injuries. Bicycle or scooter handlebars, spokes or pedals and fence posts or tree limbs from climbing accidents are other common piercing injuries. Obviously, intentional injuries can be created with a variety of found or purchased knives, blades, or tools.

Bites or stings from domesticated or wild animals can also be included in the spectrum of piercing injury. Apart from the usual human, dog or cat bites, rarer perpetrators can include bear, large canines and felines, shark, snake, scorpion, spider, and others, depending on geography. Animal bites and stings can produce significant local tissue loss, whether from mechanical shear or tissue envenomation. Venomous bites or stings can produce significant systemic effects as well, depending on the animal delivering the bite.

Injury Patterns

The unique anatomy and physiology of infants and children applies equally in penetrating injury. Increased vulnerability due to thin body wall (decreased insulation from traumatic injury), increased head to torso size ratio, ability to maintain blood pressure despite larger percentage volume loss, with subsequent precipitous decline, and decreased ability to maintain normal temperature all complicate the care of the child injured by a penetrating mechanism. Injured children will present with tachypnea, tachycardia, and poor tissue perfusion, while hypotension is a very late sign of impending cardiovascular collapse. Their smaller size means that one projectile could just as easily miss important structures, or injure many contiguous structures, depending on the trajectory, velocity, and angle of entry. Adult-sized adolescents may not have equal body mass/density and body wall thickness as a similarly sized fully developed adult and may accrue more severe injury from penetrating objects. Multiple body cavities and parts may be injured by the same projectile or penetrating objects, which may pass through or become lodged in an extremity.

Treatment

Laparotomy

Preparation—This should occur for the most part in the operating room. If available, a hybrid trauma operating room should be utilized to allow for the option of simultaneous percutaneous, catheter-based interventions. A Foley catheter should be inserted for monitoring of temperature and urine output. An arterial line can provide more accurate information than a standard non-invasive blood pressure cuff. Venous access lines, if not done in the trauma bay, should include venous access above and below the chest, and should be single-lumen large bore catheters with short length to allow for rapidity of infusion. Large bore short peripheral intravenous catheters can infuse much more rapidly than triple lumen central access lines. Intraosseus infusion sites in the tibia, femur and humerus can be useful if hypovolemia makes initial intravenous access difficult. Life-saving hemorrhage control should not be delayed while obtaining access; this process can be ongoing by the anesthesia team outside the operative field, or by the surgical team in the operative field after draping.

Preparation for laparotomy should include betadine spray of the neck, chest, groins, and axillae as well as the abdomen. Given the wide draping field and the extreme vulnerability of children to hypothermia, care should be taken to ensure the temperature of the operating room is elevated to near body temperature if possible and all fluids and blood products given are warmed to body temperature as well. Fluids used for irrigation in the field should be warmed to above normal body temperature (around 110 degrees Fahrenheit) to prevent evaporative heat losses. A Cell Saver (Haemonetics, Boston, MA) or other blood salvage device should be readily available to encourage autotransfusion and limit allogeneic blood product transfusion. Enteric content contamination is ***NOT*** a contraindication to blood salvage device usage with current centrifuge and cell washing techniques.

Initial approach—The only goal of this initial operation is to perform lifesaving, rapid control of hemorrhage and/or spillage of intestinal contents. A standard midline laparotomy from xiphoid to pubic symphysis gives access to all major intraabdominal and pelvic structures. It can be extended into a median sternotomy if needed, or to a right or left thoracoabdominal incision for exposure of one side of the chest and diaphragm. Initial laparotomy in a hemodynamically abnormal patient should be conducted in a "damage control fashion". Damage control laparotomy begins with rapid entrance into the peritoneal cavity and placement of laparotomy "packs". These packs, if applied correctly, should provide hemorrhage control sufficient to allow a brief pause for the anesthesia team to catch up with blood product requirements and stabilize the vital signs and the operating room team to continue gathering helpful equipment. Once the patient has stabilized, a methodical four quadrant exploration of the abdomen can ensue, slowly removing packs and evacuating clot until life-threatening injuries are isolated and repaired or extirpated.

Hollow viscus injury—Openings in the small bowel and colon should be managed by rapidly stapling off either side. Gastric, duodenal, rectal, and intraabdominal esophageal injuries may not be able to be stapled and should be oversewn rapidly during an initial operation to prevent continued spillage of succus. Large bore nasogastric tube placement should be confirmed and optimized by direct palpation of the stomach.

Solid organ hemorrhage—The liver can be mobilized by releasing the falciform ligament superiorly up to the level of the hepatic veins, as well as the right and left triangular ligament attachments to the diaphragm. This allows for better compression of liver parenchyma in case of bleeding lacerations. A Pringle maneuver (direct compression of the portal triad between the operator's thumb and fingers after opening the gastrohepatic ligament) can diminish bleeding from portal vein and hepatic artery branch injuries but will not affect hepatic vein or inferior vena cava hemorrhage. Other methods of Pringle maneuver that can be used are an atraumatic vascular clamp or encircling portal triad with a Rumel tourniquet. A Pringle maneuver should not be held for more than 90 consecutive minutes. Complete hepatic exclusion can be achieved by adding compression of the infra-hepatic IVC above the right adrenal gland and supra-hepatic IVC just below the diaphragm with vascular clamps or vessel loops. Hepatorrhaphy can be conducted with 0 or 2-0 chromic gut pledgeted sutures, often buttressed with commercially available hemostatic oxidized regenerated cellulose membranes. Drains should be left widely around sites of hepatic laceration in case of bile leakage. Of historical interest, past attempts to control hepatic hemorrhage have included the Schrock (atriocaval) shunt for juxtahepatic venous injuries [11].

Splenectomy is often necessary for hemorrhage control from the spleen. There is no role for splenorrhaphy during damage control laparotomy. The life-threatening downside to splenectomy is overwhelming post-splenectomy infection (OPSI), which may be more frequent than previously suspected, and vaccinations against encapsulated Gram stain positive bacteria (*Haemophilus influenzae, Neisseria* *meningitidis, Streptococcus pneumoniae*) must be given around two weeks after emergency splenectomy. Splenorrhaphy may be considered in a hemodynamically normal patient taken to the operating room to address concomitant injuries without life-threatening hemorrhage.

Renal injury can cause life threatening hemorrhage and may require nephrectomy. If the patient is stable, injury to kidney can be evaluated by CT with cystogram and intravenous pyelography (IVP) or IVP alone if CT is not available. Unstable patients need to undergo emergent laparotomy to control hemorrhage. The kidney should be explored if there is expanding hematoma, extravasation, or arterial bleeding. If ureter injury is possible, on-table IVP can be performed. When emergent nephrectomy is necessary the surgeon should first ensure that an opposite kidney is present by palpation if the presence of the opposite kidney has not already been proved by CT or IVP. Nephrorrhaphy is an alternative but can be complicated by persistent bleeding, urine leakage, and long term renovascular hypertension from scarring. Renal repairs should be widely drained to identify post-operative urine leakage.

Vascular injury—Retroperitoneal hematomas require exploration in penetrating trauma (see Fig. 19.1). Zone 1 hematomas include the abdominal aorta and major branches including the celiac axis branches, superior and inferior mesenteric arteries, proximal renal arteries and the aortic bifurcation, abdominal inferior vena cava

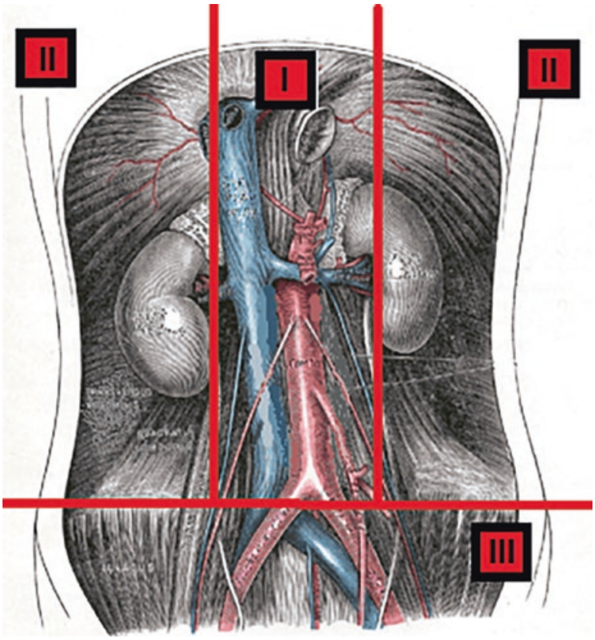

Fig. 19.1 Zones of Retroperitoneal Injury (Modified from: Gray H, Gray's Anatomy, 20th ed., Lea and Febiger, 1918, used under Creative Commons license: Public domain. (Downloaded from: https://commons.wikimedia.org/wiki/File:Aortadiagramgray.png 13 OCT 2021)

(IVC) and major tributaries, including the superior and inferior mesenteric veins, portal vein, proximal renal veins, and the iliac vein bifurcation, as well as the pancreas and duodenum. Zone 2 includes the kidneys, proximal ureters and adrenal glands and is further subdivided into 2R (right, which includes the ascending colon) and 2 L (left, which includes the descending colon). Zone 3 is the pelvic retroperitoneum below the sacral promontory and includes the rest of the iliac vasculature including the rectal mesentery, the distal gonadal vessels, and distal ureters.

Injuries to major vessels should be temporized only and not repaired during initial exploration. Pediatric sized chest tubes can be inserted in either end of a large vessel and secured with umbilical tapes tightened through red rubber catheters or silk ties to bridge gaps in vessels that cannot be primarily ligated. In patients with temporary vascular shunts in place, low-dose continuous heparin infusion should be considered until vascular repair is possible, if initial hemorrhage control is effective.

Pancreaticobiliary injury—The pancreas and duodenum can be approached initially by opening the gastrocolic (lesser) omentum. Trauma to the pancreatic head—common bile duct—duodenal complex should be fully explored using a Kocher maneuver to mobilize this complex. A cholangiogram should be performed to identify or exclude damage to the ampullary structures. Some injuries can be temporized with temporary pyloric exclusion (by application of a non-cutting stapler or oversewing with PDS) with or without primary repair and accompanied by wide closed-suction drainage. During a second look operation, draining gastrostomy and feeding jejunostomy tubes may be placed. A surgical gastrojejunostomy is an ulcerogenic procedure and should be avoided at all costs in children. Rarely, complete disruption of the pancreatic head, bile duct and duodenum complex will require extirpation and Whipple reconstruction with pancreaticojejunostomy, choledochojejunostomy and gastrojejunostomy (sparing the pylorus, if possible, to prevent dumping). Injuries to the pancreatic body or tail are best handled with distal pancreatectomy, sparing the spleen if it is not a source of hemorrhage.

Exposure of the retroperitoneum—The large abdominal vasculature will need to be approached through medial visceral rotation, maneuvers intended to mobilize the colon and small bowel mesenteries off of the retroperitoneum. The Kocher maneuver consists in releasing the filmy retroperitoneal attachments right lateral to the duodenum as it enters the retroperitoneum.

Mobilization of the right colon (right medial visceral rotation or Cattell-Braasch maneuver) is performed by incising the right colon attachments to the abdominal side wall and carefully separating the colon mesentery off of the right Gerota's fascia. When combined with a Kocher maneuver, this allows exposure of the IVC, portal triad, right kidney, renal vessels and proximal ureter, right adrenal gland, and pancreatic head-duodenal complex. Mobilization can continue up to the middle colic vein, which can be traced superiorly to identify the superior mesenteric vein.

Mobilization of the left colon (left medial visceral rotation or modified Mattox maneuver) involves incising the left colon attachments to the abdominal side wall and carefully separating the left colon mesentery off of the underlying Gerota's fascia. This allows exposure of the pancreatic tail and body, left kidney, renal vessels, and proximal ureter/gonadal vessels, duodenojejunal junction and inferior mesenteric vein [12]. A full Mattox maneuver includes the spleen, distal pancreas, and left kidney in the visceral rotation by dividing the splenic attachments to the diaphragm and opening the left Gerota's fascia deep to the descending colon. This allows for elevation of these structures off of the abdominal aorta for full exposure of this structure and its large splanchnic branches.

Closure—Damage control laparotomy should conclude with placement of a temporary abdominal dressing over an open abdomen, with plan for return to intensive care unit and operative reexploration in the next 24–48 h once the patient has stabilized. In a hemodynamically normal, warm patient whose injuries have been completely addressed, primary closure may be considered if such a maneuver does not threaten respiratory compromise from compartment syndrome.

Alternatives to Laparotomy

Non-therapeutic laparotomy (i.e., laparotomy without significant findings) has been documented in up to 25% of firearm injuries and up to 53% of piercing injuries in adults. Non-therapeutic laparotomy has also been noted to have a relatively high risk of short- and long- term complications, up to 40% [13].

Alternative to laparotomy include non-operative observation, local wound exploration, laparoscopy, or interventional radiology catheter-based therapies. In a recent survey of pediatric surgeons, there was variation in choice of alternative to laparotomy for a hemodynamically stable child with penetrating abdominal trauma [14]. In this scenario, 39% chose observation, 32% chose laparoscopy, and 30% chose local wound exploration.

Select patients with normal vital signs, no evidence of peritonitis and a reliable abdominal examination (no concomitant traumatic brain or spinal cord injury) are potential candidates for fully non-operative management of penetrating trauma. The main reasons for failure of non-operative management are covert diaphragmatic and hollow viscus injuries; however, non-therapeutic laparotomy can be avoided in a carefully chosen subset of patients. The failure rate in children, in particular, seems to be low, without increasing the risk of complications in non-operated patients [15].

Local wound exploration can be used a selective method to determine which patients need laparotomy. After a stab injury, the wound can be explored, and for those patients in whom the stabbing object traversed the muscular fascia of the abdominal wall, laparotomy to investigate for visceral injury can be performed. It should be employed with caution because it can be less accurate in young, slim children who have a short distance from the skin to the fascia, and difficult to visualize and detect facial injury in obese patients. Also, it can be problematic to arrange safe sedation for a potentially unstable pediatric trauma victim outside of the operating room.

Those patients who require operative intervention but are hemodynamically normal may be candidates for laparoscopy. Laparoscopy can provide improved views of the diaphragm over laparotomy. It should follow a systematic plan of exploration to exclude all injuries and there should be a low threshold for conversion to laparotomy if there are unexpected findings, changes in hemodynamics or difficulty in

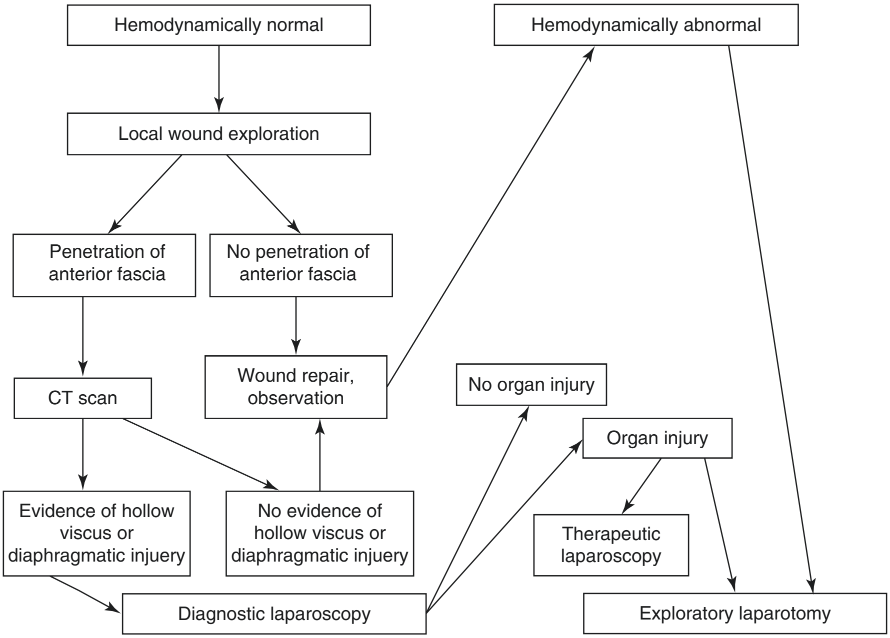

Fig. 19.2 For abdominal stab wounds or tangential gunshot wounds, this algorithm can be used to help select patients in whom alternatives to laparotomy may offer the best risk to benefit ratio. (Source: Dr. Tara Loux)

visualization and/or repair of injuries [16]. Figure 19.2 outlines an algorithm for decision-making regarding intervention in the pediatric patient with penetrating abdominal trauma.

Interventional radiology techniques may be indispensable to assist in control of life-threatening hemorrhage and should be considered as an adjunct when hepatic, renal or pelvic arterial injury is not fully controlled with operative maneuvers. Particle or coil embolization of branch arteries of the solid organs or internal iliac arteries can assist in hemorrhage control. Use of a hybrid operating room that allows both open and catheter-based therapy at the same time can be lifesaving for children who need both simultaneously. Endovascular treatment of aortic injuries has become nearly standard of care in the adult world, though long-term follow-up has not been reliably carried out in adults, much less in pediatric patients [17].

Emerging Adjuncts

Strategies for minimizing coagulopathy and limiting transfusion—Rapid thromboelastography (rTEG) use in children has been found to have prognostic significance in terms of severity of injury and can direct blood product infusion therapy towards specific deficits. Whole blood administration is gaining popularity in trauma centers, including pediatric trauma centers. A recent retrospective propensity-matched national databank analysis suggests that severely injured children treated with whole blood as part of a massive transfusion protocol had similar overall mortality but significantly fewer ventilator days and less overall blood product requirement than matched controls (Anand 2021) [18]. Tranexamic acid (TXA) administration in pediatric combat injuries requiring massive transfusion has been demonstrated retrospectively to be associated with decreased mortality. Bolus doses between 15 and 30 mg/kg followed by an 8-h infusion of 2–4 mg/kg/h are currently being studied in ongoing prospective randomized trials.

Extracorporeal Membrane Oxygenation (ECMO) has been described as an adjunct for the treatment of trauma in children, with upwards of 50% survival rate. Penetrating trauma cases were in the minority of those reports. Traumatic brain injury, need for operation, and solid-organ injuries are NOT absolute contraindications to ECMO utilization and should not necessarily limit its use [19]. Use of ECMO during active cardiopulmonary resuscitation (E-CPR) has been reported very infrequently in penetrating trauma patients and never in pediatric trauma.

Resuscitative endovascular balloon occlusion of the aorta (REBOA) has not been well studied in younger pediatric patients, but case reports have described the use of aortic occlusion techniques down to age 7 years, for non-traumatic bleeding [20]. Newer delivery systems with 7 French sheaths may increase its applicability for use in small children, however the infrequency of need will make it hard to train pediatric surgeons in use of the technique. With assistance from colleagues in interventional radiology, interventional cardiology, or adult trauma surgery, it may be a feasible adjunct.

Outcomes

Survival

Mortality is much higher in patients with penetrating injury, due to the most part to non-accidental gunshot wounds. The pediatric-adjusted shock index (SIPA) can predict severity of trauma and various outcomes and may even be trended as a vital sign (Table 19.1) [21, 22]. For adolescent patients (ages 15–18) with penetrating

Table 19.1 Normal pediatric vital sign ranges based on patient age

Age	Heart rate	Systolic blood pressure	Diastolic blood pressure	Respiratory rate	Maximum normal SIRA
4–6 years	65–110	90–110	60–75	20–25	1.222222222
6–12 years	60–100	100–120	60–75	14–22	1
>12years	55–90	100–135	65–S5	12–20	0.9

SIPA—shock index, pediatric age adjusted; equal to maximum normal heart rate/minimum normal SBP

From: Acker SN, Ross JT, Patrick DA, Tong S, Bensard DD, Pediatric specific shock index accurately identifies severely injured children. J Pediatr Surg 50(2): 331–334, 2015., no permission required for one table/figure.

trauma, retrospective evidence suggests that those treated at pediatric trauma centers have lower mortality and fewer surgical interventions than those treated at adult trauma centers, though it is unclear what role selection bias may have in these data [4]. This information may have a significant impact on public health policy and triage decision-making at the level of city, state, and federal emergency services.

Morbidity

There is little published data on functional and psychological outcomes after pediatric trauma. However, a recent study looking prospectively at functional outcomes and quality of life instrument scores found penetrating trauma to be a risk factor on multivariate analysis for lower functional status scores at 6 months after discharge [23]. Any caregiver who takes care of pediatric trauma patients is impressed with their resilience and ability to recover from serious life-threatening illness or injury, but it is currently unknown what exact circumstances determine the effect of injury on lifelong health and health-related quality of life.

Conclusions and Take-Home Points

Reemphasis of Key Points:

1. Trauma is the most common cause of death in children; while penetrating trauma is less common than blunt, it is significantly more lethal.
2. The algorithmic process of Advanced Trauma Life Support (ATLS) is designed to rapidly identify and treat injuries after trauma in children, penetrating and otherwise.
3. Immediate threats to life after penetrating trauma, such as airway compromise, tension pneumothorax, pericardial tamponade, and hemorrhage with hemodynamic instability must be immediately found and addressed.
4. A good proportion of abdominal penetrating trauma in children will require rapid operative intervention. Avoidance of prolonged hemorrhage, hypothermia, acidosis, and coagulopathy is the key to survival. Nonoperative management and diagnostic or therapeutic laparoscopy can be options in carefully selected patients.

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Chapter 20
Liver Injury

Carolyn Gosztyla and Ryan M. Walk

Abstract Liver injury in children can result from either blunt or penetrating mechanisms and can result in hemodynamically significant bleeding. The initial management of pediatric patients presenting with abdominal trauma follows ATLS principles to facilitate timely and lifesaving interventions. The index for suspicion for abdominal trauma is based on mechanism and physical exam findings. Elevation in liver-associated enzymes can be suggestive of liver injury in equivocal cases. CT evaluation of the abdomen defines the extent of liver injury. Hemodynamic status dictates intervention including transfusion, angioembolization, and operative intervention. The majority of blunt liver injuries can be managed non-operatively, and recently published society guidelines should serve as a reference for this strategy. Follow-up imaging is not recommended in asymptomatic patients and should be used to diagnose complications in patients demonstrating symptoms. Complications following liver injury managed either operatively or non-operatively are rare but may need additional interventions for management.

Keywords Liver trauma · Solid organ injury · Blunt solid organ injury · Pediatric trauma · Pediatric solid organ injury

Key Concepts/Clinical Pearls (Learning Objectives)
- Hemodynamic status dictates the management pathway for pediatric patients with liver injury.
- CT Abdomen/Pelvis with IV contrast is the gold standard for diagnosis of hepatic injury.

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- Non-operative management of acute blunt hepatic trauma is the standard of care for the hemodynamically stable patient.
- Operative control of hemorrhage may be needed in hemodynamically unstable patients who do not respond to resuscitation.

Initial Management of Trauma Patient

Management of all trauma patients begins with systematic evaluation and management of the airway, breathing, and circulation as dictated by the principles of Advanced Trauma Life Support (ATLS®). The majority of patients who sustain blunt abdominal trauma resulting in liver injury have severe mechanisms that require assessment for concomitant injuries. Suspicion of liver injury is heightened in patients with blunt force trauma to the upper abdomen or chest. In particular, hepatic injuries can be seen with motor vehicle collisions, pedestrian versus motor vehicle, all-terrain vehicles, bicycle crashes, falls, and sports-related injuries. Liver injuries seldom occur in isolation. Assessment for traumatic brain injury, thoracic trauma, pelvic injuries, and musculoskeletal injury as the etiology of hemorrhagic shock is essential during the initial trauma survey.

Hemorrhagic abdominal trauma remains a major cause of morbidity and mortality, with the liver being the most commonly injured solid organ, followed by the spleen. More than 50% of hypotensive injured children have a severe traumatic brain injury without significant intra-abdominal bleeding [1]. In penetrating injuries, location should drive suspicion for associated liver injury. Physical exam findings that may be suggestive of abdominal solid organ injury include abdominal bruising, abrasions, seatbelt sign [2], and handlebar sign [3]. Tenderness to palpation and distension in the context of other signs of shock suggest solid organ injury as a source of bleeding. Costal margin tenderness in conjunction with other signs of abdominal trauma can be indicative of liver injury; however, in isolation has a low risk of associated intraabdominal injury [4]. In patients with hepatic injuries, other intraabdominal injuries are frequently present [5].

Initial Radiographic/Laboratory Studies

Laboratory evaluation of a pediatric trauma patient at the time of presentation is rarely diagnostic but instead guides imaging studies. Urinalysis with >5 rbc/hpf, and elevation in aspartate aminotransferase and alanine aminotransferase in conjunction with an abnormal abdominal exam are associated with intrabdominal injury, not necessarily specific to liver trauma [6, 7]. Hemoglobin, base deficit,

Table 20.1 AAST Liver injury scale. The grade of liver injury is determined radiographically on contrast-enhanced liver CT according to this grading system. In pediatric patients it is important to remember that hemodynamic status and response to blood product resuscitation dictate intervention rather than the grade of the injury

AAST Liver Injury Scale		
Grade I	–	Hematoma: subcapsular, <10% surface area
	–	Laceration: capsulartear, <1 cm parenchymal depth
Grade II	–	Hematoma: subcapsular, 10–50% surface area
	–	Hematoma: intraparenchymal <10 cm diameter
	–	Laceration: capsular tear l–3 cm parenchymal depth, <10 cm length
Grade III	–	Hematoma: subcapsular, >50% surface area of ruptured subcapsular or parenchymal hematoma
	–	Hematoma: intraparenchymal >10 cm
	–	Laceration: capsulartear >3 cm parenchymal depth
	–	Vascular injury with active bleeding contained within liver parenchyma
Grade IV	–	Laceration: parenchymal disruption involving 25–75% hepatic lobe or involves 1–3 Couinaud segments
	–	Vascular injury with active bleeding breaching the liver parenchyma into the peritoneum
Grade V	–	Laceration: parenchymal disruption involving >75% of hepatic lobe
	–	Vascular: juxtahepaticvenous injuries (retrohepaticvena cava/central hepatic veins)

Additional points:

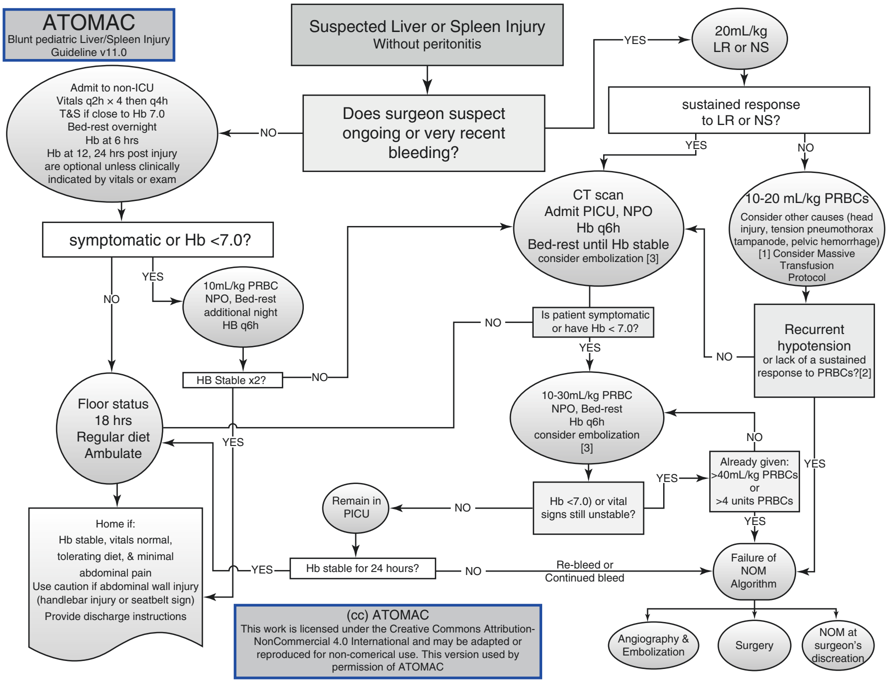
- Advance one grade for multiple injuries up to Grade III
- "vascular Injury" (i.e. pseudoaneurysm or AV fistula)—appears as a focal collection of vascular contrast which decreases in attenuation on delayed images
- "active bleeding"—focal or diffuse collection of vascular contrast which increases in size or attenuation on a delayed phase

international normalized ratio (INR), lactate, thromboelastography (TEG) can help guide resuscitation for patients in hemorrhagic shock, especially in patients with ongoing or massive transfusion requirements. The focused assessment with sonography for trauma (FAST) exam has not translated well to the pediatric population, and it is neither sensitive nor specific for identifying abdominal injuries or the need for operative intervention [8]. However, a negative fast exam may predict successful non-operative management of patients with blunt solid organ injury [9].

Computed tomography (CT) scan of the abdomen and pelvis with IV contrast remains the gold standard for the diagnosis of intraabdominal injuries including liver injury. Liver Injury is classified according to the American Association for the Surgery of Trauma liver injury scale (Table 20.1). Grade of injury on CT does not dictate a need for emergent surgical intervention—this should be based on the hemodynamic status of the patient.

Non-operative Management

Non-operative management of blunt hepatic trauma has become the standard of care over the last three decades with improvement in imaging, resuscitative protocols, and pediatric intensive care [10]. Management of a pediatric patient with blunt abdominal trauma is largely algorithm-based at pediatric trauma centers, following validation of this approach by the ATOMAC group in 2015 [11]. The diagnostic challenge in these cases is to successfully identify the severely injured patients who would benefit from aggressive blood product resuscitation and expedite laparotomy when indicated [12]. Transfusion is indicated for ongoing hemodynamic instability after initial crystalloid bolus, for a hemoglobin <7, or signs of ongoing or recent bleeding.



In 2019, American Pediatric Surgical Association (APSA) published a simplified algorithm for the management of patients with blunt liver and spleen injury (BLSI) (Table 20.2). Indications for ICU admission include abnormal vital signs after initial volume resuscitation. Tachycardia in pediatric blunt abdominal trauma should be viewed cautiously. Hypotension is a grave finding, particularly in younger patients, and should prompt immediate intervention. Guidelines for the ICU management of BLSI include guidance for activity, labs, and diet, with the endpoint for this phase of care set as normalization of vital signs. Bedrest is suggested during this phase. Serial complete blood count (CBC) is recommended at 6-h intervals, and the

Table 20.2 Updated APSA Blunt Liver/Spleen Injury Guidelines 2019. These updated guidelines simplify the clinical decision making pathway for children with blunt liver injury without peritonitis on physical exam. Clinical decision pathways are arranged according to phase of care

Updated APSA Blunt Liver/Spleen Injury Guidelines 2019	
Admission • ICU Admission Indicators-abnormal vital signs after initial volume resuscitation ICU • Activity—Bedrest until normal vitals • Labs—q6hour CBC until vitals normal • Diet—NPO until vitals normal and hemoglobin stable Ward • Activity—no restrictions • Labs—CBC on admission and/or 6 h after injury • Diet—regular diet	Procedures Transfusion • Unstable vitals after 20 cm^3/kg bolus of isotonic IVF • Hemoglobin <7 • Signs of ongoing or recent bleeding Angioembolization • Signs of ongoing bleeding despite pRBC transfusion • Not indicated for contrast blush on admission CT without unstable vitals Operative exploration with control of bleeding • Unstable vitals despite pRBC transfusion • Consider massive transfusion protocol
Set Free • Based on clinical condition NOT injury severity (grade) • Tolerating a diet • Minimal abdominal pain • Normal vital signs	Aftercare Activity Restriction • Restricting activity to grade plus 2 weeks is safe • Shorter restrictions may be safe but there is inadequate data to support decreasing these recommendations Follow up Imaging • Risk of delayed complications following spleen and liver injuries is low • Consider imaging for symptomatic patients with prior high grade injuries

patient should remain NPO until vital signs are normal and hemoglobin has stabilized.

If the patient has a diagnosed BLSI without abnormal vital signs or the need for an emergent or urgent procedure, admission to the ward is appropriate with no activity restrictions. A CBC is recommended at the time of admission and 6 h following injury. A regular diet is recommended for these patients.

The use of selective angioembolization (AE) should be considered for patients with signs of ongoing bleeding after attempts at stabilization with transfusion [13]. Appropriate patient selection requires a sustained response to resuscitation and the absence of both peritonitis on exam and other operative intra-abdominal injuries. The presence of contrast blush on CT should be considered an indication for angioembolization in conjunction with ongoing transfusion requirements or other signs of ongoing bleeding. Prophylactic AE for higher-grade injuries or the presence of a contrast blush on CT imaging (absent ongoing transfusion requirements) is accepted practice in adults but should NOT be performed in children. AE may be considered in hemodynamically stable children who have ongoing hepatic bleeding after attempted operative control. AE may be performed with endogenous clot, microspheres, embolization coils, or gel-foam sponge at the discretion of the operator.

Complications such as access-site pseudoaneurysm or liver ischemia leading to biliary leaks or infectious complications are well described and may require further intervention.

Eligibility for Non-operative management include: initial hemodynamic stability or response to trauma-bay resuscitation, and absence of additional injuries excluding a non-operative approach. Peritonitis is an absolute indication for operative exploration, and this finding should exclude the patient from non-operative treatment algorithms. Penetrating abdominal injuries are usually the result of stabbing or firearms injuries and should be managed operatively at the discretion of the surgeon. Additional abdominal injuries that require surgical management may prompt operative management of liver injury at the time of surgery. The goal of the operative management in both blunt and penetrating mechanisms in operative cases of hepatic trauma is primarily hemorrhage control.

Operative Intervention

Operative management of a liver injury is more commonly performed during exploration for management of associated intraabdominal injuries. Those patients that require operative intervention for ongoing liver bleeding alone have a high associated mortality rate [14]. In acute operative management of liver injury, the primary focus of the intervention is hemorrhage control followed by debridement or resection of devitalized liver and control of any bile leak with appropriate drainage [15]. This should be coupled with damage control resuscitation both in the operating room and following operative hemorrhage control with the goal of restoring tissue oxygenation, limiting acidosis and coagulopathy, and active warming [16, 17].

The operative approach to controlling liver hemorrhage first begins with laparotomy followed by evacuation of any intraabdominal clot, then packing the abdomen. Perihepatic packing above and below the liver helps to restore normal hepatic anatomy without applying packs to the bleeding surface. It is important to place packs below the liver to sandwich it between packs to obtain tamponade. If a damage-control approach is being undertaken in a patient with a compromised physiologic state, liver packs can be left in place once bleeding is temporized. The patient can be transferred to the PICU with a temporary abdominal dressing and an open abdomen. The intent of this approach is to return to the operating room after correction of coagulopathy, hypothermia, and acidosis [18].

Early and frequent communication with the anesthesia team performing ongoing resuscitation is essential. Coagulopathic bleeding should prompt the surgeon to consider a damage control approach. If massive hemorrhage is identified on opening the abdomen, controlling hemorrhage by first compressing the supra-celiac aorta at the esophageal hiatus can slow inflow while access to the specific site of bleeding is achieved. Once the portal triad is identified and isolated, a Pringle maneuver can be performed by compressing the portal triad at the Foramen of Winslow. This should temporize bleeding by stopping hepatic arterial and portal venous inflow to the liver. Care must be taken not to injure the common bile duct when performing a Pringle maneuver. If ongoing bleeding is present after a Pringle maneuver, the surgeon should have suspicion for hepatic vein or retrohepatic inferior vena cava injury [19]. At least initially, either of these injuries is best approached with perihepatic packing.

An important anatomic consideration for a surgeon who manages pediatric liver trauma includes the cartilaginous nature of the ribs and the relative mobility of the liver when compared to adult patients. The pliability of the ribs may result in less effective tamponade when packing the liver. Care should be taken not to cause an abdominal compartment syndrome when an increased number of packs is needed to achieve adequate hepatic packing. The distance from the anterior abdominal wall to the spine is much shorter in children, which allows for easier access to the retrohepatic vena cava. This factor may provide an opportunity for active measures of hemorrhage control with suture repair of injuries in the region.

Once vascular control of the liver has been achieved, attention can be turned to each injury individually for management. Hepatorrhaphy utilizes deep parenchymal sutures to reapproximate disrupted tissue and reduce dead space. One of the pitfalls of using this technique is that large portions of tissues can become ischemic, leading to infarction and subsequent infection. Hepatotomy, the contemporary surgical maneuver for liver bleeding, requires exposure of the actively bleeding area followed by control with a surgical energy device, clips, staples, or suture ligation. This technique may seem counterintuitive, as this often requires enlargement of the traumatic wound to expose the bleeding vessel and facilitate ligation. Resection of ischemic or devitalized tissue should be performed with either anatomic or non-anatomic partial hepatectomy. Resection of a large segment of the liver is most frequently required when the liver is split along either the right hepatic vein with sequestration of segments VI and VII, or along the Falciform with segments II and III avulsed.

Selective hepatic artery ligation can be considered when the source of arterial bleeding cannot be identified, but bleeding is stopped with a Pringle maneuver. This technique is contraindicated when a major venous injury is suspected, as it will completely devascularize the corresponding segment of the liver. In cases where there is a significant dead space due to parenchymal defects, the omentum can be used to fill the space. Raw surface bleeding from the liver or capsular tears can be controlled with topical agents, including electrocautery or the argon beam coagulator. A variety of topical agents made from oxidized cellulose, such as Surgicel©, and Nu-Knit© can augment an intact coagulation cascade. Moreover, these can be ‘welded’ to the raw liver surface using cautery or argon. Tissue adhesives such as fibrin-based products can be used to seal small blood vessels and raw surfaces. Their use in trauma is limited by the lengthy time required to prepare the polymer before use.

Special note should be made of trauma to the infant or neonatal liver, as the thin liver capsule makes these challenging to repair. These are most frequently iatrogenic, sustained at time of exploration for another disease process. Such injuries can be especially grave, and the strategies described above are commonly employed in combination. Liberal blood product administration, including use of recombinant factor VII, has been described. Nevertheless, these injuries are often mortal, particularly in premature infants, and are therefore best avoided.

Hemorrhage control will always remain the highest priority in the acute management of liver injury; however, injuries to the biliary tract can be identified and repaired in the appropriate setting. In damage control surgery, the hallmark of biliary management is external drain placement. Time-consuming repairs of the external biliary tree should be reserved for patients who are hemodynamically normal.

Complications of Liver Trauma

Complications following liver injury are rare, but can require intervention for management. Pseudoaneurysm formation has been found in 1.7% of children imaged 5–7 days following injury [20]. Rare complications such as hemobilia and delayed hemorrhage as the result of pseudoaneurysm formation have been reported and should be treated with angioembolization. Biloma and bile leak can be treated with percutaneous drainage and may require ERCP for definitive management.

Discharge and Follow-up

Discharge guidelines are based on clinical condition (not the grade of liver injury as was previously recommended). Criteria for discharge include the ability to tolerate a diet, minimal abdominal pain, and normal vital signs. Recommended duration of activity restriction is the AAST grade of injury plus 2 weeks.

Following blunt liver injury, reimaging without a clinical indication is not recommended in either the APSA or ATOMIC guidelines. Selective reimaging is warranted in symptomatic patients [21]. Contrast-enhanced CT or contrast-enhanced ultrasound can be used depending on institutional capabilities [22].

Conclusions and Take Home Points

Liver injury in children from either blunt or penetrating mechanisms and can result in hemodynamically significant bleeding. CT evaluation of the abdomen defines the extent of liver injury; however, the patient's hemodynamic status dictates the management algorithm. The majority of blunt liver injuries can be managed successfully non-operatively with the adjuncts of transfusion and angioembolization. Surgery is reserved for hemodynamically unstable patients or those with concomitant abdominal injuries requiring operative intervention.

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Chapter 21
Pancreas, Duodenum and Biliary Tree

Pamela Mar and Mary J. Edwards

Abstract Injuries to the pancreas, duodenum and biliary tree are fortunately rare in children and are extremely rare in isolation. However, they can cause significant acute morbidity and have the potential for long-term complications. In general, evaluation and diagnosis are similar to adults and combines clinical, laboratory and CT findings with a high index of suspicion. Every reasonable effort should be made to limit exposure to ionizing radiation in children. Therefore, the utilization of MRI and ultrasound for follow-up imaging in lieu of CT should be considered. In many cases, these modalities are superior to CT for visualization of ductal anatomy. Treatment considerations are slightly different in the pediatric population than in adults. Non-operative management for many of these injuries has a high success rate in children. Gallbladder injuries and full-thickness duodenal lacerations will require operative repair, but cholecystectomy and primary duodenal repair are usually sufficient. Controversy still exists regarding the optimal management of blunt pancreatic injuries in children when the pancreatic duct is involved; however, both operative and non-operative treatment are reasonable options. Regardless of treatment strategy, long term follow-up is essential.

Keywords Pancreatic injury · Duodenal injury · Biliary Tree · Gallbladder · Pediatric · Trauma

Key Concepts/Clinical Pearls (Learning Objectives)
- Understand the evaluation of suspected biliary and pancreaticoduodenal injuries in children.
- Understand optimal imaging, both timing and modality.
- Recognizes operative and non-operative management of pancreatic injuries involving the duct in children as options.

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- Understand the need for long term follow up for pancreatic and biliary injuries.
- Articulate the principles of repair of full-thickness duodenal lacerations.
- Understand injury patterns that are suspicious for physical abuse in children.

Initial Management of Trauma Patient

As with all trauma victims, initial evaluation of the injured child should focus on airway, breathing and hemorrhage control. Hemodynamically unstable patients with an intra-abdominal injury that do not respond to blood product resuscitation should undergo prompt laparotomy. Stable patients with a clinical picture worrisome for serious abdominal injury should under computed tomography (CT) scan of the abdomen and pelvis with intravenous contrast. Stable patients at risk for blunt abdominal injury should undergo a clinical exam and laboratory evaluation which includes serum amylase or lipase levels and hepatic aspartate aminotransferase (AST) levels, with imaging reserved for those with abnormal findings.

Initial Radiographic/Ancillary Studies

Previously published clinical decision rules can help determine which patients are at high enough risk for significant abdominal injury to warrant abdominal and pelvic CT [1, 2]. In general, children who present with abdominal pain and tenderness, evidence of abdominal wall injury, and elevation of serum AST or serum amylase should undergo cross-sectional imaging with CT. Unfortunately, CT evaluation immediately after an injury has a relatively lower sensitivity for injuries to the duodenum, pancreas and biliary tree than for other solid organ injuries [3]. Therefore, persistent pain or elevation of amylase and bilirubin should prompt further evaluation. Depending on the clinical concern, this can be done with ultrasound, magnetic resonance cholangiopancreatography (MRCP), or if needed, repeat CT.

Injuries to the biliary system, pancreas, and duodenum are relatively rare and are seldom isolated, given the significant compressive force required [4]. An associated injury is common given their close anatomic relationship to each other and to other organs such as the liver and spleen (Fig. 21.1) [5]. Pancreatic injury is most commonly associated with duodenal injury [4], and biliary tree injury usually occurs in the setting of a high-grade hepatic injury [6].

Symptoms due to injury of the biliary tree, duodenum, and pancreas are nonspecific and include progressively worsening or persistent pain, tenderness, and vomiting. They may be masked by other injuries or attributed to known injuries to other solid organs. As a result, delayed diagnosis is common. All of these factors mandate the surgeon to have a high degree of suspicion when symptoms and laboratory abnormalities persist [6, 7]. Once diagnosed, the grading symptoms for these injuries are usually done in accordance with the classification by the American Association for Trauma (Table 21.1). While the grade of injury often guides management in adults, this is not necessarily the case in children, as nonoperative management in many of these injuries is successful [8].

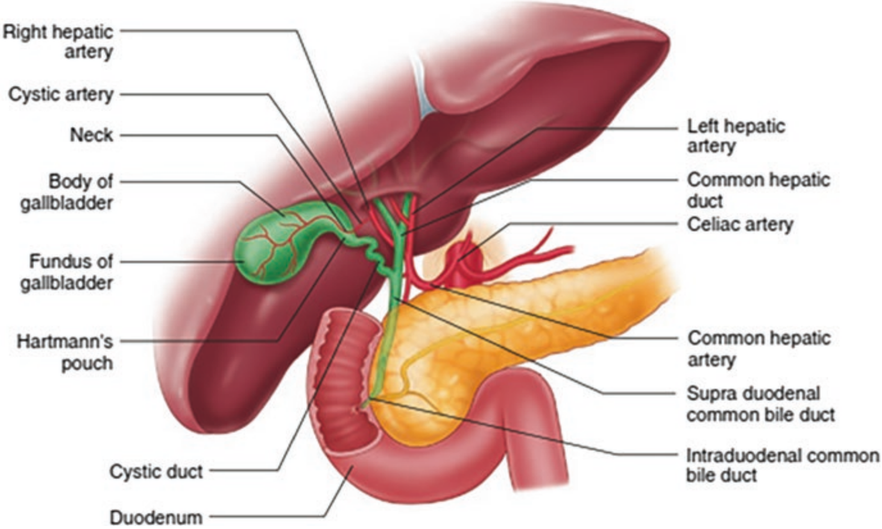

Fig. 21.1 Anatomic relationships between the biliary tree, duodenum, and pancreas. (Reproduced with permission from Color Atlas of Pediatric Anatomy, Laparoscopy, and Thoracoscopy (1st edition) ed. Edited by Merrill McHoney, Edward M Kiely and Imran Mushtaq, 2017 Springer. Chap. 24 Laparoscopic Cholecystectomy, by Augusto Zani and Niyi Ade-Ajayi p 169)

Biliary Tree Injuries

Biliary tree injuries, particularly in isolation, are incredibly rare. Approximately 1–4% of pediatric liver injuries are found to have concomitant biliary tree injury. Conversely, 83% of patients with gallbladder injuries have an associated liver injury [6, 9].

Traumatic extrahepatic biliary injury has a reported incidence of 0.009% in the pediatric population, with isolated extrahepatic biliary injury compromising only 2–3% of those cases. In addition to nonspecific symptoms at the time of presentation, shifts of care towards nonoperative management of liver injuries may lead to a delay in diagnosis [10].

Symptoms are nonspecific and may take several days to manifest after the injury. These include abdominal pain, jaundice, distension, ileus, and ascites [11]. Fever, abdominal pain, and prolonged ileus are the most common symptoms and should prompt further imaging. When a biliary injury is present, findings are usually consistent with a biloma [12].

Imaging studies to determine the presence of gallbladder perforation or other disruptions of the biliary system include ultrasonography, CT, MRCP, hepatobiliary iminodiacetic (HIDA) cholecystoscintigraphy, endoscopic retrograde cholangiopancreatography (ERCP), and percutaneous transhepatic cholangiography (PTC). Signs

Table 21.1 AAST-OIS injury grading scale

Grade	Extrahepatic Bilary Tree	Duodenum	Pancreas
I	Gallbladder Contusion/ Hematoma Portal Triad Contusion	Hematoma: Involving a single portion of duodenum Laceration: Partial thickness, no perforation	Minor contusion without ductal injury Superficial laceration without ductal injury
II	Partial Gallbladder avulsion from liver bed; cystic duct intact Laceration of perforation of the gallbladder	Hematoma: Involving more than one portion Laceration: disruption of <50% of circumference	Major contusion without ductal injury or tissue loss Major Laceration without ductal injury or tissue loss
III	Complete Gallbladder avulsion from the liver bed Cystic duct laceration	Laceration: Disruption of 50–75% of D2 Disruption of 50–100% of D1, D3, D4	Distal (SMV) transection or parenchymal injury with ductal involvement
IV	Partial or complete right or left hepatic duct laceration (<50%) Partial Common Duct Laceration (<50%)	Laceration: Disruption of >75% of D2 Involving ampulla or distal common bile duct	Proximal (left of SMV) transection or parenchymal injury involving ampulla
V	>50% transection of common hepatic duct >50% transection of common bile duct Combined right and left hepatic duct injuries Intraduodenal or intrapancreatic bile duct injuries	Laceration: Massive disruption of pancreaticoduodenal complex Vascular: devascularization of duodenum	Massive disruption of pancreatic head

of gallbladder perforation on CT include an anomalous contour of the gallbladder wall, collapsed lumen, or presence of pericholecystic fluid [13]. MRCP or ERCP are usually needed to more definitively assess bile duct and ampullary injury [10].

Once a biliary injury is identified, either percutaneous, surgical or endoscopic management is indicated [10]. Therapeutic options range from minimally invasive approaches, which include ERCP and percutaneous drain placement, to operative interventions with biliary tree reconstruction. Initial percutaneous drain placement of the biloma in biliary injury may decrease the risk of infection and usually alleviate symptoms caused by mass effect and chemical peritonitis from the bile [7, 12]. In addition, effective drainage converts leaks to controlled fistulas, and small injuries may spontaneously close without further intervention [12].

Following drainage, ERCP and MRCP can provide excellent visualization of the biliary tree and localization of injury. The successful utilization of endoscopically placed stents and sphincterotomy for iatrogenic biliary injury following cholecystectomy are very well established and also applicable for traumatic injury [7]. The time between stent placement and removal typically ranges from 3 to 8 weeks [7, 11].

If ERCP is unsuccessful or not feasible, percutaneous transhepatic cholangiography (PTC) is another option for injury localization and treatment [10]. Patients treated by ERCP or PTC will often require multiple procedures [7, 12]. With either approach, stent placement can be fraught with complications due to clogging and migration, occasionally requiring multiple interventions for retrieval and replacement prior to healing of the injury. Although success rates with percutaneous and endoscopic treatments are high, long-term follow-up is essential. The injured biliary tree may cause delayed strictures, resulting in chronic obstruction. When this occurs, minimally invasive approaches for dilation can be attempted, but operative reconstruction is often necessary [12].

When required, surgical options in the acute setting include primary repair of biliary laceration with or without T-tube and patch closure using gallbladder or the cystic duct. In the acute or delayed setting, Roux-en-Y choledochojejunostomy, choledochoduodenostomy, cholecystojejunostomy, and Roux-en-Y hepatoportoenterostomy are all options available based on the site of the injury and anatomy of the patient [6, 12]. Complications of biliary tree repair and reconstruction include biliary leak with resulting bile peritonitis, biloma, or biliary stricture [6, 12, 14].

As with biliary tree injuries, the diagnosis of injury to the gallbladder is often delayed due to the need to accumulate a biloma for symptoms to develop [7, 13]. It is thought that patients with healthy gallbladders, such as children, are more vulnerable to injury as those with diseased gallbladders have thicker walls due to chronic inflammation or fibrosis. Additionally, fasting patients are believed to be more susceptible to injury as the gallbladder wall is typically more distended after several hours without food [13].

The incidence of isolated traumatic gallbladder injury is also low, being reported with an incidence of 2% of all abdominal trauma, as the gallbladder is protected by the ribs and cushioned by the liver [9, 13, 15]. Although there is an established classification scheme for gallbladder injuries to include contusion, laceration/perforation, and avulsion, cholecystectomy is the accepted method of management for all injuries causing symptoms when possible [13, 15].

Duodenum

The duodenum is a retroperitoneal organ that is relatively protected. Injury from blunt trauma requires a significant degree of force directed to the upper abdomen. Most serious injury results from compressive force pinning the duodenum against the vertebrae [7, 16–18]. While penetrating mechanism is the most common etiology for adult duodenal injuries, blunt mechanism is most common in children [18]. Duodenal trauma presents in less than 5% of all pediatric intraabdominal injuries [4, 16, 18–20]. It is most commonly associated with high impact mechanisms such as MVC, bicycle accidents, sports-related accidents, being crushed by an object, and all-terrain vehicle collisions [16, 21, 22]. In children under age 2 years, up to half of the duodenal injuries can be ascribed to physical abuse [21, 22]. Additionally, children suffering duodenal injury from abuse are more likely to have severe injuries such as complete transection [22].

Clinical signs of traumatic duodenal injuries are nonspecific. Patients typically present with epigastric, right upper quadrant, or back pain several hours after injury

[10, 18]. Initial imaging on presentation may establish the diagnosis; however,it is not always reliable. As with all hollow viscous injuries, a high level of clinical suspicion must be maintained when symptoms persist. Extraluminal air on CT abdomen and pelvis may not be visible immediately after the trauma, and hematomas may require time to develop; thus, repeat imaging may be needed [10, 18].

When imaging reveals evidence of duodenal injury, management is dictated by the clinical setting and findings. All penetrating duodenal injury requires operative management. Alternatively, stable patients with isolated peri-duodenal fluid or intramural hematomas seen on admission CT scan or intraoperatively do not require immediate exploration, and non-operative treatment has a high success rate in children [23].

Grade 1 and Grade 2 duodenal hematomas (Fig. 21.2) are routinely treated with bowel rest, gastric decompression (if needed due to obstruction) and supportive care. This approach should be considered even if this is an intraoperative finding during exploration for other injuries. Numerous retrospective studies report that nonoperative treatment for duodenal hematomas has a very high success rate in children, but there is an average length of stay of 7–14 days and often requires parenteral nutrition [18, 19]. The most recent single institutional published experience was of 19 children and revealed that all responded to non-operative management, aside from one child who underwent percutaneous drainage. Of these 19, 5 were discovered intraoperatively and left alone. Mean duration of TPN was 6 days for Grade 1 injuries and 12 days for Grade 2 [23].

Surgical repair is indicated for full-thickness lacerations of the duodenal wall. While various surgical techniques are described, primary repair has a high success rate in children with good outcomes, even in Grade 3 or 4 injuries [19, 24, 25]. Clendenon et al. demonstrated that Grade 3 and 4 injuries repaired primarily had similar, if not better, outcomes than children treated with resection and reconstruction [18]. This is consistent with recent AAST guidelines recommending primary repair in all injuries where this is feasible, regardless of grade [10]. Duodenal resection and reconstruction with or without a pyloric exclusion should be considered

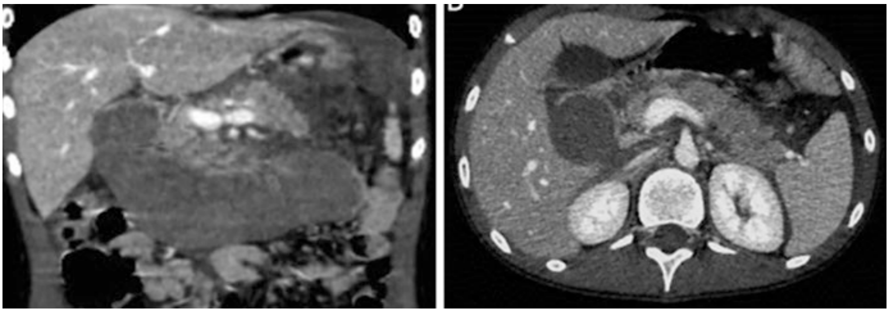

Fig. 21.2 Grade II duodenal hematoma causing obstruction. (Reproduced with permission from: Carmela Brillantino C, Restivo G, Rossi E, Baldari D, Minelli R, et al. Duodenal hematoma in pediatric age: a rare case report. Journal of Ultrasound, Nov 2020. https://doi.org/10.1007/s40477-020-00545-9)

when a primary repair is not possible [17, 18, 20, 26]. Postoperative complications include postoperative ileus, wound infection, traumatic pancreatitis, intra-abdominal abscess, fistula, and enterocutaneous fistula [18, 19].

In severe injuries where the entire pancreaticoduodenal complex is severely injured, a complex resection and reconstruction of the foregut, such as a pancreaticoduodenectomy, may be needed. Damage control techniques such as wide drainage and diversion should be employed acutely, followed by staged reconstruction [10]. This allows for a complex surgery to be done under more controlled circumstances in a well-resuscitated child. A recent report of 13 children with combined pancreaticoduodenal injuries revealed an operative intervention rate of 75% and a survival rate of 85%. Three patients required staged pancreaticoduodenectomy and two survived [27].

Pancreas

Like the duodenum, the pancreas is relatively protected from injury given its retroperitoneal location adjacent to the spine. Similar to the duodenum, traumatic pancreatic injuries in children are usually the result of blunt force due to a focal compression in the epigastrium over the spine [19, 28], and accounts for the association of blunt pancreatic injuries with lumbar spine fractures. They represent 0.3% of all pediatric traumas presenting to National Trauma Database centers and 0.6% of significant abdominal trauma [29, 30]. Recent reviews reveal that pancreatic injuries are associated with an overall 25% operative intervention rate, a 5% mortality and a 25% morbidity [30, 31].

As with biliary and duodenal trauma, a pancreatic injury may be difficult to diagnose in the immediate post-traumatic period. Clinical signs often become more apparent 12–24 h post-injury [10]. Often, these injuries are not isolated [32]. Key laboratory markers that may suggest a pancreatic injury are the elevation of serum amylase and lipase. These findings are not specific, and in children, suspicion for the diagnosis must remain high as the total rise in value is usually lower than is seen in adults and may be delayed [33, 34].

The initial imaging modality of choice to detect pancreatic injury is contrast-enhanced CT. This has a specificity of 90–95% but a sensitivity of 52–93% [3]. In general, CT is useful to detect evidence of parenchymal injury; however, ductal injury detection is significantly less accurate. MRCP and ERCP are significantly more useful for evaluation of a ductal injury [19, 31, 33–35]. Therefore, delayed or alternate imaging should be considered if the clinical condition of the patient does not improve, or in the case of severe parenchymal injury when ductal disruption seems likely.

Treatment guidelines for Grade 1 and Grade 2 pancreatic injuries (not involving the duct) are similar for children and adults [19, 29, 33, 36]. These patients should be managed non-operatively in the acute setting. Follow-up after discharge is essential as pseudocyst formation can be seen in any pancreatic injury regardless of grade, and delayed intervention for drainage may be necessary [29, 31, 37]. Controversy surrounds the optimal management of acute Grade 3–5 pancreatic injuries, where the duct is always involved [19, 29–31, 33]. Historically, distal pancreatectomy has been the treatment of choice for Grade 3 injuries (ductal disruption to the left of the mesenteric artery). This continues to be the recommendation for adult patients [10]. Recently, nonoperative treatment has emerged as an alternate safe and effective treatment option in children [38]. However, there is continued debate as to which treatment strategy is optimal. In 2006, Mattix et al. reviewed outcomes after nonoperative or operative management of traumatic pancreatic injuries from 7 Level 1 pediatric trauma centers. Although not statistically significant, patients with injury Grades 3 through 5 were more likely to fail nonoperative management and require surgery. Definition of failure was at the discretion of the surgeon. They also found that nonoperatively managed children had longer lengths of stay and higher incidences of pseudocyst, drainage procedures, and pancreatitis [31]. In 2013, The Pancreatic Trauma in Children Study Group (PATCH) reviewed 167 patients with Grade 2 and 3 traumatic pancreatic injuries from 14 pediatric trauma centers in the United States. Of these, 95 were treated nonoperatively, and 72 were treated surgically. Of the 72, 57 underwent distal pancreatectomy, and 15 were surgically drained. There was no difference in overall morbidity rates between nonoperatively and operatively managed patients. On average, children treated surgically were found to start enteral feeds sooner, meet goal feeds sooner, and have shorter hospitalizations with shorter times to complete resolution [36]. However, the nonoperative vs. operative treatment strategy in this study was also dictated by the discretion of the individual surgeon.

The largest study of pediatric pancreatic injuries with ductal injury was a review of the National Trauma Database from 2002 to 2011. This included 467 children. Children treated non-operatively had a shorter length of stay compared to children treated with immediate or delayed surgery. A review of the data revealed that operative management was more likely to occur in older children and delayed operative management more likely in patients with a concomitant head injury. Overall complication rates and mortality were similar between groups [39]. A recent meta-analysis of 1014 patients revealed that non-operative management was associated with a higher likelihood of pseudocyst formation, which is expected, but otherwise similar outcomes. Given the only available studies were uncontrolled and most were retrospective, the conclusion was that the quality of the data was not adequate to recommend for or against surgical treatment [40].

Treatment of high-grade (IV and V) pancreatic trauma is difficult given the complexity of these injuries and should be individualized, but non-operative management has been successful in multiple studies [30, 40]. When this fails, or with unstable patients, damage control surgery followed by delayed resection and/or reconstruction with internal entero-pancreatic drainage is recommended [27].

In adult trauma patients, nonoperative management of pancreatic injury involving the duct is often facilitated by ERCP is as the injury can be identified and possibly treated with stent placement and/or internal drainage with sphincterotomy [29]. However, in children, utilization of this modality as a therapeutic intervention is not as well established. This is likely complicated by the limited availability of endoscopic interventionists that are comfortable with pediatric patients and equipment limitations in small children. A recent, multi-institutional retrospective study of 14 pediatric trauma centers and 26 patients demonstrated utility for ERCP in the diagnosis of ductal injury and the management of late complications, but no benefit was seen with early endoscopic intervention with stent placement or sphincterotomy [41].

Complications of pancreatic injury include the formation of pancreatic leaks, fistulae, strictures, and pseudocysts [32, 34–36, 42]. A concern unique to pediatric patients is the long-term effects of pancreatic resection or atrophy on endocrine and exocrine function. While insulin-dependent diabetes has been reported following non-operative treatment of pancreatic trauma [43], there are many single institutional studies demonstrating long-term follow-up after distal pancreatectomy with patients free of insulin dependence [44]. However, a growing body of evidence from the surgical oncology literature reveals that while insulin dependence is uncommon following distal pancreatectomy, glucose intolerance and exocrine dysfunction are frequently seen [45]. While organ preservation certainly should be considered and prioritized in young patients, it should be remembered that pancreatic atrophy is relatively common following non-operative management of pancreatic injuries. In up to 40% of patients, atrophy of the gland distal to the site of ductal injury occurs [46]. This has led some to suggest internal enteric drainage as an alternative to resection or non-operative management for pancreatic ductal injuries [47].

Due to the known risks of pseudocyst formation, glandular atrophy, and ductal dilation following non-operative management (Fig. 21.3), both clinical and ultrasonographic follow-up should be done for many months following injury. In patients treated with distal pancreatectomy, preservation of the spleen should be prioritized, and it is often straightforward. In many cases, the procedure can often be done laparoscopically [48]. If distal pancreatectomy would likely result in concomitant splenectomy, then this may be a reason to strongly consider non-operative management in a child.

Fig. 21.3 CT appearance of Grade 3 pancreatic injury in 3-year-old child. (**a**) one day after injury. (**b**) 3 months after injury. (**c**) Ductal injury appearance on ultrasound 6 months later

Conclusions

Available literature and clinical guidelines regarding pediatric biliary, pancreatic, and duodenal injury management are limited by their rarity. However, nonoperative management is the preferred option for most duodenal hematomas and pancreatic injures without ductal involvement. Primary repair should be done whenever possible in full-thickness duodenal lacerations. Significant controversy surrounds the optimal acute management of blunt pancreatic injuries involving the duct. However, both operative treatment with spleen-preserving distal pancreatectomy and nonoperative treatment are acceptable options, and treatment should be individualized. Gallbladder trauma should be managed with cholecystectomy. In complex injuries involving the proximal pancreas, extrahepatic biliary tree and pancreaticoduodenal complex, damage control techniques should be done in the acute setting, with delayed resection and reconstruction once the patient has stabilized.

Take Home Points
Biliary Trauma:

- Usually seen in the setting of severe hepatic injury, rare in isolation.
- Whenever possible, endoscopic or percutaneous drainage should be considered.
- Surgical treatment if less invasive maneuvers fail and typically involves delayed hepatic resection, or biliary enteric drainage and reconstruction.
- Gallbladder injuries typically manifest as a contracted gallbladder with significant ascites on imaging. Treatment is cholecystectomy.**Duodenal Trauma:**

- Rare in isolation, typically diagnosed by CT.
- Delayed clinical and radiographic presentations are common.
- Physical abuse should be considered as an etiology in toddlers and infants.
- Nonoperative treatment is highly successful for duodenal hematomas, even in the event of an obstruction.
- Full-thickness lacerations of the duodenum should be repaired primarily if possible, regardless of grade.
- Complex lacerations requiring resection and foregut reconstruction are rarely required, and in unstable patients should be managed with damage control surgery followed by a staged reconstruction.
- Complex pancreaticoduodenal injuries requiring pancreaticoduodenectomy should be managed acutely with damage control techniques, followed by staged resection and repair.**Pancreatic Trauma:**

- As with duodenal trauma, this is rare in isolation, and clinical symptoms may be delayed.
- CT with contrast is sensitive for parenchymal injury, but ductal involvement can be difficult to detect.
- ERCP and MRCP have excellent sensitivity and specificity for ductal involvement.
- Early endoscopic intervention with stenting and sphincterotomy for ductal injury in children is of questionable benefit.
- Nonoperative treatment for pancreatic ductal injury is typically successful but may result in pseudocyst formation requiring delayed intervention.
- There is considerable controversy as to whether surgical management or nonoperative management is superior for Grade 3 injuries in children. Both are reasonable options, and treatment should be individualized.

- Grade IV and V injuries have been managed non-operatively with success. If surgery is required, resection and entero-pancreatic drainage should be done.
- Complex pancreaticoduodenal injuries requiring pancreaticoduodenectomy should be managed by initial damage control techniques, followed by staged resection and repair.
- Follow-up is essential after both non-operative and operative treatment for any grade of pancreatic injury as pseudocysts and pancreatic fistula are common complications.

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Chapter 22
Splenic Trauma

Kristine Griffin and Robert Gates

Abstract This chapter overviews the initial trauma bay workup for splenic trauma in children. It details the nuances of nonoperative management, as well as operative intervention and angioembolization. Complications of splenic trauma such as pseudoaneurysm and overwhelming postsplenectomy infection (OPSI) in asplenic children are also discussed.

Keywords Spleen · Pediatric · Trauma · Solid organ injury · OPSI

Key Concepts and Learning Objectives
- Describe initial evaluation and workup in trauma bay for pediatric patients with suspected splenic injury.
- Understand the utility of radiologic studies such as ultrasound and computed tomography (CT) scan.
- Detail nuances of nonoperative management such as length of stay, level of care, blood transfusion, activity restrictions.
- Describe the basic principles of splenectomy and splenorrhaphy.
- Understand the utility of angioembolization for splenic injury in pediatric patients.
- Outline vaccination plans and antibiotic prophylaxis for asplenic pediatric patients.

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Introduction

Splenic injury is not uncommon in abdominal trauma, making up about one-third of all blunt abdominal injuries in children. Prior to the 1960s, splenectomy was the mainstay of management in children with splenic injuries [1]. Nonoperative management (NOM) of splenic injuries was proven to be safe and successful in children, which eventually led to a change in the dogma of treatment in adult patients as well [2]. This allows for preservation of the immunologic function of the spleen, while avoiding general anesthesia, the morbidity of a trauma laparotomy, and postoperative complications such as OPSI and incisional hernia. Ultimately, the surgeon should make the decision to pursue operative or nonoperative management based on clinical signs.

Initial Management of Trauma Patient with this Injury

Injured children should first be evaluated per ATLS protocol. The physical exam findings for splenic injury are non-specific, so any sign of abdominal trauma should prompt a suspicion for splenic injury. Pediatric patients may present without tachycardia or hypotension initially due to their robust physiologic reserve. Older patients may be able to localize their pain to the left upper quadrant. Left shoulder pain in the setting of abdominal trauma may be Kehr's sign, referred pain due to irritation of the left phrenic nerve. Splenic injury is associated with high-impact injuries such as concomitant rib or pelvic fractures, injury to other solid organs, and intestinal injuries. A high degree of suspicion for multiple injuries should be present and any concern should lead to further investigation.

Radiographic/Ancillary Studies

Focused assessment with sonography in trauma, or FAST, is an adjunct commonly used in the assessment of an intraabdominal injury. Recent studies in children cite a sensitivity for FAST of 68–96% and a specificity of 68.9–99% when compared to CT [3–5]. In adults, FAST is typically reserved for hemodynamically unstable patients with blunt trauma to the abdomen. Pediatric patients may undergo a FAST exam, even if hemodynamically stable, to aid the clinician's decision as to whether or not to obtain a CT scan.

Abdominal CT scans are the most useful diagnostic test for hemodynamically stable patients for which clinicians have a high suspicion of intraabdominal injury. CT scans detect the presence of and extent of splenic injury. The American Association for the Surgery of Trauma (AAST) grading system for splenic injury denotes the severity of injury, which can guide treatment (Table 22.1).

Table 22.1 AAST grades of splenic injury

Grade	Radiologic features (CT findings)	Operative criteria	Pathologic criteria
I	• Subcapsular hematoma <10% surface area • Parenchymal laceration <1 cm depth • Capsular tear	• Subcapsular hematoma <10% surface area • Parenchymal laceration <1 cm depth • Capsular tear	• Subcapsular hematoma <10% surface area • Parenchymal laceration <1 cm depth • Capsular tear
II	• Subcapsular hematoma 10–50% of surface area • Intraparenchymal hematoma <5 cm • Parynchemal laceration 1–3 cm depth	• Subcapsular hematoma 10–50% surface area • Intraparenchymal hematoma <5 cm • Parenchymal laceration 1–3 cm	• Subcapsular hematoma 10–50% surface area • Intraparenchymal hematoma <5 cm • Parenchymal laceration 1–3 cm
III	• Subcapsular hematoma >50% of surface area • Ruptured subcapsular or intraparenchymal hematoma ≥5 cm • Parenchymal laceration >3 cm depth	• Subcapsular hematoma >50% surface area or expanding • Ruptured subcapsular or intraparenchymal hematoma ≥5 cm • Parenchymal laceration >3 cm depth	• Subcapsular hematoma >50% surface area • Ruptured subcapsular or intraparenchymal hematoma ≥5 cm • Parenchymal laceration >3 cm depth
IV	• Splenic vascular injury or active bleeding within splenic capsule • Parenchymal laceration involving segmental or hilar vessels causing >25% devascularization	• Parenchymal laceration involving segmental or hilar vessels producing >25% devascularization	• Parenchymal laceration involving segmental or hilar vessels producing >25% devascularization
V	• Shattered spleen • Splenic vascular injury with active bleeding beyond splenic capsule and into the peritoneum	• Shattered spleen • Hilar vascular injury with devascularization of the spleen	• Shattered spleen • Hilar vascular injury with devascularization of the spleen

Nonoperative management

Length of Stay

Early protocols for nonoperative management of blunt solid organ injury included ICU stays, up to a week of bed rest, and up to 2-week observation periods prior to discharge. Prior to 2000, there was no consensus in the pediatric surgery community regarding the criteria to discharge these patients. In 2000, the American Pediatric Surgical Association (APSA) trauma committee published guidelines for the management of pediatric solid organ injury. They proposed the hospital length of stay (LOS) should be equal to at least the grade of injury seen on CT plus 1 day [6]. These recommendations were based on a review of 832 patients over 2 years among 32 pediatric surgical centers. The study analyzed ICU stay, LOS, transfusion requirement, need for operative intervention, need for repeat imaging, and restriction of physical activity. They observed an increase in resource utilization with an increasing grade of solid organ injury.

Many surgeons felt that the grade plus one day rule was too conservative and aimed to discharge patients sooner. In 2008, St Peter et al. published a retrospective review of blunt liver and spleen injury among patients over a 10-year period. They proposed an abbreviated protocol of overnight bed rest for grade 1 and 2 injuries, and 2 nights for grade 3 and higher [7]. In 2013, they validated their protocol with a prospective study of 249 patients. They found that the need for bed rest was the limiting factor for length of stay for 62% of patients. Their mean days of bed rest was 1.6 ± 0.6 compared to a predicted mean of 3.6 ± 1.0 days per the 2000 APSA guidelines [8]. In contrast to grade-based algorithms, two hemodynamically-driven protocols where discharge was based upon hemodynamic stability rather than grade demonstrated decreased LOS, decreased ICU stay, fewer blood draws, and lower hospital costs [9, 10].

In 2015, the Arizona-Texas-Oklahoma-Memphis-Arkansas Consortium (ATOMAC) released guidelines (Fig. 22.1) regarding treatment of children with blunt liver or spleen injuries. They recommended an abbreviated bed rest protocol

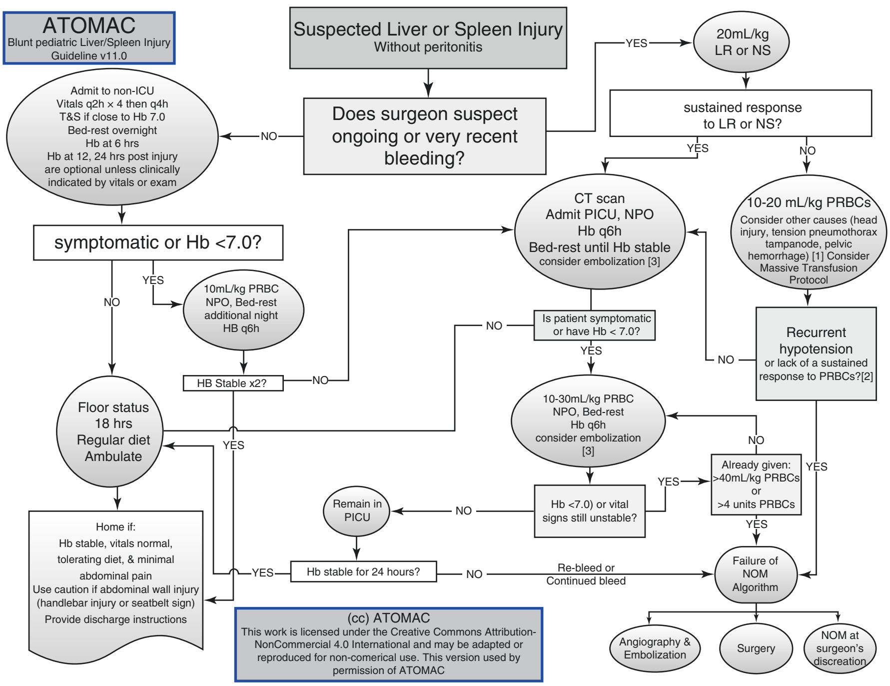

Fig. 22.1 The Arizona-Texas-Oklahoma-Memphis-Arkansas Consortium (ATOMAC) Guidelines. (Source (used with permission): Nonoperative management of blunt liver and spleen injury in children: Evaluation of the ATOMAC guideline using GRADE. Journal of Trauma and Acute Care Surgery79(4):683–693, October 2015 [11])

Table 22.2 2019 APSA Solid Organ Injury (SOI) guidelines

Question	Conclusion
What is the recommended LOS and level of care based upon grade of injury?	LOS for children with isolated solid organ injury should be based upon clinical presentation; there is insufficient evidence to support the use of injury grade alone to determine LOS
Following blunt SOI, what activity restrictions are recommended?	Restricting activity to grade of injury plus 2 weeks is safe
What is the role of interventional radiology in the acute treatment of SOI?	Arterial embolization is a useful tool in the non-operative management of solid organ injuries in patients with an arterial blush on imaging AND hemodynamic instability. Prophylactic embolization in hemodynamically stable patients, even with contrast extravasation, is NOT indicated
What, if any, follow-up studies are necessary for SOI?	Routine follow-up imaging for asymptomatic, uncomplicated, low-grade injuries in children with solid organ injuries is not indicated. The risk of complications in high-grade injuries is low but may require interventions. Imaging should be reserved for symptomatic patients at follow-up

of 1 day or less for stable patients. For patients with isolated solid organ injury with no signs of bleeding and stable hemoglobin, they suggested discharge before 24 h could be reasonable [11]. In 2019, based upon a systematic review by the Outcomes and Evidence Based Practice Committee, APSA updated the guidelines for blunt spleen and liver injuries, suggesting that LOS be based upon clinical status rather than the radiographic grade of the injury (Table 22.2). Discharge criteria should be based on hemodynamic stability, ability to tolerate a diet, having minimal abdominal pain, and the overall clinical condition of the child [12].

Transfusion Requirement

The need for blood transfusion has traditionally been part of the clinical decision-making for nonoperative management. In order to avoid risks associated with blood transfusions, several studies have been published comparing rates of blood transfusion in patients treated nonoperatively versus those who underwent laparotomy [13–16]. The conclusions from these studies suggest that fewer laparotomies may correlate with fewer transfusions. It has been observed that hemodynamically stable patients are no longer actively bleeding. Thus, the clinician may accept lower hemoglobin and hematocrit in order to avoid blood transfusion; therefore, surgeons should transfuse based on clinical indicators of ongoing bleeding. The ATOMAC guidelines cite a transfusion hemoglobin threshold of 7.0 g/dL for stable patients undergoing nonoperative management. They also suggest blood transfusion beyond 40 mL/kg or >4 U PRBC indicates failure of nonoperative management (Fig. 22.1) [11].

Associated Injuries

Historically, proponents of early operative intervention expressed concern regarding missed intraabdominal injuries in the setting of severe splenic injuries. In a review of the National Pediatric Trauma Registry of 2977 patients with solid organ injury, only 3.2% had concomitant hollow viscus injury. Higher rates of hollow viscus injury were noted in patients who had multiple solid organs injured, those with pancreatic injuries, or children who were assaulted [17].

Classically, the presence of an intracranial injury and splenic injury has lowered the threshold for surgeons to operate. However, in a 2000 study of over 100 patients from the National Pediatric Trauma Registry, rates of operative intervention in patients with closed head injuries and concomitant spleen or liver injury were similar to those without head injury [18]. Prophylactic splenectomy in the setting of an intracranial injury should be avoided.

Activity Restriction

Several studies have used follow-up imaging to determine patterns of healing for solid organ injury. A study by Lynch et al. performed weekly ultrasounds for patients with spleen and liver injuries. They discovered that healing occurred within 3 to 21 weeks after trauma, and the grade correlated with healing time [19]. A similar study by Rovin et al. used CT scans to assess healing. They noted no correlation between radiographic evidence of healing and clinical parameters [20]. Based on these findings, the 2019 APSA guidelines recommended restricting athletic activity to the grade of injury plus 2 weeks [12].

Follow-up Imaging Studies

Rarely, delayed complications may arise after nonoperative management of splenic injuries. Delayed rupture may occur at a rate of 0.2–0.3%, based on multi-center studies [21–23]. One study examined ultrasounds at discharge for patients treated nonoperatively with splenic injuries. Of the grade IV injuries, 17% developed pseudoaneurysms. Ten patients overall (5.4%) developed a pseudoaneurysm, 3 of those required an intervention, and only 1 patient was symptomatic [24]. Although pseudoaneurysms may develop in higher grade injuries, it appears this may not be very clinically significant. Per APSA guidelines, follow up imaging may be considered in higher grade injuries, though it should generally be reserved for symptomatic patients [12].

Operative Management

In a patient who is hemodynamically unstable upon presentation and is unresponsive to initial fluid resuscitation, or with persistent signs of bleeding during nonoperative management, exploratory laparotomy with splenectomy is the treatment of choice. In patients with penetrating injuries to the spleen, there must be a lower threshold to operate due to a higher incidence of hollow viscus injury and diaphragmatic injury.

Splenectomy can be performed via midline or transverse laparotomy. The abdomen should be packed in all four quadrants. Any bowel injury may be controlled, even if temporarily with clamps or rudimentary sutures, to avoid ongoing contamination. As packs are removed, the spleen should be mobilized to the midline. The splenophrenic and splenorenal ligaments are mostly avascular, so they may be sharply divided to access the spleen. Next, the spleen and the tail of the pancreas should be mobilized to the midline. Packs can be placed posterior to the spleen in the left upper quadrant to assist with exposure and to tamponade the splenic fossa. The gastrosplenic ligament should then be divided with either clamps and ties or an electrosurgical device to control the short gastric vessels. Care should be taken to avoid injuring the greater curve of the stomach. The splenocolic ligament should then be divided, taking care to avoid injury to the colon. The splenic hilum should then be isolated. The vessels may be divided with clamp and tie technique, an electrosurgical device, or a laparoscopic stapler. Once the spleen is removed, the surgeon should carefully inspect the integrity of the left hemidiaphragm, as well as the tail of the pancreas. If there is a concern for a pancreatic injury, a suction drain may be left near the tail of the pancreas.

Splenic salvage techniques are reserved for less severe injuries. Options include topical hemostatic sprays and patches, argon beam coagulator, and bipolar sealers. The spleen may also be packed and the abdomen left open, with plans to return to the operating room for a second look laparotomy. Splenorrhapy is uncommonly performed, and most surgeons are not familiar or comfortable with this option. Attempts may be made at suturing the spleen with or without an omental flap or by wrapping the spleen in Vicryl mesh. Partial splenectomy may be performed as well. The raw surface may be controlled with chromic sutures in vertical mattress fashion, with a buttress such as hemostatic dressings, absorbable mesh, or Teflon strips [25].

Angioembolization

Angioembolization has become much more prevalent in adult trauma centers over the last several decades. Adult patients with contrast extravasation, or blush, on CT scan often undergo splenic angioembolization (SAE) if hemodynamically stable, in the absence of a concomitant injury requiring laparotomy. The APSA outcomes committee addressed the utilization of angioemoblization in their updated 2019 review. Relevant studies either compared splenectomy to splenic artery embolization (SAE) or examined patients with contrast extravasation on CT scan. In a study from the National Trauma Data Bank for severe splenic injuries in children under 16 years of age, there was no difference in morbidity or mortality for patients undergoing SAE versus splenectomy [26]. In a study of 270 pediatric patients with blunt splenic injury, 47 patients (17.5%) had contrast blush on CT and noted no significant difference between patients with or without contrast blush in terms of length of stay (3.1 vs. 3.3 days), need for blood transfusion (12.5% vs. 11.1%), or need for splenectomy [27]. Based on these findings, APSA suggested SAE for patients with an arterial blush on imaging only in the presence of hemodynamic compromise. Prophylactic embolization in hemodynamically stable patients is not indicated, regardless of the presence of arterial blush on CT scan [12].

OPSI/Vaccinations

Overwhelming post-splenectomy infections (OPSIs) are life-threatening sequelae for asplenic children. In contrast to healthy children who underwent splenectomy for trauma, asplenic patients secondary to hemolytic disorders tend to have a higher risk of OPSI [28]. For optimal effect, patients who undergo trauma splenectomy should receive pneumococcal, *H influenza* type B, and meningococcal vaccines 14–21 days postoperatively because of a heightened immune response. Antibiotic prophylaxis should be started in the immediate postoperative period. For children younger than 2 years, oral penicillin V may be given. Amoxicillin should be given to children over 2 years of age, and erythromycin may be given to patients with a penicillin allergy. Antimicrobial prophylaxis should be considered until at least age 5 and for at least 1 year after splenectomy. For patients with immunocompromise, consider lifelong antibiotic prophylaxis [29].

Preservation of splenic immunological function following splenic angioembolization is unclear. A systematic review by Schimmer et al. examined 12 studies of both children and adults who underwent SAE for splenic injury. Various indices such as ultrasound with Doppler, Howell-Jolly bodies, IgM, antibody titers for encapsulated organisms, complement components, splenic volume on CT scan, and nuclear medicine spleen scans were used to try to assess residual splenic function after SAE. None of the studies reported an OPSI after splenic embolization, and all but one study indicated some preservation of splenic function after SAE [30]. A case-control study by Skattum followed 11 pediatric patients for 8 years who underwent SAE for trauma. None of the patients received post-splenectomy vaccinations or antibiotic prophylaxis, and no OPSIs were observed. All patients had preserved splenic size, normal levels of immunoglobulin, Howell-Jolly bodies, and normal

Table 22.3 Instructions for using ATOMAC guidelines

Follow ATLS protocol first
Patients with peritonitis are managed per surgeon discretion. Do not use this algorithm for patients with peritonitis
Guideline was based on pediatric studies with predominantly younger patients, so take caution in patients 16 years or older
May be used for trauma patients with multiple injuries when not contraindicated
Important recent or continued bleeding as defined by the surgeon. Examples include pallor, hypoperfusion, hemodynamic signs of hypovolemia, anemia, inadequate hemoglobin increase to transfusion, and lactic acidosis
"Stable hemoglobin" means a hemoglobin value not dropping >0.5 g/dL in 12 h. Repeat hemoglobin at 24 h is optional
Any laboratory value suspected to be erroneous may be repeated before medical decision making
Times refer to the time of injury
Late presentation: • Stable patients presenting within 48 h after injury are admitted for observation (18 h), but hemoglobin rechecks are optional • Injuries presenting >48 h after injury are managed at surgeon's discretion

Nonoperative management of blunt liver and spleen injury in children: Evaluation of the ATOMAC guideline using GRADE. Journal of Trauma and Acute Care Surgery79 (4):683–693, October 2015 [11]

lymphocyte counts [31]. Thus, splenic function in children undergoing SAE is likely preserved.

Guidelines

Several trauma societies have developed guidelines and management algorithms for pediatric splenic injury. These guidelines are summarized in Tables 22.2, 22.3 and Fig. 22.1.

Conclusions and Take Home Points

Nonoperative management for splenic injury remains the mainstay of treatment in pediatric trauma patients; however, splenectomy and angioemoblization are options reserved for those patients with signs of ongoing bleeding. These patients may be observed in the inpatient setting until they have proven hemodynamic stability. OPSI remains a critical concern for asplenic pediatric patients, and appropriate vaccination protocols must be observed.

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Chapter 23
Gastric Injury

Rachel E. Hanke, Olivia R. Ziegler, and Shawn D. Safford

Abstract The stomach, while composed of thick muscular wall with robust blood supply and protected by left costal margin, is at risk of injury in both penetrating and blunt traumatic mechanisms. Initial evaluation of the patient should follow the ATLS algorithm, with increased concern for potential gastric injury in the presence of penetrating abdominal injury, seat belt sign, free intra-abdominal fluid, pneumoperitoneum or peritonitis. Evaluation should include basic laboratory evaluation, with adjuncts of chest radiograph, abdominal ultrasound and computed tomography when appropriate. Any patients with identified gastric injury should receive antibiotic and antifungal therapy, and undergo surgical evaluation. Laparoscopic evaluation can be considered if hemodynamically stable. Regardless of open or laparoscopic approach, complete evaluation of the entire stomach and other abdominal viscera should be completed. Gastric injuries can often be managed with primary repair, but management should be modified pending mechanism and extent of injury. Post-operative care should closely monitor for potential bleeding and leak.

Keywords Gastric injury · Gastric perforation · Gastric trauma · Hollow viscus injury · Gastrointestinal injury

Key Concepts/Clinical Pearls (Learning Objectives)

- A high index of suspicion is required in both penetrating and blunt mechanisms to avoiding missed gastric injury.
- Gastric injury requires surgical intervention and laparoscopic evaluation can be considered in hemodynamically stable patients.

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- The majority of gastric injuries can be managed with primary repair, but higher-grade injuries may require partial gastrectomy with reconstruction.
- Management of all injuries and timing of reconstruction should be performed in the context of other concomitant intra-abdominal injuries.
- Post-operative management involves perioperative antibiotics and antifungals, gastric decompression and early nutritional support.

Initial Management of the Trauma Patient

Children rarely present with *an isolated* gastric injury, thus the initial evaluation and management should follow that required for all potential injuries resulting from blunt or penetrating mechanisms. Diagnosis of gastric injury requires a high index of suspicion *in all patients.* Initial assessment should follow the Advanced Trauma Life Support (ATLS) algorithm with increased concern for potential gastric injury in the presence of penetrating abdominal injury, seat belt sign, free intra-abdominal fluid, pneumoperitoneum or peritonitis.

Initial Radiographic/Ancillary Studies

As patients with gastric injury are more likely to have associated hollow and solid organ injury—broadly evaluate for all of these possibilities.

1. Blood work:
   - Complete blood count (CBC), basic metabolic panel (BMP), amylase, hepatic function panel, type and screen, coagulation profile.
2. Imaging:
   - Chest and abdominal radiographs: evaluate for pneumoperitoneum or diaphragmatic injury.
   - FAST exam in blunt injury: evaluate for free fluid.
   - *If mechanism, physical exam, or FAST are concerning for abdominal injury and the patient is hemodynamically stable*.
     – Computerize tomography of abdomen/pelvis (and/or chest as appropriate) with IV contrast

The stomach's thick muscular wall and robust blood supply, as well as its location underneath the left costal margin, makes it less susceptible to injury when compared to other hollow organs. The distended stomach, however, is at increased risk of injury regardless of penetrating or blunt mechanism [1].

Traumatic injury to the stomach, as well as other hollow viscus injuries (HVI), is seen more often after a penetrating mechanism. Stab or gunshot wounds result in gastric injury in 5–20% of patients, with patient outcomes dependent on type of weapon and wound trajectory [1, 2]. It is important to have high index of suspicion for concomitant gastric injury in patients with left chest wounds as well, as up to 40% of patients with left-sided diaphragmatic injury have an associated gastric injury [3].

In comparison, the incidence of HVI and gastric injuries after a blunt mechanism are quite low, with reports of 0–1.8%, as solid organ are more likely to be injured [1, 4–6]. Patients will often present after a fall, bicycle accident, physical assault, motor vehicle collision, or as a pedestrian struck. Certain elements of the patient's history and mechanism should raise concern for potential gastric injury, including recent large meal, high energy mechanism, or improper seat belt placement [4–6].

Regardless of mechanism, children rarely present with an *isolated* gastric injury, thus the initial evaluation and management should follow that required for all potential injuries.

Initial Assessment

Evaluate the patient following the ATLS algorithm.

A. Verify or establish airway.
B. Evaluate for injury to the chest and/or compromised breathing.
   (a) Left-sided diaphragm injuries have high rate of gastric injury.
C. Assess hemodynamic stability, obtain IV access and volume resuscitate as appropriate.
   (a) If there is evidence of or concern for extensive blood loss, forego crystalloid and transfuse blood according to ATLS guidelines, including potential for massive transfusion protocol.
   (b) If unstable despite resuscitation, proceed to the operating room.
D. Assess Glasgow-Coma Scale (GCS).
   (a) Depressed GCS will limit ability to monitor serial abdominal exams as a way to monitor for missed injuries.
E. Exposure.
F. Adjuncts:
   (a) Chest and abdominal radiographs: evaluate for pneumoperitoneum or evidence of chest trauma, including evidence of diaphragmatic injury.
      - Note: nasogastric tube tracking toward the left chest may be a sign of a diaphragmatic injury.
   (b) Consider a FAST exam in blunt injury to evaluate for free fluid.
G. Secondary survey.
   (a) Note *all* potential sites of injury, particularly with penetrating mechanism.
   (b) Concerning findings include:
      - Seatbelt sign (associated hollow viscus injury).
      - Bloody nasogastric tube output.
      - Peritonitis.
      - Fever, tachypnea, hypotension, metabolic acidosis, leukocytosis.
         – For patients who present for evaluation in delayed fashion, more often seen with blunt mechanisms.

Laboratory and Radiologic Evaluation

Patients with gastric injury are more likely to have associated hollow and solid organ injury. It is imperative to broadly evaluate for all of these possibilities.

1. Laboratory evaluation:
   (a) Complete blood count (CBC).
   (b) Basic metabolic panel (BMP).
   (c) Amylase.
      - May be normal initially, but subsequent elevation could be seen with small bowel perforation or pancreatic injury.

   (d) Hepatic function panel—to monitor for blunt liver injury.
   (e) Type and screen and coagulation profile.
   (f) Urinalysis to evaluate for genitourinary tract injury.
2. Radiographic studies:
   (a) Chest and abdominal radiographs: as above.
   (b) FAST exam: evaluate for free fluid.
      - Consider if patient has persistent tachycardia, hypotension unresponsive to fluid, or physical exam findings concerning for intra-abdominal injury.
      - Positive FAST in the pediatric population is consistent with intraabdominal injury.
      - Importantly, a negative FAST does not rule out injury [7].

   (c) Computerize tomography of chest/abdomen/pelvis with IV contrast should be considered in certain patients.
      - The Pediatric Emergency Care Applied Research Network (PECARN) developed a clinical prediction tool to guide necessity of CT scan in a hemodynamically stable patient [8].
      - If a patient has the following characteristics, they are at very low risk of injury and likely do *not* require CT imaging [8].
         – No seat belt sign.
         – GCS >14.
         – No abdominal tenderness.
         – No thoracic wall trauma.
         – No abdominal pain.
         – Normal breath sounds.
         – No vomiting.
      - Radiologic findings concerning for gastric injury include: [9]
         – Pneumoperitoneum or extraluminal air near stomach (see Fig. 23.1).
         – Free intra-abdominal fluid without solid organ injury.

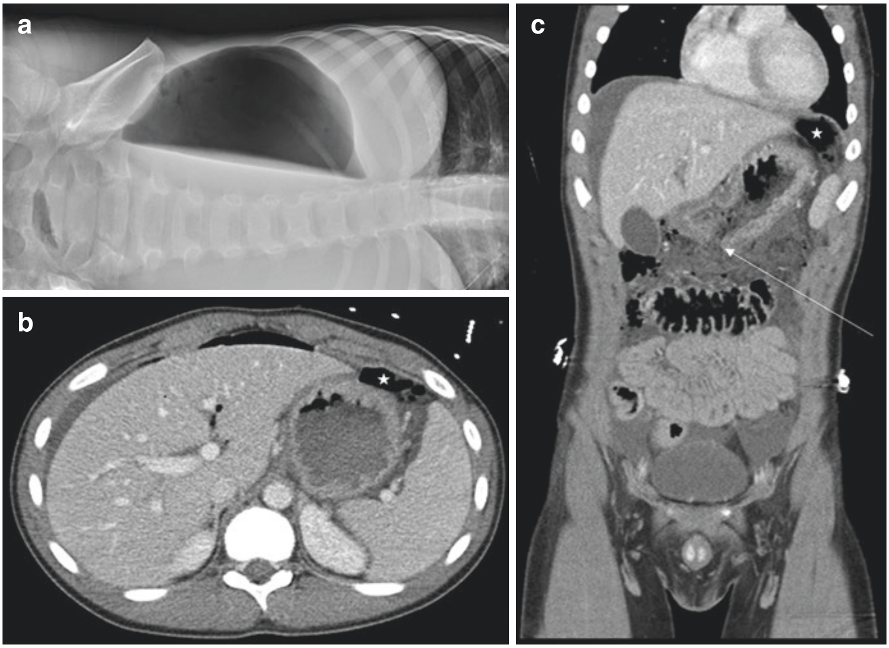

Fig. 23.1 Radiologic findings concerning for gastric perforation. (**a**) pneumoperitoneum demonstrated on lateral decubitus radiograph. (**b**) pneumoperitoneum (*star*) along gastric body on sagittal view of CT scan. (**c**) pneumoperitoneum superior-lateral to gastric body (*star*) with disruption of gastric wall on coronal view of CT scan (*arrow*)

- – Fat-stranding near stomach.
- – Intraluminal hematoma (particularly with penetrating mechanisms).
- – Any penetrating injury of spleen, diaphragm, or left hepatic lobe.

- Patients with radiologic evidence of gastric injury require surgical intervention.
  - – *Remember: CT scan may appear normal even with injury* [9].

Management

Patients may *not* have obvious findings of hollow viscus injury on initial evaluation, have equivocal imaging findings, and remain hemodynamically stable. Management of these patients varies but evidence supports consideration of closely monitoring vital signs and serial abdominal exams. If the patient develops any signs of intra-abdominal leak or peritonitis, the next step is operative evaluation with antibiotic and antifungal coverage [1]. Historically these patients would undergo a laparotomy or peritoneal lavage. In hemodynamically stable patients with concerning physical exam and equivocal imaging, diagnostic laparoscopy is sensitive and also allows for intervention [10]. Further studies demonstrate that laparoscopic therapies can safely be performed with similar or even improved outcomes [11]. There is significant variation in practice, based on surgical specialty (trauma versus pediatric surgeons) and type of injury pattern (isolated blunt, multi-system, presence of traumatic brain injury or penetrating injury) with historically more pediatric surgeons exploring laparoscopically [12, 13].

Patients who have concerns for hollow viscus injury on physical exam or radiologic evaluation require surgical intervention.

Operative Exposure Techniques: [14]

Regardless of open versus laparoscopic approach, the stomach should be fully evaluated, from the gastroesophageal (GE) junction to the pylorus, both anteriorly and posteriorly [1].

1. Visualizing the anterior stomach and GE junction (Fig. 23.2):
    - Divide the left triangular ligament to mobilize the left lobe of the liver (and improve visualization of the GE junction and proximal stomach).
        - Division of the left crus of the diaphragm may also help evaluate the GE junction.
        - Placing a Penrose drain around the GE junction and retracting caudally may help assess proximal stomach.

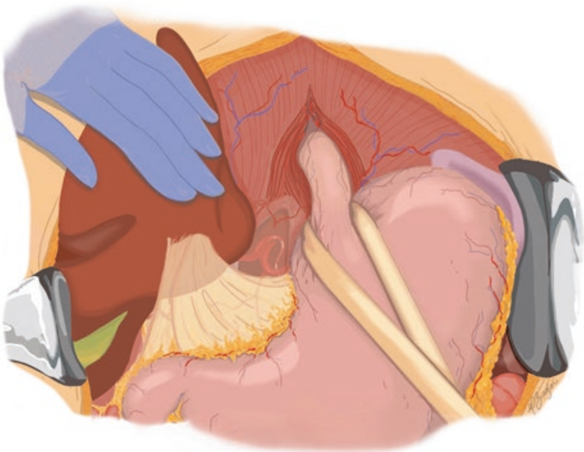

Fig. 23.2 Mobilize the left lobe of the liver and divide the left crus of the diaphragm to better visualize the anterior stomach and GE junction

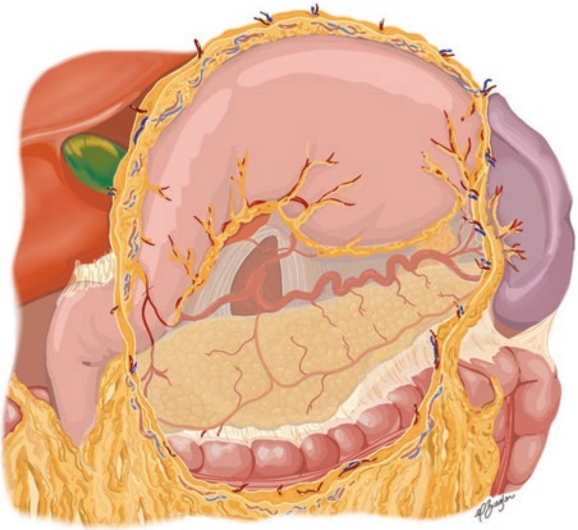

Fig. 23.3 Evaluate the posterior stomach after dividing the avascular gastrocolic ligament, with ligation of the short gastric vessels for additional mobility

2. Visualizing the posterior stomach (Fig. 23.3):

- Retract the stomach cephalad and the transverse colon caudally.
- Enter the lesser sac through the avascular gastrocolic omentum along the body or antrum of the stomach (being sure to leave the gastroepiploic vessels intact) and divide the gastrocolic ligament.
  - *This also allows for thorough assessment of lesser sac, notably the pancreas.
- Take down the avascular gastropancreatic adhesions to fully evaluate the posterior stomach wall.
- Consider ligating the short gastric vessels if needed to adequately mobilize the stomach.

If an injury is found, assess the grade of injury, debride devitalized tissue and treat accordingly (see Table 23.1). Always perform a leak test to evaluate for occult injury and to assess repair. This can be done easily by insufflating the stomach under water and evaluating for bubbles.

Table 23.1 Gastric Injury grading system from the American Association for the Surgery of Trauma (AAST) [15] and recommended surgical management

Grade	Findings	Management
I	Contusion/hematoma *or* partial thickness laceration	(Penetrating) explore *any* hematoma (Blunt) explore *expanding* hematoma Oversew
II	Laceration <2 cm @ GE junction/pylorus <5 cm in proximal 1/3 stomach <10 cm in distal 2/3 stomach	Repair in 1–2 layers *Could consider stapling depending on the extent of the injury but be sure to account for the thickness of the stomach *repair GE junction over bougie or endoscope *if any concern for pyloric narrowing may require pyloroplasty
III	Laceration >2 cm @ GE junction/pylorus >5 cm in proximal 1/3 stomach >10 cm in distal 2/3 stomach	
IV	Tissue loss or devascularization <2/3 stomach	Depends on location of injury and concomitant injuries
V	Tissue loss or devascularization >2/3 stomach	

*For multiple injuries, advance grade x1 up to a grade III

Surgical Management: [1, 14]

1. Hematomas:
   - Blunt mechanism + expanding = explore.
   - Penetrating mechanism = explore.
   - Unroof hematoma, establish hemostasis, imbricate the area.
2. Partial thickness injuries should be oversewn.
3. Grade II and III lacerations:
   - Can be repaired in one to two layers with either absorbable or nonabsorbable suture.
   - Depending on location of injury, consider stapled repair.
     – Be sure to account for the thickness of the stomach in staple selection.
4. Grade IV injuries may require proximal or distal gastrectomy with appropriate reconstruction depending on concomitant injuries.
   - May need gastroduodenostomy, gastrojejunostomy or Roux-en-Y gastrojejunostomy.
5. Grade V injuries may require total gastrectomy with Roux-en-Y esophagojejunostomy.

Intraoperative Pearls

- If dividing the gastrohepatic ligament, be sure to avoid the vagus nerve or possible replaced left hepatic artery.
- Minimize retraction on the greater curvature to avoid tearing the splenic capsule or avulsing the short gastric vessels.
- If both splenic and gastric injury is present, be sure to mobilize the spleen to evaluate both injuries fully.
- For injuries at the GE junction, repair over bougie to avoid stenosis and buttress the repair with omentum or gastric fundus wrap.
- Injury to the greater curvature may require ligation of gastroepiploic vessels for safe repair.
- If there is an injury to the anterior *and* posterior stomach along the greater or lesser curve, connect the injuries and repair as one.
- For grade V injuries requiring reconstruction, consider the stability of the patient after control of contamination *prior* to reconstruction. These patients often require resuscitation and staged reconstruction in 24–48 h.

Post-operative Management and Complications [1, 14]

Post-operative management will vary widely given other potential injuries. If there is an isolated gastric injury, give perioperative antibiotic and antifungal therapy for at least 24 h, consider short term gastric decompression, and initiate nutritional support promptly after resuscitative phase.

The risk for complications is increased with presence of the following factors:

- Gastric resection (as opposed to primary repair).
- Massive transfusion of fluids.
- Pancreatic injury.
- Abdominal compartment syndrome.
- Failure to close abdomen within five days.
- Hypoperfusion or use of pressors in early resuscitation and perioperative period.

It is important to monitor for post-injury and post-operative complications. The most concerning complication of gastric injury comes from unrecognized injury leading to intra-abdominal sepsis. Patient with identified gastric injury who have undergone repair or reconstruction can develop a leak from the repair site. Bleeding may develop from short gastric avulsion or unrecognized splenic capsule tear. These patients are also at risk of developing post-operative intra-abdominal adhesions and associated small bowel obstruction in the immediate and long-term post-operative course.

Conclusions and Take Home Points

Patients will rarely present with isolated gastric injury and a high index of suspicion is required after penetrating and blunt mechanisms. Given the stomach's location in the abdomen, concomitant diaphragmatic and thoracic injuries, especially with penetrating mechanisms are not uncommon. Delayed recognition of gastric injury contributes significantly to morbidity and mortality. The majority of these injuries can be repaired primarily. Management of all injuries and timing of reconstruction should be performed in the context of other concomitant intra-abdominal injuries. Post-operative management involves perioperative antibiotics, gastric decompression and early nutritional support.

- Initial management should include evaluation for all potential traumatic injuries including bloodwork, chest/abdominal radiograph, FAST exam and potentially CT scan when indicated.
- Diagnostic laparoscopy is a viable option to evaluate for and intervene on injury in hemodynamically stable patients, depending on surgeon experience. Thorough examination of the entire stomach is crucial.
- The majority of injuries can be managed with primary repair, but higher-grade injuries may require partial gastrectomy with reconstruction.

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Chapter 24
Small Intestine and Colon

Lexie H. Vaughn and Jeffrey S. Upperman

Abstract Traumatic injury is a major cause of critical illness and death in the pediatric population. Small intestinal and colon injuries after trauma are particularly difficult to diagnose in this population, thus providers must maintain a high index of suspicion for these injuries. Initial workup includes assessment of primary and secondary survey and may incorporate laboratory studies and advanced imaging. Definitive operative intervention is indicated in setting of identified injury on axial imaging or hemodynamic instability with high clinical suspicion. Prompt operative repair, typically with open surgery, is recommended to limit risk of complications.

Keywords Blunt abdominal trauma · Penetrating trauma · Hollow viscus organ injury · Colon injury · Small intestinal injury · FAST exam

Learning Objectives

- Injuries to the small intestine and colon are rather rare in the setting of blunt abdominal trauma. Small intestinal injury, specifically to the jejunum and ileum, is more common than colon injury.
- Intestinal injuries are, at times, difficult to diagnose in children, so every provider must maintain a high index of suspicion.
- Most pediatric patients who are hemodynamically stable after abdominal trauma are managed non-operatively.
- Traumatic hollow viscus injuries have historically been managed with laparotomy, which is both efficient and effective for diagnosis and treatment.

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Table 24.1 American Association for the Surgery of Trauma (AAST) Organ Injury Scale for Small Intestinal injury

Small Intestine:		
Grade	Injury	Management
I	Contusion or hematoma without devascularization OR partial thickness laceration; no perforation	Invert with 3-0 or 4-0 silk seromuscular suture
II	Laceration, < 50% circumference of the bowel	Debridement, primary closure
III	Laceration, > 50% circumference without transection of the bowel	Resection, primary anastomosis
IV	Transection of the bowel	Resection, primary anastomosis
V	Transection with segmental tissue loss OR devascularized segment	Resection, primary anastomosis

Table 24.2 American Association for the Surgery of Trauma (AAST) Organ Injury Scale for Colon injury

Colon			
Grade	Injury	Type	Management
I	Contusion or hematoma without devascularization OR partial thickness laceration; no perforation	Non-destructive	Invert with 3-0 or 4-0 silk seromuscular suture
II	Laceration, <50% circumference of the bowel		Debridement, primary closure OR Resection, primary anastomosis
III	Laceration, >50% circumference without transection of the colon		Debridement, primary closure OR Resection, primary anastomosis
IV	Transection of the colon	Destructive	Resection, primary anastomosis +/− diversion
V	Transection with segmental tissue loss OR devascularized segment		Resection, primary anastomosis +/− diversion

- Operative management of small intestinal injuries is dependent on the injury grade (Tables 24.1 and 24.2).
- Early post-operative complications include wound infection, anastomotic leak, and abdominal septic complications like intraabdominal abscess.

Initial Management of Trauma Patient

The standard workup of a pediatric trauma patient should begin with a primary survey through the evaluation of the airway, breathing, and circulation as per the Advanced Trauma Life Support (ATLS®) protocol. Vascular access should be obtained, neurologic status evaluated, and the patient should be fully exposed to allow for an adequate secondary survey, which will incorporate head-to-toe examination. Physical exam findings of abdominal distension or tenderness, and abdominal or flank ecchymosis, abrasions, lacerations, or penetrating wounds should raise suspicion for an intraabdominal injury [1].

Initial Radiographic/Ancillary Studies

Plain abdominal x-rays in the upright or left lateral decubitus position may identify free air as a marker of bowel injury; however, an upright x-ray is rarely performed in the acute evaluation for trauma. The Focused Assessment with Sonography for Trauma (FAST) is a non-invasive examination that utilizes ultrasound in four specific locations (Fig. 24.1) to detect free intraabdominal or pericardial fluid. Computed tomography (CT) is the gold standard for identification of intraabdominal injuries in hemodynamically stable patients. The presence of free fluid, extraluminal air, contrast extravasation, or bowel wall thickening on CT is suggestive of a bowel injury.

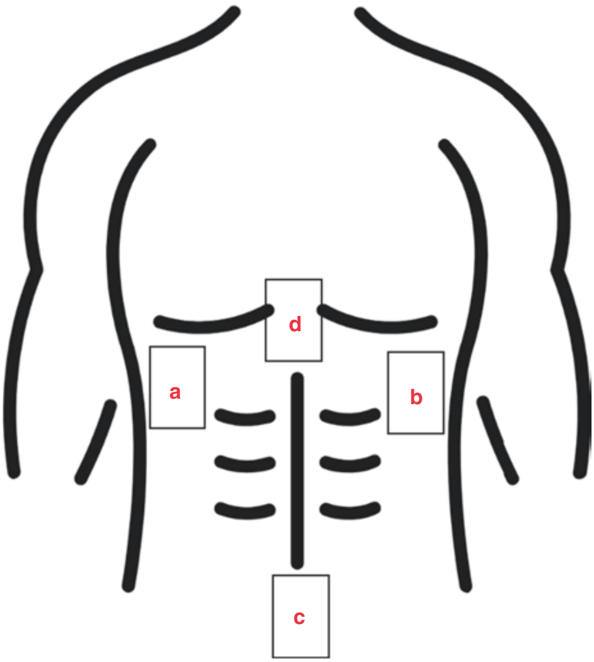

Fig. 24.1 The Focused Assessment with Sonography for Trauma (FAST) is a non-invasive examination that utilizes ultrasound to detect free intraabdominal or pericardial fluid. The operator should examine patients in 4 specific anatomic regions with patient supine and using the 3.5–5.0 MHz convex transducer. These are: (**a**) perihepatic view (right flank or Morrison's pouch), (**b**) perisplenic view (left flank), (**c**) suprapubic view (Pouch of Douglas), and (**d**) pericardial view (subxiphoid or parasternal)

Introduction/Epidemiology

Traumatic injury is the main cause of morbidity and mortality in the pediatric population, age 1–18 years. While penetrating trauma is currently the most common mechanism of injury affecting all trauma patients in the United States, penetrating trauma accounts for less than 10% of admissions to trauma centers in patients <18 years. The majority of serious injuries in children older than 1 year occur secondary to blunt-impact trauma [2–4].

Injuries to the small intestine and colon are rather rare in the setting of blunt abdominal trauma, with a reported incidence of roughly 1%, and occur much less frequently than solid organ injury after blunt trauma. In both blunt and penetrating mechanisms, small intestinal injury, specifically to the jejunum and ileum, is more common than a colon injury [5].

Unintentional trauma is the most common mechanism of trauma and the most common cause of death in patients age 1–18 years. In 2019, the Centers of Disease Control (CDC) reported that motor vehicle crashes account for over 24–54% of deaths within this cohort. Incidence and severity of abdominal injuries secondary to motor vehicle crashes vary depending on age and restraint utilization, with more abdominal injuries observed in patients 8–12 years old and in those improperly or unrestrained [6]. Although less common, non-accidental trauma should always be considered in the workup of pediatric trauma patients.

Mechanism

In blunt trauma, there are four main mechanisms of injury affecting the small intestine and colon. These are: (1) deceleration shear injury occurring at points of fixation (i.e., Ligament of Treitz, ileocecum, splenic flexure, and rectosigmoid junction), (2) free rupture secondary to pseudo-closed loop with increase luminal pressure, (3) compression of the bowel between the abdominal wall and the vertebrae, and (4) mesenteric avulsion leading to delayed perforation (this affects the mesocolon primarily). [7].

Penetrating injuries to the small intestine and colon are caused by direct puncture to the mesentery or enteric lumen by sharp objects or ballistics [8].

A common but unique blunt traumatic mechanism in younger pediatric patients is the bicycle handlebar injury. The identification of handlebar injuries is heavily reliant on the patient's history so the true incidence may be underreported but should be considered in any bicycle-related injury. While the majority of handle bar trauma results in solid organ and soft tissue injury, hollow viscus injuries have a reported incidence of over 9% [9].

Diagnosis

Intestinal injuries are at times difficult to diagnose in children, especially in the setting of blunt trauma; however, diagnostic delay can contribute to significant morbidity, mortality, and complications. Thus, one must have a high index of suspicion.

Physical Exam

The standard workup of a pediatric trauma patient should begin with a primary survey through the evaluation of the airway, breathing, and circulation as per the Advanced Trauma Life Support (ATLS) protocol. Vascular access should be obtained, neurologic status evaluated, and the patient should be fully exposed to allow for an adequate secondary survey. In young children, a smaller torso size, lower amount of intraabdominal fat, and relatively larger viscera increase the likelihood of internal injury when compared to adult trauma patients. The physical examination is paramount for appropriate and efficient identification of intestinal injury in children [8, 10]. In early screening for intestinal injury, laboratory and radiographic evaluations are often equivocal so the provider must rely on exam findings and evolving clinical status to triage management of patients beyond the initial resuscitation [9]. The secondary survey will incorporate head to toe examination, but physical exam findings of abdominal distension or tenderness, and abdominal or flank ecchymosis, abrasions, lacerations, or penetrating wounds should raise suspicion for intraabdominal injury [1].

The use of seatbelts has decreased overall mortality associated with motor vehicle crashes but has increased the incidence of intestinal injuries. More specifically, the presence of a "seatbelt sign" or thoracoabdominal ecchymosis along the distribution of a seat belt or lap belt increases the likelihood of intestinal injuries and should prompt a high index of suspicion with close observation and potentially advanced imaging studies [11, 12].

Most handlebar injuries are accompanied by physical exam findings consistent with the injury pattern. However, diagnosis of this injury relies heavily on the patient's history as physical exam findings may be absent, even when intraabdominal injuries requiring operative intervention are present [13].

Serum Laboratory Considerations

Serum laboratory tests are utilized in hemodynamically stable patients to screen for suspected intraabdominal injury. Abnormalities in hematocrit, metabolic panel, liver function tests, pancreatic enzymes, and urinalysis have been used in a routine fashion to screen patients, but these tests lack sensitivity and specificity in the setting of blunt abdominal trauma. Several investigators have demonstrated that the prevalence of laboratory abnormalities is low in moderately injured patients and patients with a normal physical exam of the abdomen typically have normal laboratory tests [14]. Microscopic hematuria, elevated hepatic transaminases, and leukocytosis have been associated with intraabdominal injury after blunt trauma when present with abnormal abdominal physical exam findings, but not in isolation [15, 16].

Imaging

Plain abdominal x-rays in the upright or left lateral decubitus position may identify free air as a marker of bowel injury; however, upright x-ray is rarely performed in the acute evaluation for trauma as concomitant injury or possible spine instability may preclude this positioning.

The Focused Assessment with Sonography for Trauma (FAST) is a non-invasive examination that utilizes ultrasound in four specific locations (Fig. 24.1) to detect free intraabdominal or pericardial fluid. With FAST examinations, there is no radiation exposure to the patient, and the exam can be performed quickly and efficiently even in the setting of hemodynamic instability. However, FAST does not identify specific anatomic abnormalities, and there is a risk of missed injury with FAST [13, 17]. A 2008 survey of almost 100 trauma centers demonstrated that only 15% of dedicated children's hospitals routinely use FAST exams versus 96% of dedicated adult hospitals. FAST exam is more commonly used at higher-volume centers [4].

The reported sensitivity, specificity, and accuracy for FAST for injured adult patients in the setting of blunt abdominal trauma is 80–88%, 98–100%, and 97–99%, respectively. Conversely, these metrics for the pediatric patient population are not as reassuring, with many studies noting a sensitivity as low as 20%. Further, up to 37% of intraabdominal injuries (hollow viscus and solid organ) in patients <18 years do not present with free fluid even on CT scan, which may severely limit the utility of FAST in the workup and triage of pediatric trauma patients [4, 18].

The Current ATLS recommendations for the use of FAST in pediatric trauma remain vague. Generally, in a hemodynamically unstable injured patient, FAST can be used to quickly determine the need for emergent operative intervention and appropriately triage the post-emergency department disposition (Fig. 24.1).

As provider-documented clinical suspicion for intraabdominal injury increases, so too does the use of FAST exam. Additionally, patients with low clinical suspicion for intraabdominal injury and a negative FAST are less likely to undergo CT scan. If the initial FAST exam is negative and the patient experiences any subsequent change in hemodynamics, a CT scan may ultimately be required. If the FAST is negative and no CT is obtained, current recommendations include 6 h of observation with a repeat FAST exam prior to discharge from the Emergency Department. There is limited data to support or reject the role of serial FAST exams in this patient group. With limited sensitivity and poor generalized adoption, the FAST is not uniformly used in this cohort, and CT remains the gold standard [4].

Computed tomography (CT) is commonly used for identification of intraabdominal injuries in hemodynamically stable patients with both high sensitivity (60–88%) and specificity (97–99%) [17, 19]. The presence of free fluid, extraluminal air, contrast extravasation, or bowel wall thickening on CT is suggestive of bowel injury. Further, free fluid without identifiable solid organ injury is indicative of possible hollow viscus or mesenteric injury and should prompt further evaluation [9]. Use of CT in pediatric patients must be balanced with the possible adverse effects including radiation and risk of future malignancy [20]. Roughly half of children undergo CT scans after abdominal trauma, but few of this group go on to require procedural or operative intervention. Excessive use of CT may lead to overidentification of incidental findings irrelevant to the traumatic mechanism [21]. Multiple centers have established clinical practice guidelines for abdominal trauma, which have demonstrated decreased CT use with no significant difference in outcomes. Thus, judicious use of CT scan in hemodynamically stable patients is currently advised [22–24].

Grading Scales

The Organ Injury Scale from the American Association for the Surgery of Trauma (AAST) is the most commonly used grading system for small intestinal and colon injuries and dictates management as summarized in Tables 24.1 and 24.2. Notably, grading can be based on autopsy, laparotomy, or radiographic evaluation (specifically by CT), and the grade is advanced by one for multiple injuries in the same organ [25].

Management

Most pediatric patients who are hemodynamically stable after abdominal trauma are managed non-operatively. Non-operative management in this setting includes close clinical monitoring with serial abdominal examinations, which may be unreliable in this population. As a result, there is a risk for delayed diagnosis of hollow viscus injury and associated morbidity with non-operative management.

The choice between close observation with serial examinations and operative intervention (either laparoscopy or laparotomy) as the initial management strategy in a hemodynamically stable patient is variable. Factors influencing this choice include the presence of distracting injuries, traumatic brain injury with intubation, and specialty training; pediatric surgeons choose observation more frequently than trauma surgeons [26].

Surgeons monitoring a patient with a concerning or worsening physical exam and equivocal imaging and/or laboratory results should intervene with additional imaging or operative intervention. The goal of the operation, in this case, is both diagnostic and therapeutic, with high suspicion for occult hollow viscus organ injury [27].

Traumatic hollow viscus injuries have historically been managed with laparotomy, which is both efficient and effective for diagnosis and treatment. However, laparoscopy is becoming more common as it may yield similar diagnostic and therapeutic results while avoiding the morbidity associated with a non-therapeutic laparotomy, large incisional wounds, and decrease post-operative pain, length of stay, wound complications, and risk of long-term bowel obstruction [27]. Several retrospective studies have demonstrated the safety and efficacy of therapeutic laparoscopy in hemodynamically stable pediatric patients after abdominal trauma with mortality similar to laparotomy and no reported missed injuries. In busy trauma centers, longer operative times with therapeutic laparoscopy may bias surgeons towards laparotomy. A conversion rate of roughly 40% is reported in multiple studies of blunt abdominal trauma in children (relative to 1–6% for appendectomy), which may represent surgeon preference for diagnostic confirmation or conversion to laparotomy once pathology is identified. Further, laparoscopy is more commonly utilized in dedicated pediatric level I and II trauma centers than adult-only centers, and pediatric surgeons are more likely to choose a laparoscopic approach relative to trauma surgeons [26–31].

Small Intestine

In children over the age of 5 years, a midline laparotomy incision is preferred for adequate exposure. For children younger than 5 years, a transverse supraumbilical incision is also used to access the abdominal cavity. For this approach, the incision is made about one-third of the distance between the umbilicus and xiphisternum, the rectus muscle is divided, and the ligamentum teres is clipped, divided, and tied [32–34]. In the setting of hemodynamic stability and identification of a specific injury on pre-operative imaging, a smaller, more targeted incision may be employed.

Upon entry, the surgeon should control significant hemorrhage with packing. Next, the surgeon should get definitive bleeding control prior to a general four-quadrant exploration. After bleeding control, the surgeon should systematically explore the abdominal cavity. First, she examines the small bowel seeking evidence of gastrointestinal contamination. The surgeon removes or eviscerates the small bowel and starts to examine the bowel at the Ligament of Treitz. It may be necessary to employ right medial visceral rotation (Catell-Braasch) and dissection of the lateral peritoneal attachments of the duodenum (Kocher) to fully evaluate and repair injuries to the proximal jejunum. The bowel should be evaluated in small segments from the Ligament of Treitz to the cecum, with attention paid to the mesentery throughout the exploration. The surgeon should control contamination from the viscera with an atraumatic intestinal clamp or a running absorbable suture closure, but no injuries should be definitely repaired until the entire bowel has been inspected.

Significant mesenteric hemorrhage should be controlled by identification of the injured vessel and suture ligation. Repair of any mesenteric defect should not occur until after complete inspection.

Operative management of small intestinal injuries is dependent on the injury grade (Tables 24.1 and 24.2). Serosal injuries should be repaired with interrupted silk sutures by partial thickness inversion suture pattern (Lembert). Contusions or mural hematomas (Grade I injury) should be repaired with inversion of the injured segment using 3-0 or 4-0 silk suture. Grade II injuries (full-thickness lacerations involving less than 50% of the luminal diameter) require debridement and primary repair in two layers. The injury should be closed transversely without tension if possible, using absorbable sutures in running fashion for the inner layer and interrupted silk for the outer layer. Multiple Grade II injuries should be closed individually, avoiding bowel resection if possible. Grade III–V injuries should be managed with resection and primary anastomosis to avoid luminal narrowing with primary repair. The blood supply to the bowel adjacent to the resection margin should be examined thoroughly. Isolated mesenteric hematomas should be opened for adequate examination of the mesenteric side of the bowel.

Primary repair can be approached with stapled or hand-sewn anastomosis with similar rates of complication between the two types of repair in the setting of trauma [35–37]. The size of the child may limit the utility of automatic stapling devices. Hand sewn anastomosis can be performed in a single layer or in two layers in either a running or interrupted technique. The common enterotomy created during stapled anastomosis should be closed primarily with either a running suture or a non-cutting stapler. The choice of anastomosis is surgeon specific and should be performed expeditiously in the setting of trauma. The key principles of a tension-free suture or staple line, maintaining adequate blood supply, and ensuring appropriate luminal diameter should be maintained regardless of the chosen method. In the setting of hemodynamic instability, a damage control procedure may be utilized, and the bowel may be left in discontinuity after control of contamination with plans for delayed repair within 48 h.

Colon

Historically, almost all colon injuries were managed with diverting colostomy. However, there was a significant paradigm shift in the trauma community in the late 1990s towards primary repair of non-destructive (Grade I–III, Table 24.2) colon injuries. Multiple prospective studies demonstrate similar or even lower complications rates and postoperative mortality with primary repair when compared to diverting colostomy. Primary repair has also been shown to be safe and effective for injuries to the colon that require resection; however, management of these destructive colon injuries (Grades IV and V, Table 24.2) is less straightforward and impacted by multiple factors. These include the clinical status of the patient, location of the injury and potential anastomosis, and transfusion requirement during initial resuscitation. Diversion is most often accomplished with end colostomy and Hartman's pouch or loop colostomy with the closure of the distal lumen to achieve complete diversion [38–43].

Similar to small intestinal injuries, the question of handsewn versus stapled anastomosis for primary repair remains controversial. A retrospective study sponsored by the Western Trauma Association in 2001 examined the two types of anastomosis in both small and large intestinal trauma. This group showed a significantly higher rate of anastomotic leak and intra-abdominal abscess formation in the stapled group [36]. A second multicenter trial sponsored by the AAST looked at stapled versus handsewn anastomoses specifically in colon injury and demonstrated similar rates of abdominal complications and anastomotic leak between the two types of repair [44]. Based on the available evidence, there is no consensus recommendation for the type of anastomosis in traumatic colon injury, and the decision remains surgeon specific at this time. Notably, these data are limited to adult trauma patients and have not been performed in children. Regardless, one may extrapolate that children may have similar approaches, and stapling may be limited by the size of the intestine in infants. Handsewn anastomosis can be performed in a single or two layers. The colon may also be left in discontinuity after control of contamination in a damage control setting. In adults, the skin is often left open as closed wounds increase the risk of wound infection, but pediatric surgeons typically close the skin in most cases since wound management and suture removals can be difficult for young children. There is a risk of subsequent wound dehiscence and necrotizing soft tissue infection [45].

Post-operative Care and Outcomes

Post-operative care should include no more than 24-h of prophylactic antibiotics after source control, typically with a single agent [46]. Routine nasogastric decompression after repair of traumatic intestinal injury is controversial, but it may be initiated based on surgeon preference and continued until resolution of post-operative ileus with the goal to initiate enteral feeding within 48 h post-injury [47]. One should also recognize that the return to bowel function in smaller children may be different timeframe than adults, and the re-insertion of a nasogastric tube may be fairly traumatic. Therefore, the early removal of nasogastric tubes for smaller children bears further evaluation.

Early postoperative complications include wound infection, anastomotic leak, and abdominal septic complications like intraabdominal abscess. Anastomotic disruption typically presents with peritonitis and may progress to the formation of an enterocutaneous fistula. Leaks can be managed with re-operation and primary repair or diversion in the early post-op period (<10–14 days) or with percutaneous drainage if anatomically and clinically amenable. Empiric antibiotic coverage should be initiated and tailored according to culture results.

Wound infection and intraabdominal abscess typically present with post-operative fever and new or persistent leukocytosis. These complications are significantly impacted by time to index operation, and delay beyond 24 h post-injury increases the incidence of abdominal complications but does not have a significant impact on mortality [48, 49].

Children are also at risk for nosocomial infection in addition to injury-related infections. Sepsis occurs in nearly 2% of trauma patients post-injury, with a higher incidence associated with a higher injury severity score (ISS) [50].

Late complications after intestinal trauma include stricture and adhesive bowel obstruction. Stricture may occur at the site of a contusion (Grade I injury) or at the site of a primary repair or anastomosis. Bowel obstruction occurs in less than 10% of patients after trauma laparotomy and typically present 1–6 weeks post-operatively. In children, obstructions are typically managed non-operatively, and a CT scan should be employed to differentiate prolonged ileus from mechanical obstruction [51, 52].

Conclusion

Intestinal blunt trauma is a critical and morbid injury for children. Practitioners should maintain a high index of suspicion for such injuries. Axial imaging is useful in determining potential candidates for operative intervention. Hemodynamic status will dictate whether the surgeon opts for laparoscopic interventions. Most complete operative interventions will require an open operation so that small intestinal injuries are not overlooked. Surgical remedies in a timely fashion are ideal for primary repairs as long as the injuries do not alter hemodynamic status. The key maneuver in gaining control is source control and definitive repair if the patient is stable. Second look procedures are needed if time is needed to look for additional problems if the patient needs timely intensive care unit interventions and resuscitation. The variability in children's sizes often leads to remedies that are unique to the pediatric population.

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Chapter 25
Rectal Injury

Allison L. Mak and Michael L. Nance

Abstract Pediatric rectal injury can occur as a result of penetrating or blunt abdominal/pelvic trauma. The approach to, and management of, rectal injury depends on the precise location and extent of the injury. Knowledge of the anatomy of the rectum and the ability to identify the level of the injury guides management. This chapter provides an overview of the approach to suspected rectal injury in a pediatric trauma patient.

Keywords Pediatric rectal injury · Management of rectal injury · Abdominal/pelvic trauma

Key Concepts/Clinical Peals
- Understand the anatomy of the rectum and its relationship to surrounding structures.
- Review the workup of the trauma patient, injuries that raise suspicion for rectal injury, and identification and localization of rectal injury.
- Management of intraperitoneal versus extraperitoneal injury.

Initial Management of the Trauma Patient

- As with any trauma patient, the initial assessment is guided by the primary survey, as described by the Advanced Trauma Life Support (ATLS®) criteria to identify and treat life-threatening injuries expeditiously [1].
- A secondary survey should include an evaluation of the abdomen, pelvis, perineum, and genitalia. Treating clinicians should maintain a high suspicion for

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rectal injury, even in the absence of external findings, if there is a blunt or penetrating injury to the lower abdomen or pelvis.
- Suspect possible concomitant rectal injury in patients with pelvic fracture.
- If there is a concern for non-accidental trauma, additional considerations include screening/treatment of sexually transmitted infections and forensic evidence collection. Many healthcare systems have incorporated Sexual Assault Nurse Examiners (SANE) or specifically trained providers who should be mobilized and may assist with medical forensic care [2].

Initial Radiographic/Ancillary Studies

Pediatric rectal injury can occur as a result of penetrating or blunt abdominal/pelvic trauma. The approach to, and management of, rectal injury depends on the precise location and extent of the injury. Knowledge of the anatomy of the rectum and the ability to identify the level of the injury guides management. The following imaging modalities may assist the treating physician with identifying the level and/or location of a rectal injury.

- Abdominal plain film.
- Pelvic plain film.
- Water-soluble contrast study.
- Computed tomography (CT) scan (±rectal contrast).Anatomy

- The sigmoid colon continues distally and transitions to the rectum, where the taenia converge.
- Anterior and lateral upper 2/3 of the rectum is intraperitoneal.
- Anterior lower 1/3 and posterior lower 2/3 of the rectum is extraperitoneal.
- Posterior to the rectum are the three inferior sacral vertebrae, the coccyx, the sacral vessels.
- Anterior to the rectum are the prostate and bladder in males, posterior vaginal wall in females.
- Blood supply to the rectum: superior rectal, middle rectal, inferior rectal arteries.
- Venous return from the rectum: superior and middle rectal veins.

Initial Assessment

On presentation to the emergency department, assessment of the trauma patient begins with the primary survey, as directed by the Advanced Trauma Life Support (ATLS) criteria. Injuries that pose threat to life are prioritized. Less immediately life-threatening injuries to the rectum can then be identified and addressed.

Traumatic injury to the rectum is categorized as penetrating or blunt. The most common cause of penetrating injury is gunshot wound, but other causes include stab wounds, impalement, sexual assault, and foreign body. Blunt injury to the rectum is uncommon, and mechanisms include motor vehicle accidents, falls, assault/blow to the abdomen, and pedestrian injuries.

When there is concern for sexual abuse, early mobilization of resources is essential [2]. Depending on the facility, this may be sexual assault response teams, Sexual Assault Nurse Educators (SANE), or specially trained personnel who can support patient care and medical forensic care. There should be a low threshold for suspecting abuse and all instances must be reported. In addition to standard laboratory studies, consider testing for sexually transmitted infections (gonorrhea, chlamydia, trichomonas, HIV), and offering pregnancy testing and HIV prophylaxis. Physical findings must be clearly and thoroughly documented, and care taken to save clothing for forensic evidence collection.

Physical Exam

- Physical exam should include focused examination of the lower abdomen, pelvis, genitalia/anus, buttocks.
- A digital rectal exam (DRE) may be performed and the presence of blood would raise suspicion for rectal injury. However, the sensitivity of DRE for detection of rectal injury in children is limited, and it is no longer recommended as part of the routine exam of all pediatric trauma patients [3].
- Injuries commonly associated with rectal injury include pelvic fracture, and urethral or bladder injury. A review of adult patients with traumatic rectal injury showed that 28% had concomitant bladder injury, and that concomitant injury did not increase rates of abdominal complications, mortality, or length of stay [4].

Plain Films

- Imaging should be guided by clinical concerns that need resolution.
- Abdominal radiograph: pneumoperitoneum is indicative of hollow viscus injury, and would be an indication for operative exploration. Intraperitoneal injury to the upper rectum can be explored at the time of laparotomy.
- Pelvic radiograph: identification of pelvic fracture. The presence of pelvic fracture raises concern for intra or extraperitoneal bladder injury, urethral injury, and rectal injury.

Imaging/Studies

- CT scan—cross-sectional imaging of the abdomen and pelvis can help elucidate injury level and extent in a stable patient. Triple contrast (IV, PO, rectal) can be considered based on clinical findings. In cases of obvious perineal and rectal injury, rectal contrast or manipulation should be avoided.

- Water-soluble contrast study—barium enema, retrograde urethrogram may aid in diagnosis if there is clinical suspicion for GU or rectal injury. Contrast extravasation localizes the injury, which would then guide management.
- Cystogram, proctosigmoidoscopy—procedures under sedation or anesthesia should be considered if high suspicion for GU or rectal injury, allowing visualization of the injury and confirmation of its presence, level, and extent.

Management

Rectal injury is overall rare, and its management has evolved over time. In a two-year review of 1.7 million trauma patients, 0.1% sustained a rectal injury [5]. In the pediatric population, a one-year national database review identified trauma patients aged 14 years and younger, 0.3% of whom sustained colorectal injury, 25.7% of these had an identified rectal injury [6].

The operative management of traumatic colorectal injury is informed by experience with military injuries. It has evolved, over the years from pre-American Civil war to World War II, from watchful waiting to surgical exploration and then to mandated fecal diversion [7]. The years of the Vietnam War brought the advent of presacral drainage and distal rectal washout to the treatment algorithm [8]. Mortality has decreased significantly with these changes in technique, but also with substantial advances in medical care, such as the understanding of antisepsis and sterile technique, antibiotics, improved resuscitation measures, and surgical instruments. The distinction between high velocity military injury and low velocity civilian gunshot wound suggests that standard operative management as learned from wartime experience may be tailored and refined for civilian trauma care [9].

- Management of rectal injury is largely driven by the level and extent of the injury and the patient's condition.
- Maintain a high index of suspicion for a rectal injury in patients with pelvic fracture, perineal, or lower abdominal injury.
  - The incidence of rectal injury with pelvic fractures is overall very low (1–2%). However, the rates of pelvic fracture with associated rectal injury are much higher in children than in adults (pelvic fractures are much less common in pediatric (0–14 years) age group compared to adult) [10].
  - Pelvic sepsis portends high mortality [11] and can result from missed rectal injury.
- Operative management of rectal injuries may include laparotomy, primary repair, resection and primary anastomosis, fecal diversion, presacral drainage, or distal rectal washout. Presacral drainage and distal rectal washout have not conclusively shown benefit and may be associated with increased abdominal complications [5]. Figure 25.1 provides a suggested algorithm for the management of penetrating rectal injury.

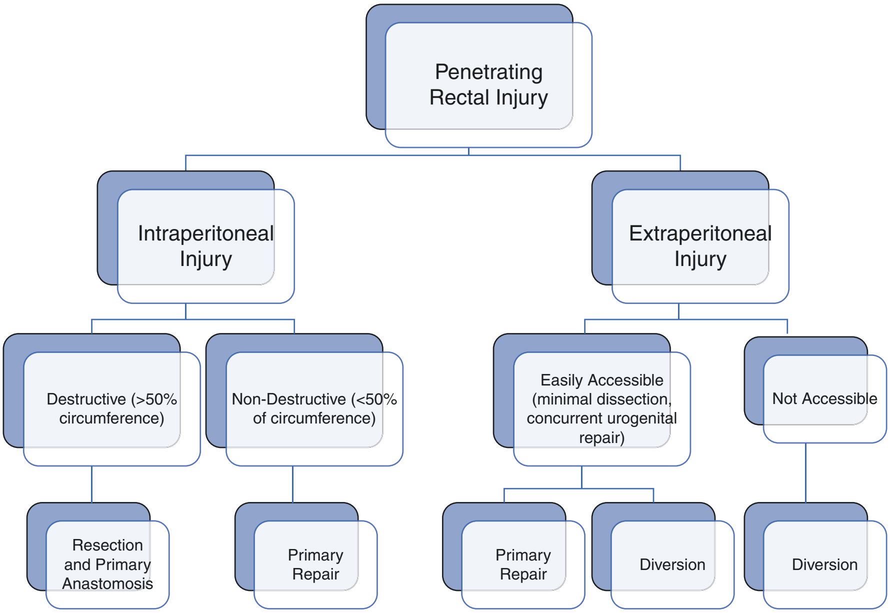

Fig. 25.1 Algorithm for the treatment of penetrating rectal injury

Intraperitoneal Rectal Injury

- Injuries to the upper rectum (anterior and lateral upper 2/3) are intraperitoneal and should be managed according to the algorithm for management of colonic injuries.
- Laparotomy and exploration of upper rectal injury should be performed if there is a concern for penetrating injury and perforation. Supporting findings include peritonitis, pneumoperitoneum, or extravasation of oral/rectal contrast on abdominal plain film or CT scan.
- The principles guiding management of penetrating colon injury are applied:
  - Primary repair of upper rectal injury may be performed if an injury is non-destructive (less than 50% of colon wall circumference).
  - Resection and primary anastomosis may be performed if a destructive injury is noted (50% of wall circumference or greater).
  - Fecal diversion should be considered; however, data now supports operative management without ostomy is safe in most clinical scenarios.

Extraperitoneal Rectal Injury

- Injury to the lower rectum (anterior lower 1/3 and posterior lower 2/3) is extraperitoneal.

- Repair of low rectal injury may be performed if the injury can be visualized without extensive dissection, or if an operation for repair of associated genitourinary injuries is required. Operative repair may be performed via laparotomy or trans-anally.
- Presacral drain placement and distal rectal washout is not beneficial in the treatment of extraperitoneal rectal injuries [7, 9].

Fecal Diversion

- There is debate over the need for routine fecal diversion in the trauma patient population. This has been studied more extensively in the adult than the pediatric population.
- Historically, fecal diversion was the standard of care for all penetrating colorectal injuries and was mandated as operative management by the U.S surgeon general in World War II [8]. Important studies since that time have demonstrated safety in the management of colorectal injury with primary repair or resection and anastomosis without diversion in adult [9, 12] and pediatric patients [6, 13]. The extent of injury must be considered, particularly the presence or extent of fecal contamination or devascularization of the injured segment. Critical patient factors include hemodynamic status, time to operative intervention, estimated blood loss/transfusion requirement.
- Isolated extraperitoneal rectal injuries may be safely managed without fecal diversion [14].
- Presacral drainage and distal rectal washout are not recommended as routine management as they do not decrease infectious complications [5, 14].

Conclusions and Take Home Points

Rectal injuries are uncommon in the pediatric trauma population. Like all injuries, they require an individualized, thorough assessment (exam and imaging) to formulate a management plan.

- Most rectal injuries are amenable to local repair and control of contamination without fecal diversion.
- Devastating injuries with significant tissue destruction or, patients with clinical instability are best managed with diversion and resuscitation.
- The potential for non-accidental trauma should be considered.

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Chapter 26
Perineal Injury

Torbjorg Holtestaul and John Horton

Abstract Perineal injury in children is relatively rare and can present either as an isolated injury or as a part of multisystem trauma. The mechanism of perineal trauma can be categorized as straddle, non-straddle blunt, penetrating, or sexual. In children, perineal trauma should always prompt consideration of sexual abuse, and suspicion of such should prompt immediate appropriate referrals. The primary method of diagnosing the extent of the perineal injury is a thorough physical examination. If this cannot be done at the bedside, then an examination under anesthesia (EUA) is mandatory. If diagnostic radiography is required, this should be completed prior to EUA. Endoscopic evaluation during EUA should be performed at the discretion of the surgeon, including proctoscopy, vaginoscopy, and cystoscopy. Most children with minor perineal trauma can be managed non-operatively, and of those requiring surgical repair, the majority are treated with simple, primary closure. A low threshold for pediatric urologic consultation should be maintained if there is a concern for injury to the bladder, urethra, or testicles. Involvement of the anorectum often necessitates more complex repair, with the most severe injuries requiring exploration and fecal diversion.

Keywords Perineal injury · Straddle injury · Anorectal trauma · Vaginal laceration

Key Concepts/Clinical Pearls (Learning Objectives)

- Non-accidental trauma, particularly sexual abuse, should be considered in any child presenting with perineal injury.
- If the extent of the injury is not readily apparent at the bedside, perform an examination under anesthesia with appropriate endoscopy at the surgeon's discretion.
- Primary repair is appropriate for simple lacerations to the perineum.
- Complex anorectal injury can require a fecal diversion.

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Initial Management of the Trauma Patient with Perineal Injury

As in all trauma, the patient should be first appropriately resuscitated and stabilized. Once immediately life-threatening injuries have been excluded or treated, a focused history should be performed with special attention to the mechanism of injury. If there is a concern for sexual abuse, appropriate referrals should be made. A physical exam should be performed to determine the extent of the injury. If this is intolerable to the patient or the extent of the injury is not easily defined at the bedside, the child should be taken for an examination under anesthesia (EUA). Prior to taking the patient for an EUA, any relevant diagnostic imaging should be performed.

Initial Radiography/Ancillary Studies

An isolated perineal injury does not necessitate any diagnostic imaging, as often the diagnosis and extent of injury are determined based on physical exam. However, cross-sectional imaging should be considered if there is a concern for concomitant abdominal trauma. Surgeons should have a low threshold to obtain cross-sectional imaging for penetrating perineal injuries as the presence of intraperitoneal or high extraperitoneal rectal injuries can be difficult to determine during examination under anesthesia. Urethrogram and/or cystogram should be considered if a complex urologic injury is suspected. If imaging is necessary, it should be performed prior to an examination under anesthesia. If an examination under anesthesia is necessary to determine extent of the injury, then relevant endoscopy (proctoscopy, vaginoscopy, cystoscopy) is performed at the discretion of the surgeon and relevant consultants.

Pediatric Perineal Injury

Epidemiology

In children, injury to the perineum is relatively rare with an incidence of 8% and can present either as an isolated injury or as a part of multisystem trauma [1]. In girls, perineal injury is defined as an injury to the labia, vulva, urethra, vagina, hymen, perineum or rectum [2]. In boys, it is defined as an injury to the scrotum, glans penis, urethra, perineum or rectum [3].

Table 26.1 Genital Injury Score in children and appropriate treatment [3, 4]

Genital Injury Score		Treatment
GIS I	Isolated genital laceration below hymen or limited to penile/scrotal skin	Primary repair
GIS II	Isolated genital laceration including hymen or tunica dartos of scrotum/Bucks fascia of penis	Primary repair
GIS III	Isolated genital laceration including vagina or testis/penile cavernous or distal urethra	Endoscopic evaluation if necessary; Primary repair
GIS IV	GIS II or III injury plus partial tear of anorectum	Endoscopic evaluation if necessary; Primary repair
GIS V	GIS III injury plus complete tear of anorectum	Endoscopic evaluation; Primary repair; Consider diverting colostomy

Mechanism and Classification of Perineal Injuries

The mechanism of perineal trauma can be categorized as straddle, non-straddle blunt, penetrating, or sexual. In a review of accidental genital trauma in girls by Iqbal et al. in 2010, 70.5% was due to straddle injury, 23.5% to non-straddle blunt injury, and 6.0% to penetrating injury [2]. This can result in a wide spectrum of tissue compromise, from minor lacerations of the urogenital system to complete disruption of the anal sphincter, genitourinary tract or pelvic compartment [1].

The most common site of injury in girls is the labia (64%) followed by the perineum (21.5%), vulva (8.9%), posterior fourchette (7.8%), vagina (5.9%), rectum (2.9%), and hymen (8.4%) [2]. The severity of the pediatric perineal injury can be classified by the Genital Injury Score (GIS), which grades injury based on anatomic location of genital laceration and involvement of the anorectum (Table 26.1) [3, 4].

Many children with perineal injury present with few, if any, symptoms [1, 5]. The most common symptom is bleeding, followed by abdominopelvic pain and tenderness [3].

Straddle Injury

Straddle injury occurs due to the blunt trauma of an object striking a child between the legs, most commonly from a fall, causing mechanical compression of the soft tissues against the bony pelvis. The most common straddle injuries occur due to a fall on the crossbar of a bicycle (25%), followed by a fall on furniture (23%) [1].

In females, the most common straddle injury is a minor laceration or abrasion of the labia (79%), and in males is a minor laceration to the scrotum or penis [6]. Pain is the most common presenting complaint among boys with straddle injury (42.9%), and bleeding is the most common complaint among girls (68.1%) [2].

Non-straddle Blunt Injury

The most common cause of non-straddle blunt injury in girls is motor vehicle crashes, which can result in significant blunt trauma or shear injury in any child [1]. Non-penetrating blunt injury is the most likely mechanism to be associated with multi-system trauma, and a full trauma work-up, including pelvis x-ray, should be performed. Blunt perineal injury in girls is most commonly associated with head injuries (26.3%) followed by pelvic fractures (14.8%) [1]. Sixty percent of patients with blunt perineal injury will present with bleeding [1]. The perineum is well vascularized, and even patients with isolated minor lacerations can present with impressive bleeding.

Penetrating Injury

Penetrating perineal injuries most commonly occur due to falls on offending objects. These injuries can be further classified as trans-anal or perineal, and extraperitoneal or intraperitoneal [5]. Children are more prone to severe injury due to a thin recto-vaginal septum in girls in addition to a more superficial urogenital diaphragm, with the bladder, uterus and rectum lying low in the pelvis (Fig. 26.1) [5–7]. Injuries from penetrating trauma have been described to the genitourinary, anorectal, gastro-intestinal, and vascular systems [8].

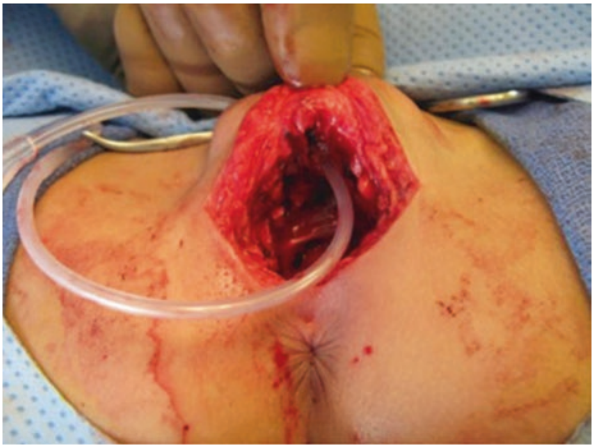

Fig. 26.1 Complete transection of urethra and vagina in a 4-year-old girl having sustained a penetrating injury after straddling a drinking glass [7]

When evaluating a patient with a penetrating injury, it is important to consider the location of the entry wound and the trajectory/depth of penetration. If possible, one should inspect the offending object. Impalement injuries can be difficult to recognize because the external appearance of the perineum may not accurately reflect the severity of the injury [5]. The most common symptoms among children with anorectal injuries are rectal bleeding, anal pain, and abdominal pain [4, 6–8].

Sexual/Coital Injury

In children, perineal trauma should always prompt consideration of sexual abuse. In a review of accidental genital trauma in females, assaults were responsible for 17% of blunt perineal injuries in girls under four-years-old [1]. In a review of 100 children with straddle injuries, Dowd et al. found that five patients were victims of sexual assault. The injury pattern from sexual trauma can be distinct from other mechanisms, most often described as hymenal disruption and injury to the posterior fourchette [2]. The injury patterns of the patients described in Dowd's review included a hymenal tear, ecchymosis of the hymen and posterior fourchette, a large labial laceration, an intraperitoneal-vaginal laceration, and ecchymosis of the labia and perineal area [6].

Sexual assault should be considered if there is a severe or extensive injury that does not correlate well with the history, if there is other non-genital injury such as facial bruising or bruising around the legs, a large hymenal diameter, or a straddle injury in a non-ambulatory child [6]. If sexual assault is suspected, appropriate referrals should be made as soon as possible. In addition, the surgeon should involve medical photography during the examination under anesthesia in order to visually document the appearance of injuries in the event legal proceedings become necessary.

Radiographic Evaluation

The primary method of diagnosing the extent of the perineal injury is a thorough physical exam. If this is unable to be done at the bedside, then an examination under anesthesia is mandatory. However, prior to taking a child to the operating room, all other indicated diagnostic imaging should be completed.

In the case of a retained foreign body, an upright abdominal x-ray should be considered evaluating for the foreign body and any evidence of free air. While cross-sectional imaging such as a computed tomography (CT) scan does not obviate the need for EUA, it should be considered if there is any concern for concomitant abdominal or intra-peritoneal injury. Of note, a retrospective review of 24 children by Leaphart et al. evaluated triple-contrast CT in comparison to proctoscopy for diagnosis of rectal injuries and found the two methods to be equivalent [9]. In patients who are found to have signs concerning for urethral trauma such as blood at the meatus or penile or vulvar hematoma, a dynamic retrograde urethrogram is recommended to assess for urethral injury [10].

Operative Evaluation

While there is some controversy regarding routine examination under anesthesia (EUA) for children with perineal injury, the authors recommend a selective approach [1]. EUA should be strongly considered if the child is unable to tolerate a thorough exam at the bedside, if the extent of injury is indeterminate, or if there is known extensive injury. In girls, EUA should be considered if the injury extends beyond the labia [2]. While awaiting transfer to the operating room, direct pressure with commercially available hemostatic gauze or knitted product can help temporize bleeding until operative repair is achieved.

Endoscopic evaluation during EUA should be performed at the discretion of the surgeon, to include proctoscopy, vaginoscopy, and cystoscopy. A nasal speculum works well for evaluation of the vagina and rectum in small children. Vaginoscopy is particularly important to rule out retained foreign body in the vagina. With regards to cystoscopy, if the child has hematuria, anterior rectal wall impairment, or if there is otherwise a high clinical suspicion of injury to the urologic system, one should have a low threshold for consulting a pediatric urologist [8, 11–13].

Operative Repair

The majority (approximately 90%) of pediatric patients with perineal trauma can be managed non-operatively, and of those requiring surgical repair, the majority are treated with simple, primary closure [1, 2, 4]. When repairing perineal injuries, the surgeon must consider both functional and cosmetic outcomes. Principles of perineal laceration repair include local debridement of devitalized tissue, wound irrigation, and primary repair in layers. For mild to moderate perineal and vaginal injuries in girls, the authors recommend using absorbable suture in an interrupted fashion to reapproximate the often jagged tissue (for example, 4-0 or 5-0 chromic). If there is any concern for testicular, urethral or bladder injury, pediatric urology should be consulted.

If there is involvement of the anorectum, repair and treatment become more complex. While there is some controversy regarding timing of repair for sphincter reconstruction in severe injuries, the majority of the literature agrees that immediate reconstruction helps prevent future fibrosis, poorly defined anatomy, and retracted structures [11, 14]. However, techniques have been described for delayed repair in the case of severe perineal disruption or wound dehiscence/fistula after primary repair [15]. A muscle stimulator can be used to help define sphincter limits and achieve an anatomical repair [11, 14].

The surgical approach to anorectal repair depends on whether the injury is extra- or intra-peritoneal. Intra-peritoneal colorectal injuries should undergo primary repair, and extra-peritoneal injuries can often be repaired primarily via a trans-anal approach if possible or drained and diverted if complex [5, 11]. Small, low energy trans-anal injuries (e.g. a stab or shard impalement) can be managed with trans-anal closure, antibiotics, and observation.

In the context of perineal trauma, a penetrating mechanism is often the most concerning for intra-peritoneal injury. As discussed above, if there is concern for peritoneal violation, diagnostic radiology should be considered prior to examination under anesthesia. If the impaling object has not yet been removed, it should remain in place until the patient is in the operating room [5]. There is a role for diagnostic laparoscopy to evaluate imaging findings which heighten suspicion of an intra-abdominal visceral injury, and one review of traumatic anorectal injuries in children endorses a laparoscopic approach to evaluate and repair a known intra-peritoneal rectal injury [11, 14]. However, traditionally exploratory laparotomy is performed for intra-peritoneal involvement [8, 15].

There is some debate in the literature regarding the need for diversion in the setting of anorectal injury. Historically, fecal diversion was recommended for all anorectal injuries except for small and isolated anal injuries [12]. In isolated anorectal injury, diversion is recommended in cases with potential life-threatening trauma, destructive anal injury, severe perineal involvement, substantial associated injuries, or gross contamination. If considering deferring diversion, the surgeon must consider whether there is risk for fecal contamination of the peri-rectal space [14]. In the case of intra-peritoneal rectal injury, diverting colostomy is generally recommended, although some authors have described primary repair without diversion in stable patients [3, 11, 16]. In patients requiring diversion, re-establishment of continuity can occur six weeks after the index operation, following confirmation of anal sphincter sufficiency and complete wound healing [3, 5].

Post-operative management of children with complex perineal injury should consist of antibiotic therapy and diligent wound care to ensure optimal functional and cosmetic outcomes [5, 12]. The most common complication after penetrating perineal injuries is wound infection, which is described in 19% of patients with anorectal injuries [4, 12]. In children with anorectal injuries, 90% have preserved sphincter continence in long term follow-up [11]. Fistula, stricture, and stenosis have been described after primary repair of both the anorectum and genitourinary system [1, 15].

Conclusions and Take Home Points

- Perineal trauma in the child should prompt consideration of sexual abuse.
- Examination under anesthesia is often required to determine the extent of injury, with endoscopic adjuncts (proctoscopy, vaginoscopy, cystoscopy) at the discretion of the surgeon and relevant consultants.

- Simple lacerations to the perineum can usually be repaired primarily.
- Fecal diversion may be required in complex anorectal injury.

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Chapter 27
Upper Tract Genitourinary Trauma

Janelle A. Fox, M. A. Colaco, and Erik T. Grossgold

Abstract Renal injuries occur in approximately 10% of pediatric blunt abdominal trauma cases, and 90% of pediatric renal injuries are the result of blunt trauma. When compared to adults, children are at a higher risk of renal injury after blunt trauma due to their relative lack of perirenal fat, weaker abdominal muscles, and less ossified thoracic cage. Although traditionally considered an operative emergency, renal injury is increasingly managed in a nonoperative or minimally invasive fashion in both children and adults. Initial management of genitourinary trauma depends on the hemodynamic stability of the patient. Stable patients will commonly require CT scan imaging of the abdomen and pelvis to identify the extent of the injury and identify associated injuries. The stage of such genitourinary injuries and the status of the patient will direct.

Keywords Renal trauma · Ureteral injury · Gross hematuria · Blunt abdominal trauma · Pediatric · Children

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Key Concepts
RENAL

- Renal imaging is indicated in children with gross hematuria, microhematuria >50 rbc/hpf with hypotension, high-risk mechanism of injury and high clinical suspicion of injury.
- The gold standard study for renal and ureteral evaluation after blunt or penetrating abdominal trauma is the triphasic abdominal computed tomography scan (CT) or CT abdomen/pelvis with IV contrast-enhanced and delayed phases.
- Nonoperative management is recommended for all grades of blunt pediatric renal trauma, in a hemodynamically stable patient.
- Angiography with embolization is favored over operative exploration for signs of ongoing bleeding in the hemodynamically stable child with renal laceration.
- Angiography with embolization or surgical exploration should be used in the unstable child with renal laceration and no response to resuscitation, large perirenal hematoma >4 cm, or active contrast extravasation on initial CT.
- Long-term blood pressure monitoring for renovascular hypertension (Page kidney and Goldblatt kidney) is recommended after high-grade pediatric renal injuries.

URETER

- The gold standard imaging study to evaluate ureteral trauma in a hemodynamically stable child is the CT abdomen/pelvis with delayed phase (which is part of the triphasic CT).
- Repair of the collecting system (calyx, pelvis, or ureter) is performed with absorbable suture plus additional drainage with a ureteral stent or percutaneous nephrostomy to reduce the risk of urine leak.
- Traumatic ureteral lacerations or avulsions should be repaired primarily, whereas ureteral contusions may be managed with a ureteral stent alone. Iatrogenic endoscopic injuries without avulsion or iatrogenic ureteral injuries with delayed recognition may also be managed with a ureteral stent or percutaneous nephrostomy alone.

Renal Trauma

Introduction

Renal injuries occur in approximately 10% of pediatric blunt abdominal trauma cases, and 90% of pediatric renal injuries are the result of blunt trauma [1].When compared to adults, children are at a higher risk of renal injury after blunt trauma due to their relative lack of perirenal fat, weaker abdominal muscles, and less ossified thoracic cage. The pediatric kidney is also larger relative to the rest of the abdominal cavity, inviting more relative volume for injury [2]. Although traditionally considered an operative emergency renal injury is increasingly managed in a non-operative or minimally invasive fashion in both children and adults [3, 4].

Diagnosis

As with all patients, the initial investigation of the hemodynamically stable patient with abdominal trauma begins with ATLS and the primary and secondary survey. The secondary survey includes a detailed history, physical exam and basic laboratory evaluation (urinalysis, hemoglobin/hematocrit, creatinine). Understanding the mechanism of injury is the driving force behind the decision to proceed with further evaluation. Although urinalysis can be a helpful tool in diagnosing renal trauma, up to two-thirds of children may have a normal urinalysis after Grade II or higher renal injuries. Hence, urinalysis alone is not the only screening tool used to predict the need for renal imaging [4]. The severity of renal injury also does not correlate with the degree of hematuria. As such the American Urologic Association (AUA), European Association of Urology and Societe Internationale d'Urologie have recommended that patients should undergo imaging for:

- The presence of gross hematuria.
- The presence of microhematuria (>50 RBC/hpf after blunt and >5 RBC/hpf after penetrating trauma) and hypotension, recognizing that significant renal trauma may still be present with lower levels of microhematuria.
- A mechanism of injury or physical exam findings concerning for renal injury (e.g., rapid deceleration, significant blow to flank, rib fracture, significant flank ecchymosis, penetrating injury of abdomen, flank, or lower chest) [5].

The gold standard for renal trauma imaging in the hemodynamically stable patient is either triphasic CT (CT urogram) or CT abdomen/pelvis with IV contrast-enhanced and delayed phases. The need for an initial non-contrast phase is not as critical, provided the enhanced and delayed phases are correctly protocoled. The second "enhanced" phase should be performed approximately 70 s after administration of 2 mg/kg of 60% nonionic iodinated contrast at a rate of 2.0–2.5 ml/s to enhance renal parenchyma and hilum. A final "delayed" phase should be performed 3 or more minutes after the initiation of contrast to assess injury to the collecting system [6]. Hypovolemia and acute or chronic kidney disease will delay renal excretion hence visualization of the entire collecting system should be ensured before the CT scan is terminated. Kidney injuries are graded based on CT scan according to the American Association for Surgery of Trauma (AAST) renal injury scale (Fig. 27.1 and Table 27.1) [7].

Although CT is the gold standard for assessing renal injury, alternate imaging modalities may be used based on availability. Ultrasound is an acceptable alternative modality in children, although it is less sensitive for renal injury [8]. For the unstable patient that must go to the operating room emergently, intravenous pyelogram is a practical option to diagnose the presence of two functional kidneys and

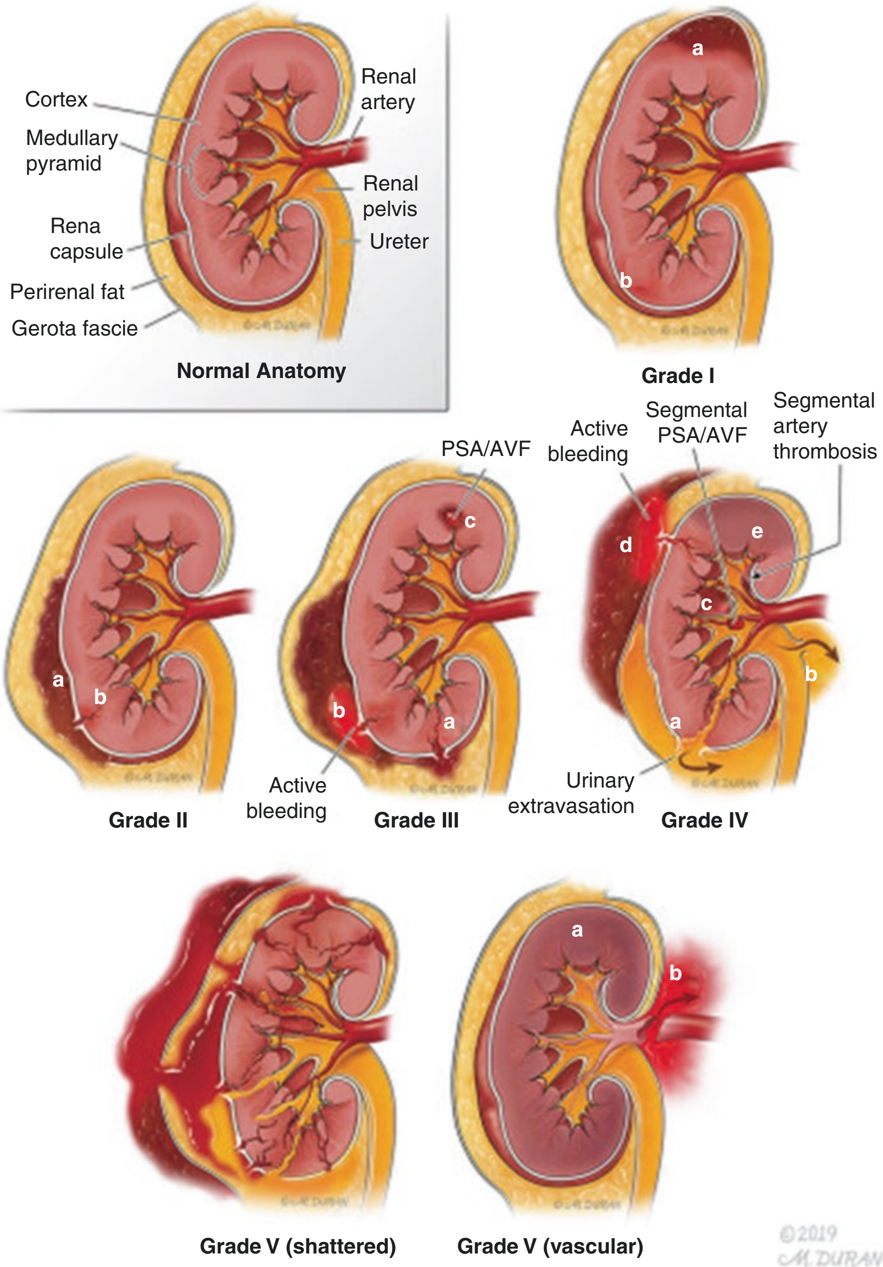

Fig. 27.1 Kidney Injury Scale by Grade. Reprinted with permission [21]. Pictorial representation of the American Association for the Surgery of Trauma Organ Injury Scale 2018 update, based upon computed tomography grading. *PSA* pseudoaneurysm, *AVF* arteriovenous fistula

Table 27.1 American Association for Surgery of Trauma (AAST) Kidney Injury Scale Based Upon CT Findings (2018 Revision)

Grade of Injury	Description
I	Renal Contusion or Subcapsular Hematoma with no Parenchymal Laceration
II	Perirenal hematoma confined to Gerota's fascia, Less than 1 cm Parenchymal Laceration without Urinary Extravasation, All Renal Segments are Viable
III	Greater than 1 cm Parenchymal Laceration without Urinary Extravasation, Renal Fragments may be Viable or Devitalized
IV	Laceration extending into the Renal Collecting System with Urinary Extravasation, Renal Segments may be Viable or Devitalized *or* Renal pelvis laceration and/or complete ureteropelvic junction disruption*or*Segmental renal vein or artery injury *or* Active bleeding beyond Gerota's fascia into retroperitoneum or peritoneum *or* Segmental or complete renal infarction due to thrombosis without active bleeding
V	Shattered Kidney with loss of identifiable parenchymal renal anatomy, devascularization with active bleeding*or*Injury to the Main Renal Vasculature with active bleeding or renal Hilar Avulsion

Derived from the AAST Renal Injury Scale [7]

potentially collecting system injury. Beyond these goals, it is limited in diagnosing grades of renal laceration. IVP is performed by injecting 2 ml/kg of IV contrast followed by a single abdominal radiograph approximately 10–15 min later (or more, should shock or hypovolemia exist). While this is not sensitive for urologic injury, IVP most importantly determines the presence and function of a contralateral kidney if nephrectomy is being considered [5].

Management

While grades IV and V renal injuries have historically been managed operatively, modern management has moved much more towards conservative management for hemodynamically stable and appropriately selected patients. As such, the AUA recommends non-invasive management with monitoring, bed rest and possible transfusion for all hemodynamically stable patients regardless of injury grade [9]. The European Association of Urology differs slightly in management recommendation, clarifying that grade V vascular or penetrating injuries have strong evidence for immediate renal exploration; though this is not specific to pediatric patients [10]. For hemodynamically unstable patients with radiographic findings of a large perirenal hematoma (>4 cm) or vascular extravasation on CT, surgeons should perform immediate intervention with either surgery or angioembolization [9]. On review of the National Trauma Data Bank, only 2% of children ever undergo renal artery angiography, which is similar to adult database studies (1.8%) [11, 12].

While admitted, serial abdominal exams and periodic monitoring of hemoglobin are used to monitor for signs of ongoing urine leak or bleeding. The frequency of laboratory investigations is typically based upon the severity of renal laceration and surgeon discretion. Uncontrolled urine leak or bleeding will present with progressive abdominal distension, ileus, possibly fever, and rising creatinine or declining hemoglobin, respectively. One should consider repeat imaging in the form of CT with delayed images for grade IV collecting system injuries at this point to evaluate for enlarging or symptomatic urinomas. Progressive urine leaks will necessitate cystoscopy with ureteral stenting and bladder drainage [13]. Large amounts of clot in the collecting system may obstruct ureteral drainage, even after ureteral stenting, which then warrant percutaneous nephrostomy drainage if the clinical picture fails to improve. Delayed renal hemorrhage is more likely after penetrating renal injury and is typically due to a ruptured arteriovenous fistula or pseudoaneurysm.

Once the child has recovered from his injury, follow-up will depend on the initial grade of injury. For short-term follow-up, Grade I–III injuries have a low risk of complications with a rare need for intervention, and as such, no further imaging is recommended. Patients with Grade IV–V injuries, however, are more prone to late-onset complications including urinoma and hemorrhage. As such, AUA recommends follow-up CT 48–72 h after initial presentation [5]. For longer term follow-up Grade I–II injuries again do not require any further imaging. Grade III injuries, however, should have follow up imaging at three months post imaging with ultrasound being sufficient. Patients with Grade IV–V injuries should have follow-up imaging with either repeat CT or MRI [14]. Finally, monitoring for hypertension is important as large urinomas or hematomas may compress the renal parenchyma causing renovascular hypertension (Page kidney). Perihilar hematomas may also compress the renal artery causing renovascular hypertension (Goldblatt kidney). Pediatric nephrologists will typically manage these with angiotensin-converting enzyme (ACE)-inhibitors for hypertension control; however, if there is a failure of medical management or hypertension becomes chronic, then laparoscopic unroofing of the hematoma or urinoma (and rarely nephrectomy) is indicated. Post-traumatic renovascular hypertension is reported in 4.2% of children on a systematic review of Grades III–V renal injury [15].

Ureteral Trauma

Introduction

Unlike renal trauma, ureteral trauma is rare occurring in less than 1% of blunt trauma cases [16] and less than 4% of penetrating injuries. The ureter is freely mobile in the retroperitoneum and is protected by the bony pelvis, psoas muscles and vertebrae. It is posterior to other major abdominal organs and the majority of ureteral trauma is seen in multiorgan trauma cases [17]. Thus, ureteral trauma requires a high index of suspicion and can easily be missed in the immediate trauma evaluation.

Diagnosis

Traumatic ureteral injuries more commonly result from penetrating abdominal trauma, and gunshot wounds are the most common etiology. Data on pediatric ureteral trauma is limited and is mostly extrapolated from the adult ureteral injury literature. One unique aspect is that iatrogenic ureteral injury is far less common in children. These injuries typically occur during gynecologic, urologic, or retroperitoneal and spinal surgery in adults, though endoscopic management of kidney and ureteral stones is becoming more common in children. Most traumatic ureteral injuries occur in the setting of multiorgan trauma, and direct visualization of the ureter during laparotomy should be sufficient to identify both the existence and location of ureteral injuries [18]. IVP is not warranted in this situation as IVP can miss injury in 51.7% of cases. For those cases where the injury is equivocal, cystoscopy with retrograde pyelogram looking for contrast extravasation is the preferred intraoperative investigation. This requires an operative table that slides to accommodate a C-arm for intraoperative fluoroscopy, or on-Table X-ray, and the ability to either frog-leg a patient or place the patient in lithotomy positioning to accommodate cystoscopy per urethra.

For those patients who are stable enough to undergo imaging, ureteral injury is best identified with the delayed phase of a triphasic CT (CT urogram). As with renal trauma, delayed imaging should identify any contrast extravasation, which when paired with an absence of parenchymal laceration, would indicate injury of the ureter or collecting system. The presence or absence of hematuria is not an accurate indicator of ureteral injury with up to 55% of ureteral injuries having a negative urinalysis [19]; hence consideration of mechanism prior to imaging is critical (Table 27.2).

Table 27.2 Ureter Injury Scale

Grade of Injury	Description
I	Hematoma – Contusion or hematoma without devascularization
II	Laceration – Less than 50% transection
III	Laceration – Greater than 50% transection
IV	Laceration – Complete transection with <2 cm devascularization
V	Laceration – Avulsion with >2 cm of devascularization

Derived from AAST Ureter Injury Scale [22]

Management

A ureteral injury should always warrant a urological consult. Management of ureteral injury is largely dependent on the location and degree of injury. Transection injuries occurring below the iliac vessels can be managed with direct ureteroneocystostomy (ureteral reimplantation into the bladder). Injuries above the iliac vessels can be managed with a primary spatulated anastomosis. In either case, if the distance required to achieve a tension-free anastomosis cannot be achieved, additional ureteral length can be created through bladder mobilization and securement to the psoas muscle (psoas hitch) or creation of a tubularized bladder flap (Boari flap). Minimal contusion injuries can often be managed with ureteral stenting, but larger contusions with any devascularized portions of the ureter should be excised and repaired with a spatulated anastomosis over a ureteral stent [20]. Ureteral stents are left indwelling for 4–6 weeks after surgical repair and require cystoscopy for removal. Children often tolerate ureteral stents better than adults but may have significant irritative urinary symptoms, including bladder spasms manifest as dysuria or pain radiating to the penis/perineum, urinary frequency, urinary urgency, intermittent hematuria and flank pain, especially with voiding.

If the ureteral injury was not identified immediately, as is common in iatrogenic ureteral injuries, options for management are focused on controlling the urine leak. Definitive repair may be deferred, especially if the injury occurred >1 week prior, due to dense scarring. Patients with high drain output, fevers, rising creatinine, new vaginal leakage/incontinence, or a developing flank mass should be investigated for a missed ureteral injury [20]. In these cases, cystoscopy with retrograde pyelograms should be performed by a urologist to assess for the presence and degree of injury. If an injury is identified within the first 5–7 days after the initial insult, then primary repair should be considered. If recognition of the injury is more delayed then drainage should be first be attempted through ureteral stent placement. If unsuccessful, proceed to nephrostomy tube placement with plans for definitive repair in 6–8 weeks [9].

Conclusion

Traumatic renal injuries are uncommon and are typically associated with blunt abdominal injuries. The initial workup of children suspected of renal trauma should follow the primary and secondary survey of ATLS. While urinalysis can provide information regarding the presence or absence of hematuria, it is not useful in predicting the severity of the injury. Instead, it provides guidance for whether further imaging is warranted. Triphasic CT of the abdomen is the study of choice for evaluating renal trauma. Management of renal trauma has transitioned over the years to nonoperative management similar to other solid organ injuries. In a hemodynamically unstable child with radiographic findings of a large perirenal hematoma

(>4 cm) or vascular extravasation on CT, operative intervention with surgical exploration or angioembolization is warranted. Ureteral injuries, also rare, are more commonly associated with penetrating abdominal injury. Aside from surgical exploration to identify a ureteral injury, the delayed phase of the triphasic abdominal CT is the best imaging modality for identifying this injury. Management of ureteral injury is largely dependent on the location and degree of injury.

Take Home Points

- The gold standard for renal trauma imaging in the hemodynamically stable patient is the triphasic CT (CT Urogram).
- The AUA recommends non-invasive management with monitoring, bed rest, and possible transfusion for all hemodynamically stable patients regardless of injury grade.
- For hemodynamically unstable patients with radiographic findings of a large perirenal hematoma (>4 cm) or vascular extravasation on CT, surgeons should perform immediate intervention with either surgery or angioembolization.
- Ureteral injury is best identified with the delayed phase of a triphasic CT (CT Urogram).
- Management of ureteral injury is largely dependent on the location and degree of injury.

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Chapter 28
Lower Tract Genitourinary Trauma

Erik T. Grossgold and Janelle A. Fox

Abstract Management of pediatric genitourinary trauma will demonstrate many similarities to trauma in adults, with common pathways for initial diagnosis and workup, stabilization and medical and surgical management, and subsequent follow-up. However, there exists certain key differences and considerations one must take into account when caring for this unique patient population. For instance, there are certain injuries that occur more or less frequently in children than in adults, given the same traumatic mechanism. This chapter will encompass trauma to the pediatric lower genitourinary tract to include the bladder, urethra, and male and female external genitalia. Each section will cover an introduction to the specific topic, classification and diagnosis of the injuries sustained, basic management, and short and long-term follow-up for these children. This chapter will have implications for deciding on when to obtain certain diagnostic tests and imaging, as well as how best to stabilize and treat these children. This is not meant to act as a surgical instruction guide, as actual details of the individual operations involved will not be discussed. Rather, the goals of the chapter will be to introduce the reader to pediatric lower genitourinary trauma in order to aid in the correct diagnosis and disposition of these patients as they begin their journey down the road to recovery.

Keywords Bladder perforation · Bladder trauma · Urethral trauma · Genital trauma · Straddle injury · Penile injury · Scrotal trauma · Testicular rupture · Perineal trauma

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Key Concepts/Clinical Pearls

- In general, lower tract genitourinary trauma in children is managed very similarly to that in adults.
- Keys to management success include the performance of a thorough history and physical, the appropriate utilization of ancillary studies, the realization when other less common injuries lurk behind the obvious, and the proper initiation of a management plan that will optimize recovery and limit future comorbidity.
- Given the relatively high incidence of abnormal findings on genitourinary examination with child abuse and neglect, it is vitally important to accurately recognize these signs and ultimately prevent future maltreatment of these children.

Initial Management of the Trauma Patient

As in adults, when a child presents as the victim of trauma, it is vitally important to initially stabilize the patient and properly assess for any and all injury. After evaluating and correcting any life-threatening airway compromise and/or bleeding, a thorough history and physical examination, laboratory studies, and diagnostic imaging should be performed. Broad-spectrum antibiotics are usually administered, as are intravenous fluids. For any penetrating trauma, the tetanus status of the patient should be assessed. Finally, for lower tract genitourinary injuries specifically, these patients will usually require some form of bladder decompression, either via a urethral or suprapubic catheter.

Initial Radiographic/Ancillary Studies

For the most part, initial radiographic studies obtained for victims of lower tract genitourinary trauma include plain films, or preferably computed tomography (CT) scans of the abdomen and pelvis with intravenous contrast. Additionally, they may require specific studies such as cystogram (either CT or fluoroscopic), retrograde urethrogram (RUG), voiding cystourethrogram (VCUG), or scrotal ultrasound. Initial laboratory studies should include a complete blood count (CBC), lactate level, comprehensive metabolic panel (CMP) to include renal function, as well as a urinalysis if possible.

Bladder Trauma

There exist many similarities between adult and pediatric patients in terms of the diagnosis and management of bladder trauma. The bladder is fairly well protected within the bony pelvis, and when injuries do occur, they are usually associated with other significant musculoskeletal and/or multi-organ trauma [1]. Pediatric bladders, however, are more susceptible to injury than are adult bladders as they are more intra-abdominal and less protected by the bony pelvis with less retroperitoneal fat and less well-developed rectus musculature their relative intra-abdominal position compared to in adults [2, 3]. Bladder injury may result from blunt, penetrating, or iatrogenic etiologies.

Bladder injury from blunt abdominal is up to three times more common than penetrating bladder injury in both adult and pediatric populations [4, 5]. Almost 90% of pediatric patients with blunt force bladder injury will have an associated pelvic fracture. However, pelvic fracture related bladder injuries are overall less common in children, again due to anatomic differences [6–9]. Blunt bladder injury can result in contusion or rupture. Ruptures will have urinary extravasation, whereas contusions may have bladder wall thickening or intraluminal clots without extravasation. A bladder rupture will present with a different clinical picture, especially if there is a delay in diagnosis.

Any severity of bladder injury may present with suprapubic or abdominal pain, inability to urinate, and/or gross hematuria. Patients may have microhematuria. Urinary ascites associated with intraperitoneal bladder rupture may also present with dilutional hyponatremia, resorptive hyperkalemia, elevated blood urea nitrogen, and elevated creatinine, though the latter does not reflect renal failure [3]. Laboratory abnormalities are often present in children with non-accidental trauma (NAT) associated with a blunt abdominal injury. These clinical presentations can be delayed due to a lack of known mechanism of injury.

Classification and Diagnosis

Bladder injuries can be characterized as either extraperitoneal or intraperitoneal, with special consideration given to any injuries involving the bladder neck. Extraperitoneal injuries are by far the most common, making up 60–90% of cases, but it is important to note that both extra- and intraperitoneal injuries can be found simultaneously in 5–10% of patients presenting with bladder trauma [6, 7]. If bladder injury is suspected after blunt trauma, the patient should undergo bladder imaging in the form of a CT cystogram or fluoroscopic cystogram if CT is not available [10]. This is especially true should there be gross hematuria associated with a pelvic fracture or the inability to void [10, 11]. The false-negative rate of CT cystograms is much lower than fluoroscopic or plain film cystograms; hence it is preferred. A CT urogram (or triphasic CT done for evaluation of renal trauma) does not adequately stress or distend the bladder, hence does not have adequate sensitivity or specificity to diagnose bladder injuries. Proper performance of a cystogram in a child is as follows: contrast is diluted to 30% then gently irrigated through the urinary catheter into the bladder or filled at a column 40 cm water above the pubic symphysis in a retrograde fashion until bladder spasms occur, or estimated age-related bladder capacity is reached. At ages over 2 years, estimated bladder capacity (in *ml*) is calculated as follows: (age in years +2) × 30. At ages under 2 years, the following equation for bladder capacity is more accurate: 38 + (2.5 × age in months) [3].

When dealing with penetrating trauma, the bladder should be imaged specifically if the trajectory of the missile or object could have injured the bladder, or in the presence of pelvic or abdominal free fluid, suggesting urinoma or hematoma [12]. Gross hematuria does not always occur with penetrating bladder injuries, so mechanism suggesting injury is far more important when deciding to obtain bladder imaging. Bladder neck lacerations are a special situation and are almost double in children than in adults [12]. Care should be taken to avoid missing an injury of this type, given the risk of permanent urinary incontinence, pelvic abscess, and osteomyelitis [12, 13]. Even though these would be technically classified as extraperitoneal, they are treated differently (Fig. 28.1).

Management and Follow-Up

After stabilization of the patient and a thorough work-up to diagnose or rule out any concomitant injuries, the treatment of bladder lacerations varies depending on location and severity. Most extraperitoneal injuries can be safely managed with an indwelling urinary catheter, either via a suprapubic or urethral approach, for approximately 7–10 days [12]. However, if there exists a bony spicule within the bladder, or if bladder neck laceration is suspected, open surgical repair by a urologist should be considered [14]. It may also be reasonable to repair these lacerations if exploratory laparotomy is planned in order to address any other coexisting abdominal or pelvic injuries. If bladder neck laceration is suspected or found, it is important to consider the

Fig. 28.1 Fluoroscopic image showing extraluminal contrast extravasation suggestive of extraperitoneal bladder injury with possible involvement of the bladder neck

possibility of associated urethral or rectal injury, and these should be thoroughly evaluated with either a cystoscopy and/or proctoscopy at the time of bladder repair [13].

If intraperitoneal bladder injury is suspected based on imaging, open surgical exploration and repair should be pursued as it reduces potential morbidity and even mortality [15]. A transvesical approach is usually preferred, and the bladder neck should be evaluated at that time as well. The laceration should be closed in several layers if possible, and a large-bore urethral catheter should be left in place post-operatively. There is no consensus on the amount of time needed for post-operative catheterization; however, it is generally accepted that urinary drainage should be provided via a urethral catheter for at least 10–14 days after repair of an intraperitoneal rupture and obtaining a cystogram or voiding cystourethrogram (VCUG) prior to catheter removal should be considered to rule out persistent urinary leak [16].

Urethral Trauma

The etiology, diagnosis, and management of urethral trauma vary greatly between males and females due to obvious anatomic differences. We begin this section with a discussion on urethral injuries occurring in boys and conclude with the management of urethral trauma in girls. It is helpful to categorize these injuries as either posterior or anterior depending on the urethral segment affected. The posterior urethra includes everything proximal to the urogenital diaphragm, and in males consists of the membranous and prostatic urethra, as well as the bladder neck. Most posterior urethral injuries in children are the result of blunt trauma and are associated with a pelvic fracture [17–19]. Conversely, anterior urethral injuries can be the result of either blunt or penetrating trauma, and important consideration should be given to iatrogenic causes such as circumcision, instrumentation, and due to reconstructive surgery for other congenital abnormalities [20–22] (Fig. 28.2). A key

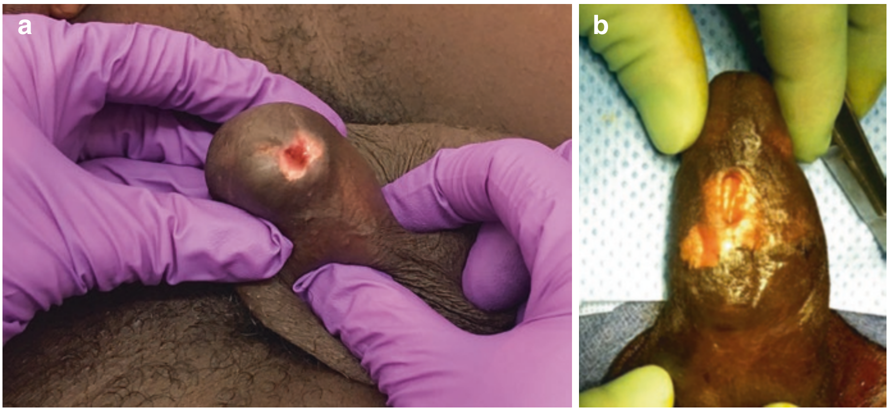

Fig. 28.2 Partial glans amputation (**a**) and urethrocutaneous fistula (**b**) from machete freehand circumcisions in a sub-Saharan African country. (Photos courtesy of Dr. Janelle Fox and Dr. David Vandersteen)

difference between urethral injuries in children compared to adults is the greater likelihood of the urethral laceration extending through the external urinary sphincter and into the anterior bladder neck. This can be properly assessed with preoperative imaging and addressed in the operative room at the time of definitive repair [13] (Fig. 28.3).

Classification and Diagnosis

As previously stated, urethral injuries in boys are generally classified as either anterior or posterior, and caused by either blunt, penetrating, or iatrogenic trauma. A careful history of the mechanism of injury should be obtained; straddle injuries, perineal impalement, abdominopelvic crush injuries, or pelvic trauma resulting in pubic symphysis diastasis, pubic rami fracture, or sacroiliac joint fracture should raise the index of suspicion for urethral injury. Imaging should be obtained whenever there is the presence of blood at the meatus, inability to void, perineal hematoma, complicated pelvic fracture involving the pubic rami, or if there is suspicion for bladder neck injury [22]. The gold standard test is a retrograde urethrogram (RUG). If a catheter has already been inserted into the bladder, a VCUG should be performed to rule out urinary extravasation.

In general, there is a high association between pediatric posterior urethral injuries and pelvic fracture, and they result from the shearing and/or disruption of the prostatic and membranous urethra from the perineal membrane [2, 7, 8]. This has the potential to displace the prostate and bladder neck off the pelvic floor, which carries a high risk of subsequent urinary incontinence, urethral stenosis, and erectile dysfunction [19]. Index of suspicion for pelvic fracture urethral injury (PFUI) is higher for multiple fractures of the pubic rami with separation of the pubic symphysis, as the presence of these findings raises the overall risk for concomitant urethral injury [23].

Fig. 28.3 Retrograde urethrogram demonstrating pelvic fracture urethral injury with separation of the prostatic and membranous urethra from the bulbar urethra

Management and Follow Up: Posterior Urethra

After stabilization and assessment for associated injuries, initial treatment for PFUI includes bladder drainage via suprapubic catheter, pain control, and broad-spectrum antibiotics [23]. The options for management after this include primary endoscopic and/or anastomotic realignment versus delayed or late urethroplasty. There exists much debate in the literature for both children and adults regarding the superiority of one pathway over the other, as there is a relative paucity of high-quality, randomized clinical trials to help answer this question [24]. Advocates for primary realignment state patients will have a lower incidence of subsequent stricture formation while allowing the patient to return to a normal quality of life with normal voiding in a timelier manner [25, 26]. Conversely, critics of this method claim that these patients will ultimately undergo more procedures due to stenosis recurrence, may have increased stenosis complexity, and will have a prolonged clinical course with the potential for delayed definitive care [27–29]. In addition, not all injuries, especially those with complete transection and distraction, are amenable to primary realignment, so this cannot be counted upon when performing preoperative consent. Realignment, if performed, should be done within 10 days after the initial urethral injury. Post-realignment urethral catheterization is typically recommended for at least 2–3 weeks for partial injuries and 6 weeks for complete transections [26]. Regardless of the strategy used, the management of these patients can be complex, and surgery should be performed by urologists with advanced reconstructive training.

If suprapubic drainage without primary realignment is performed, definitive repair of the resultant stricture should wait at least 3–6 months for urethral rest and scar maturity [3, 12]. Following definitive repair with scar excision and anastomotic urethroplasty, patients are left with a urethral catheter for approximately 3 weeks, and we routinely ensure a watertight anastomosis before catheter removal by performing a pericatheter retrograde urethrogram and/or VCUG at surgeon discretion. Sustainment of patency must be closely monitored. Since children require an anesthetic for direct visualization of the urethra with cystoscopy, we recommend uroflowmetry at 6 weeks post reconstruction as a baseline, then VCUG and/or cystoscopy at 3–6 months post-operatively, given children have difficulty providing a history of alterations to their voiding pattern. We recommend 5 years of long-term follow-up with periodic uroflowmetry. Post-urethroplasty surveillance regimens are anecdotal in children, but success rates are high. Concerns for blunting of the uroflow curve, weakening urine stream, straining to void, or urinary tract infection should prompt a VCUG or direct urethral visualization with cystoscopy to evaluate for stricture recurrence. Although dependent on multiple confounding factors, long-term success, erectile dysfunction, and urinary incontinence rates have been reported as 85–91%, 5–37%, and 4–13%, respectively [30–32].

Management and Follow-Up: Anterior Urethra

Injuries to the anterior urethra can be the result of blunt, penetrating, or iatrogenic trauma, and the management of these is highly dependent on the location and mechanism of injury. Segments involved can include the bulbar and penile urethra, fossa navicularis, and meatus, and oftentimes are accompanied by significant external genital injuries. Similar to the posterior urethra, trauma to the anterior urethra can be repaired either immediately after the injury or in a delayed fashion as long as bladder drainage can be adequately established.

Patients suspected of having urethral injury secondary to perineal or straddle trauma may present with perineal and scrotal ecchymosis and hematoma, as well as blood at the meatus and inability to void [22]. These patients should undergo an examination under anesthesia, and after confirmation of urethral injury via urethrography or urethroscopy, urethral continuity should be reestablished by placing a urethral catheter past the defect and into the bladder under endoscopic or fluoroscopic guidance [23]. Urethral catheterization is maintained for up to 3 weeks, and urethrography is performed prior to catheter removal to ensure complete healing. They are then followed with subsequent uroflowmetry beginning at 6 weeks, then with VCUG or cystoscopy at 3–6 months post-op, then periodically with uroflowmetry and/or history should they develop obstructive symptoms. Again, we recommend periodic follow-up for 5 years.

If a traumatic stricture is diagnosed in follow-up, they will undergo delayed urethroplasty utilizing either an anastomotic or substitution technique depending on characteristics of the stricture. If, however, the urethra is completely disrupted at the time of initial injury and no lumen can be identified, the bladder should be decompressed with either a suprapubic catheter or vesicostomy, and the patient will undergo delayed urethroplasty after at least 3 months of urethral rest [12]. For patients treated with delayed urethroplasty, we typically wait until the child is at least 1 year of age, or at least 3 months have passed since injury before planning for reconstruction. When possible, retrograde and voiding urethrography are performed in order to accurately assess the caliber, length, and location of the stricture.

Pediatric surgeons may be called to assess and manage iatrogenic urethral injuries. These injuries can occur as the result of urethral instrumentation, circumcision, and during surgery for other congenital abnormalities such as hypospadias or low imperforate anus with rectobulbar fistula [20–22]. These are treated in a similar fashion to other injuries caused by penetrating and blunt trauma, in that an initial attempt can be made to establish urethral continuity with urethral catheterization and/or primary repair if complete disruption is not identified [32]. Specifically, newborn and pediatric circumcision can result in injury to the meatus, fossa navicularis, and/or distal penile urethra, and it can also present as delayed urethrocutaneous fistula secondary to ischemic necrosis [33]. The specific site of injury is somewhat dependent on the technique used to perform the circumcision. Gomco clamps best protect the glans and urethra with the majority of complications arising from adhesions or skin bridges. Mogen clamps run the highest risk of penile amputation injuries, ranging from a portion of the glans to the entire phallus [34, 35]. It is thought that inadequate release of physiologic preputial adhesions with their persistent attachment to the glans results in amputation injuries with this technique. Plastibell circumcision complications are typically the result of ischemia and necrosis from a Plastibell ring left on too long. The location of ischemia results in complications ranging from permanent grooves or impression in the glans, an "hourglass" deformity of the penis due to corporal body ischemia, penile or glans necrosis and auto-amputation, urethrocutaneous fistula, necrotizing fasciitis, even urosepsis and bladder perforation from urinary retention [36–38]. Finally, ritual "freehand" circumcision in many low-and-middle income countries involves a simple knife or blade with intussusception of the foreskin over the glans. Late complications of this technique seen on humanitarian surgical missions by the authors include partial glans amputation with meatal stenosis, as well as infection with resultant urethrocutaneous fistula.

Direct injury to the meatus and distal urethra can be repaired primarily if feasible by debriding any non-viable tissue and attempting to reconstruct the meatus, glans, and distal urethra as needed [39]. However, if a primary repair cannot be safely accomplished, temporary bladder drainage with a suprapubic tube or vesicostomy can again be performed with a plan for delayed or staged urethral and glans reconstruction. Urethrocutaneous fistula is repaired in either a single- or multi-stage operation, depending on size and scarring, and may require tissue substitution depending on the viability of the urethral plate.

Female Urethral Trauma

Urethral injuries in girls are relatively rare and are usually associated with blunt trauma and concomitant pelvic fracture [19, 40]. Although rare, these injuries can be devastating, with the potential for significant complications and comorbidities in the future. Most of the current literature consists of small case series and retrospective reviews, and as a result, definitive guidelines cannot be determined. However, for a female patient with significant pelvic trauma and fracture of the pubic rami, a few key points must be made. First, assessment should be conducted to document the presence or absence of blood at the vaginal introitus and/or rectal vault, as injuries to these structures can be an indicator of coexisting urethral laceration or disruption [41]. In these circumstances, consideration should be given to perform a cystoscopy, vaginoscopy, and/or proctoscopy at the time of EUA [42]. Second, one must also consider extension of the injury into the bladder neck and bladder fundus, given the association between pelvic fracture and bladder injury [6–9]. Finally, if an injury to other pelvic organs coexists with a proximal urethral disruption or laceration, it is reasonable to perform primary anastomotic reconstruction of the urethra at the time of repair of the other injured structures, especially with bladder neck involvement [41, 43]. Ultimately, however, there exists a significant risk of stress urinary incontinence with bladder neck lacerations, with the potential need to perform permanent urinary diversion for patients with complications from these devastating injuries [12].

Perineal or straddle trauma causing either partial or complete urethral disruption in girls can also occur, especially with falls, motor vehicle accidents, and sports and bicycle-related injuries [44, 45]. Once an associated vaginal injury has been ruled out, these are generally treated in the same way as they are in boys. Additionally, the presence of perineal and subsequent urethral trauma in especially young girls with or without vaginal injury should raise concern for sexual abuse [44].

Genital Trauma

Pediatric external genital trauma is relatively common and collectively can account for almost 60–80% of all pediatric genitourinary trauma [46, 47]. For the purpose of this chapter, we define trauma of the male genitalia as involving the penis, scrotum, and testicles, and that of girls as the labia, vulva, and vagina. Taken collectively, girls and boys can be equally affected, although this may vary with age, as older boys generally have a higher incidence than younger girls [46]. Common sources of pediatric genital trauma include bicycles, toilet seats, zippers, climbing and playground equipment, sports equipment, falls, hair tourniquets, iatrogenic causes such as circumcision, and sexual abuse [47, 48]. Finally, there undoubtedly exists an overlap between genital and urethral injuries, a consideration that must be made when assessing these patients.

Male Genital Trauma

Injuries of the pediatric male genital organs to include the penis, scrotum, and scrotal contents, can be caused by penetrating, blunt, and iatrogenic trauma (Fig. 28.4). As previously stated, a concomitant urethral injury must be ruled out in the setting of significant penoscrotal trauma, given the high concurrence rate with both penetrating and blunt trauma [48]. Hence, a urinalysis should evaluate for microhematuria. If positive, or the child is unable to void, a retrograde urethrogram is the next step. For trauma involving the penis and scrotum, it is important to also consider possible testicular involvement and evaluate the testes with a scrotal ultrasound with Doppler flow. If suspected due to significant scrotal swelling, testicular tenderness on exam, or based on ultrasound findings of hematocele, testicular contusion, or rupture of tunica albuginea, the patient should be surgically explored [49]. Surgical exploration is also mandatory for any penetrating injuries of the penis or scrotum in which there is a concern for corporal body or urethral involvement, or significant tissue loss or contamination [50]. Broad-spectrum antibiotics should be administered, and tetanus immunization status should be assessed and updated if necessary. These wounds can

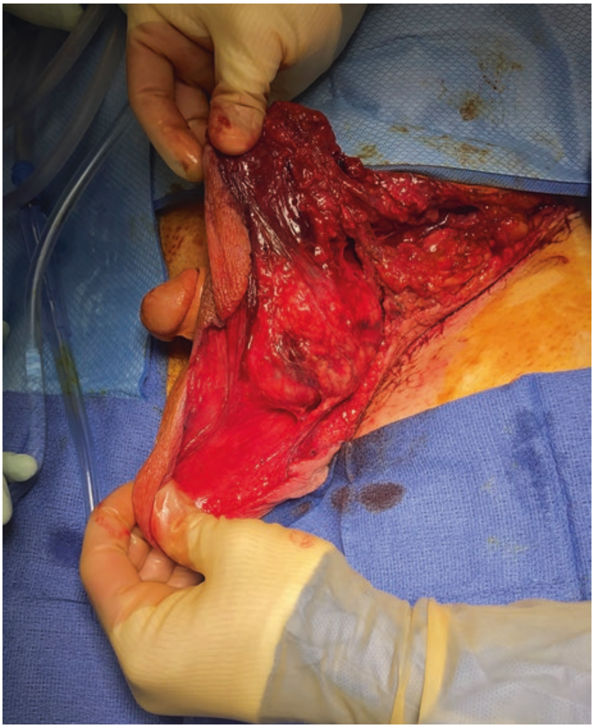

Fig. 28.4 Complex scrotal and inguinal laceration secondary to fall onto a fence. Note that injury to the urethra, corporal bodies, and/or testicles must be ruled out at time of exploration given the high likelihood of involvement of these structures. (Photo courtesy of Dr. Erik Grossgold)

be complex depending on the mechanism of injury, and the surgeon should perform a thorough EUA, wound washout and debridement of devitalized tissue, and skin closure if feasible. Based on the author's experience, localizing small missile fragments such as bullets or foreign bodies can be difficult as the trajectory of entry does not follow a straight plain in the Dartos layers of the scrotum. Using intraoperative ultrasound or fluoroscopy can assist in finding relatively small or deep foreign bodies.

Iatrogenic penile injuries are most commonly caused by neonatal and pediatric circumcision. These can be quite problematic and occur in up to 2% of cases, depending on the technique utilized [51]. If there is excessive skin loss during circumcision, most patients will do well with antibiotic ointment application and healing by secondary intent. However, if the penis is completely degloved, they may need subsequent skin grafting depending on the amount of tissue lost and would benefit from urologic consultation [48]. The foreskin, when still available, provides the best graft option even when used as a full-thickness free graft, though thick split-thickness skin grafts (STSGs) and full-thickness, defatted and minimal hair-bearing skin grafts (FTSGs) from other sites, like the groin, may also be used [52]. This technique is particularly helpful with traumatic degloving injuries, such as lawnmower accidents. Glans or urethral injury caused by circumcision should be primarily repaired if possible [39, 48]. Glans amputations must be reattached immediately, with the amputated specimen placed in chilled moist gauze (but not directly on ice). Primary urethral repair is performed with urethral catheterization to divert urine from extravasating into tissues as well prophylactic antibiotics until there is good graft take, which may be at least 2–3 weeks [53]. More proximal penile amputations warrant microvascular reattachment of the dorsal arteries, veins, and nerves and it may require leech therapy or a spongiosa cavernosal “Winter” shunt to improve venous congestion and ischemia post-replantation [34, 54]. Children appear to have better long-term sensation, penile function, and graft take than adults with penile amputations.

It is important to note that penile trauma in prepubertal children should not result in a penile fracture. In prepubertal patients, penile bruising after trauma usually indicates injury to the superficial dorsal vein or penile skin only and is managed with supportive care. Post-pubertal adolescents and men must sustain forced bending during erection to result in penile fracture, resulting in a “pop” and immediate detumescence. Most of these injuries occur during intercourse though an accurate patient history is not always forthcoming. For post-pubertal males, the “eggplant” deformity of the phallus should prompt workup with penile ultrasound evaluating for corporal disruption, and urinalysis to evaluate for microhematuria and concomitant urethral injury. Operative repair of the corporal and/or urethral defect by a urologist is always warranted. Rare case reports do exist of older school-age and adolescent boys with penile fracture following a fall, so if the clinical picture suggests (i.e., disproportionate penile and scrotal swelling, eggplant deformity), a penile ultrasound and/or exploration by a urologist are warranted [55, 56].

Female Genital Trauma

Trauma to the labia, vulva, and vagina can be the result of a fall, sporting activities, or abuse, and can also include both penetrating and blunt mechanisms [12]. Vaginal injury is the most common, and most often requires surgical repair [57]. As with boys, it is vital to assess for and rule out concomitant injury to the urethra and rectum in girls presenting with genital trauma. Patients with significant injuries should be completely assessed and treated in the operating room if an adequate evaluation cannot be made in the emergency department with or without sedation [58]. Repair of simple lacerations to the labia and/or vulva can be safely performed in the emergency department if adequate sedation or analgesia is provided [59].

Pediatric Genital Trauma and Abuse

Child abuse and neglect is unfortunately much too common and represents a significant public health and financial burden, not only in the United States, but in many other countries as well [60]. This has dramatic implications for the overall health of the child as they progress into adolescence and adulthood, and has the potential to affect them for the remainder of their lives. For both boys and girls, when injuries to external genitalia are found, one must consider the possibility of abuse, as the finding of such injuries can be seen in almost a quarter of victims of sexual and non-sexual abuse [61]. It is paramount to the safety of these children to be able to know normal variations in anatomy and then to be able to recognize anything which may appear abnormal to suggest the possibility of abuse [62]. Even after treatment of the genitourinary injury, abuse victims report higher rates of genitourinary dysfunction and incontinence compared with controls. Symptoms of incontinence after sexual abuse can be functional, resulting from voiding dysfunction or voluntary holding behaviors, or anatomic, resulting from urethral trauma. Though beyond the scope of this chapter, guidelines have been published by a consensus panel for the thorough evaluation of the child with suspected sexual abuse [63].

Conclusions and Take Home Points

- The diagnosis and management of pediatric lower tract genitourinary trauma are very similar to that in adults and require a careful history and physical with adequate laboratory and imaging studies to ensure all concomitant injuries are recognized and addressed.
- Bladder decompression with either a urethral or suprapubic catheter is usually the first step in management for patients with lower tract genitourinary trauma.
- Prompt urologic consultation should be pursued when suspicion exists for lower tract genitourinary trauma.
- Careful consideration should be given for the possibility of underlying abuse for children presenting with external genitourinary trauma.

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Chapter 29
Pediatric Hip and Pelvis Trauma

James M. Harrison, Eric D. Shirley, and Vanna J. Rocchi

Abstract The intention of this chapter is to give the non-orthopedic surgeon healthcare provider the understanding, skills, management pearls and pitfalls to acutely manage pediatric hip and pelvic trauma. This chapter will give insight to provide reliable and effective management of these injuries and help guide when to consult the orthopedic surgeon for definitive treatment. It is meant as a river guide and reference to the white waters of pediatric hip and pelvic trauma, which can be treacherous and ever changing.

Keywords Trauma · Orthopedic injury · Pelvis fracture · Reduction

Key Concepts
- The amount of energy required to cause pediatric hip and pelvic trauma is significantly greater than the lower energy injuries of elderly hip fractures due to differences in bone density.
- Pediatric periosteum is also much thicker and often remains intact on the compression side of the bone, which allows for less displacement and better reduction of fractures.
- In the setting of pedestrian versus vehicle, the pattern of injury can be predicted by the age and height of the child as they are struck by the moving vehicle. This "bumper injury" typically strikes the hip and pelvis of a 6–8 year-old child
- Up to 50% of pelvis fractures have associated musculoskeletal or visceral injury.
- Suspicion for the need for transfusion should be high in the setting of a pelvis or hip fracture.

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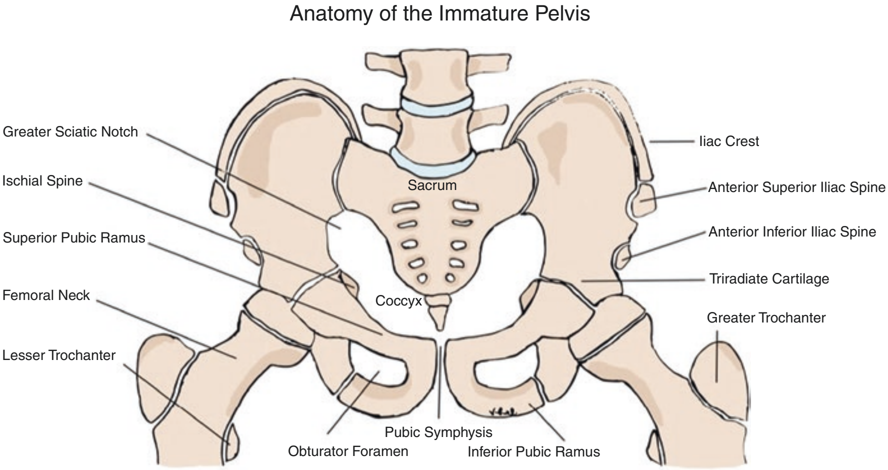

Fig. 29.1 Line drawing of the immature pelvis, detailing various physes visible (though not all always visible at the same time)

Pertinent Anatomy

The pelvic anatomy of pediatric patients is like that of adults, with the most obvious difference involving growth plates or physes. The pediatric skeleton has increased cartilaginous volume, which leads to increased plasticity and elasticity. The pediatric periosteum is also much thicker and often remains intact on the compression side of the bone, which allows for less displacement and better reduction of fractures [1–4]. These characteristics provide a greater capacity to absorb energy than in adults [4–6]. Fractures through the physis can be difficult to diagnose because they often don't appear on radiographs [5]. These characteristics contribute to specific patterns of injury which can be unique to pediatric patients. A skeletally immature pelvis is detailed in Fig. 29.1.

Mechanism of Injury

To understand pediatric hip and pelvis trauma, we need to consider energy. The amount of energy required to cause pediatric hip and pelvic trauma is significantly greater than the lower energy injuries of elderly hip fractures due to differences in bone density. The most common mechanisms of polytrauma are falls from height, with the majority from two stories or less, at or near home, and motor vehicle accidents, whether the patient is a passenger or a pedestrian [2, 5].

When a trauma alert activates for a child involved in a motor vehicle accident, there must be a high clinical suspicion for pelvic trauma. In the setting of

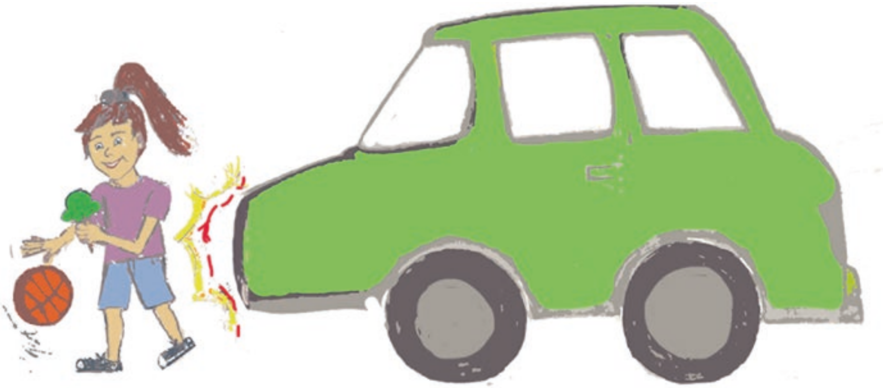

Fig. 29.2 Comic showing the typical "bumper injury", which strikes the hip and pelvis of a 6–8 year old child, or more distally in a taller adolescent

pedestrian versus vehicle, the pattern of injury can be predicted by the age and height of the child as they are struck by the moving vehicle. This "bumper injury" typically strikes the hip and pelvis of a 6–8 year-old child, demonstrated in Fig. 29.2 [5]. Because of their smaller size, children can more quickly become projectiles after collision, with additional injuries caused after a second impact. The direction the child is facing during a collision predicts the pattern of injury. A child who is struck by an ice cream truck, for example, often results in a left-sided pelvis injury, as this is the side more commonly toward oncoming traffic [7]. Children are also more likely to be trapped underneath a moving vehicle, making them more prone to crush injuries with associated severe soft tissue damage.

These are important factors to consider as the child is on the way into the trauma bay.

Initial Exam

Upon initial evaluation, the importance of a thorough ATLS survey cannot be stressed enough. Secondary and tertiary surveys evaluate for associated orthopedic and non-orthopedic injuries and can be lifesaving. Examination includes inspection of the skin for scrapes, open wounds, bruising or deformity. Noting the position of the lower extremities can help identify a hip injury. Palpatory exam of the pelvis and hips can guide radiographic workup, as areas of pain or crepitus may indicate an underlying fracture. It is also important to evaluate the motion of the hips. Asymmetry or a block to motion warrants further investigation. Musculoskeletal injuries are common in children, with 40% of boys and 25% of girls sustaining a fracture by 16 years of age [8]. These injuries need to be addressed and documented for appropriate management with consulting teams.

Associated Injuries

Up to 50% of pelvis fractures have associated musculoskeletal or visceral injury [2]. There must be a high index of suspicion for these injuries when dealing with high-energy trauma. A thorough ATLS survey covering head, neurologic, vascular, gastrointestinal, and genitourinary systems must be completed to evaluate for other signs of injury. If suspected, these injuries need to be worked up with adjunct studies. Do a thorough head-to-toe survey that documents injuries for future management. It is common to miss other minor injuries when there are life-threatening problems managed in the trauma bay. Not checking for blood in the urethral meatus or foregoing a rectal exam that reveals blood in the rectal vault could result in missing a urethral injury or open fracture [1, 9].

Pediatric patients can remain hemodynamically stable in the setting of significant blood loss. Suspicion for the need for resuscitation should be high in the setting of a pelvis or hip fracture. Intravenous (IV) access should be obtained quickly, but if there is significant difficulty obtaining IV access, intraosseous infusion may be required. The starting bolus consists of crystalloid fluid at 20 mL/kg. If after the initial bolus the patient remains hypotensive, then blood transfusion should be considered at a rate of 10 mL/kg. Total pediatric blood volume is estimated to be 75–80 mL/kg [2]. In cases of high-energy trauma, the clinician needs to be aware of potential spaces for blood loss. ATLS and PALS courses teach that the chest, abdomen, pelvis, and thigh can be spaces for blood to invade. Pelvic fractures can open the pelvis and create a bigger potential space for blood to accumulate. A simple, yet life-saving measure can be implemented to bind the pelvis and close that potential space, described below.

How to apply a pelvic binder with a sheet and 4 Kocher clamps:

- Fold the sheet in half ×2
- Place on the ground
- Roll both ends inward towards the midline
- Palpate the greater trochanters bilaterally
- Place the rolled sheet next to the patient, centered at the greater trochanters
- Log roll the patient
- Push one end of the rolled sheet under
- Pull the end of the sheet over the patient while an assistant holds the other end against the pelvis
- Tighten sheet
- Clamp Kocher clamps on the corners
- Take XR to confirm closure of pelvis

The binder goes around greater trochanters, with force propagation through femoral heads into acetabulae to close the pelvis. It should not be placed around the abdomen/pelvis, as this won't decrease space for blood accumulation. Leaving an open book pelvis without a binder (or external fixator) can result in uncontrolled hemorrhage and hemodynamic instability.

Pelvic Ring Injuries

Fortunately, pelvic ring fractures in children are uncommon, and as previously stated, the result of high-energy trauma [5, 10–12]. Nondisplaced, simple pelvic fractures have low morbidity and mortality rates and are less associated with other injuries [5]. Young patients with open triradiate cartilage are more likely to sustain pubic rami and iliac wing fractures [13, 14]. Closed triradiate cartilage in older patients is more associated with acetabular fractures and pubic/sacroiliac diastasis, which is secondary to an immature pelvis, where the bony anatomy is weaker than the elastic pelvic ligaments [10]. After the triradiate cartilage is closed, the pelvic bones are stronger than the ligaments; thus fracture is then more common [13, 14].

What to look for: Asymmetry, open book pelvis (diastasis of the pubic symphysis), cartilage avulsion, plastic deformity.

What to do: Pelvic binder, radiographs of bone and joint above/below or joint affected with correlating x-rays of bone above/below.

When to consult: Urgent—any pelvic ring fracture warrants ortho consultation, more acute if unstable.

Acetabular Fractures

Fractures of the acetabulum in children are very rare. There needs to be a very high energy mechanism, and these are seen with separation through the triradiate cartilage [1]. If these fractures are displaced, they often require advanced imaging and subsequent operative reduction and fixation by the orthopedic surgeon [15].

What to look for: Joint malalignment with high energy injury.

What to do: Stabilize patient and consult orthopedics.

When to consult: Urgent consultation to orthopedic surgery.

Hip Dislocation

Traumatic hip dislocation most commonly occurs after the age of 6 years-old, secondary to high energy mechanisms. They are more common than hip fractures in the immature patient [2]. Hip dislocations require emergent treatment with reduction and subsequent advanced imaging [16, 17]. The longer the hip is dislocated, the higher the risk for avascular necrosis (AVN) of the femoral head, which can result in premature arthritis with pain and stiffness. Gentle reduction under sedation is required, but care must be taken in the immature hip to avoid causing an injury to the femoral head physis [16].

The reduction maneuver depends on the direction of dislocation. There are three vectors of dislocation, anterior, posterior, and through the obturator foramen.

Figure 29.3 depicts dislocation types. Regardless of type, a post-reduction X-ray is required to confirm reduction. Figure 29.4 shows the injury radiograph, post-reduction radiograph and subsequent CT scan of an obturator dislocation in a teenager. Advanced imaging with a CT or MRI is then necessary to confirm congruent reduction and assess for intra-articular fragments and/or marginal impaction [18, 19]. Not obtaining a post-reduction CT or MRI can miss intra-articular fragments that require operative management [15].

Reduction Maneuvers

Anterior/Obturator Dislocation

- Sedation with muscle relaxation
- C-arm or radiology is available
- **Pull the leg in extension**
- **Then abduction**
- **Then internal rotation**
- When the hip is reduced, the femoral head should glide smoothly with range of motion.

Posterior Dislocation

- Sedation with muscle relaxation
- C-arm or radiology is available
- **Flex the hip and the knee to approximately 90 degrees each**
- **Pull traction**
- **Then external rotation**
- When the hip is reduced, the femoral head should glide smoothly with range of motion.

What to look for: Joint malalignment, lower extremity positioned in flexion and external rotation or extension internal rotation.

What to do: Needs ASAP reduction. If growth plates are open, requires consultation prior to reduction attempt given the risk for physeal injury with reduction maneuvers.

When to consult: As soon as the dislocation is diagnosed. Urgent consultation and reduction have been shown to reduce the risk of avascular necrosis.

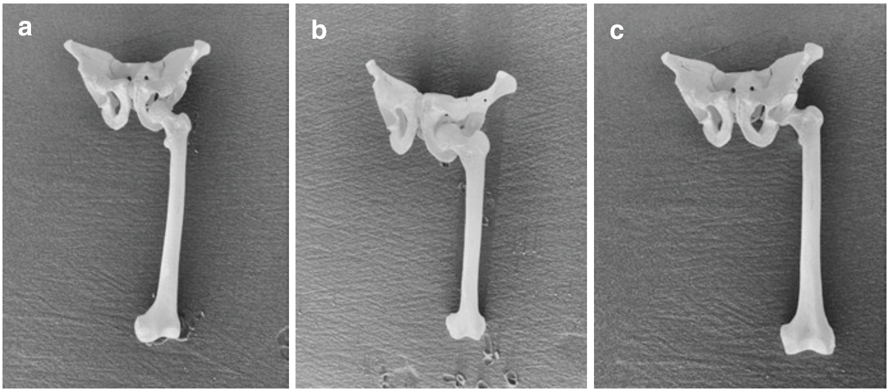

Fig. 29.3 Photographs showing an (**a**) Anterior Dislocation, (**b**) Obturator Dislocation, and (**c**) Posterior Dislocation

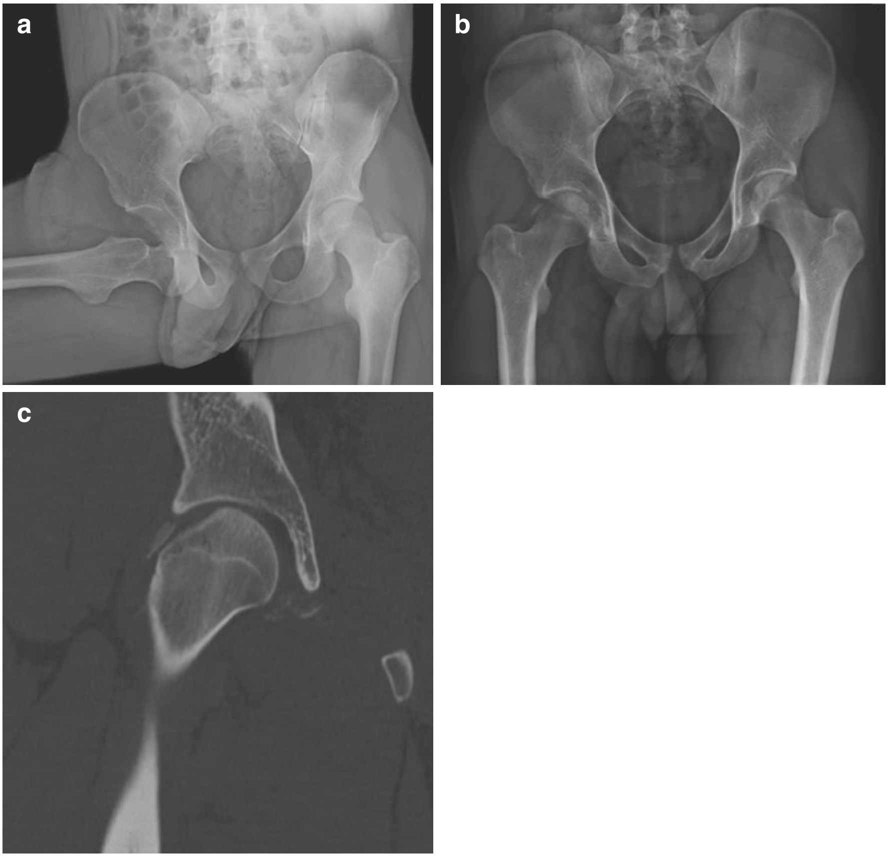

Fig. 29.4 (**a**) The injury AP pelvis XR of a teenager with an obturator dislocation, (**b**) AP pelvis XR after reduction, and (**c**) CT scan showing intra-articular body from shear fragment off the weight-bearing dome of the femoral head

Proximal Femoral Fractures

Proximal femur fractures are also rare in the pediatric population, with the vast majority (75–80%) secondary to very high energy trauma [2]. Femoral neck fractures, including transphyseal, transcervical and basal neck patterns, should be treated in under 24 h, with open reduction and internal fixation, to help decrease the risk of avascular necrosis. Examples of these fractures are seen in the radiographs shown in Fig. 29.5 [20–23]. These injuries carry the risk of serious complications and potential for long term disability if not treated appropriately. The peak incidence is between 10–13 years of age with a higher prevalence in males. Long-term complications include pain and disability that are secondary to osteonecrosis, coxa valga, nonunion and proximal femoral physeal arrest, which can occur in up to 50% of patients [22]. Proximal femoral fracture types can be seen in Fig. 29.6. The initial evaluating provider must understand the urgency of diagnosis and treatment of these fractures to decrease the risk for potentially devastating complications.

The presentation of these injuries, as stated earlier, is due to high energy trauma. The clinician must have a high suspicion for concomitant injuries to the head, chest, abdomen, hip fracture or femur fracture. The evaluating team is paramount to identifying life-threatening non-musculoskeletal injuries as well as doing a thorough secondary survey to identify other associated orthopedic injuries. Missed femoral neck fractures can have devastating complications, with AVN rates up to 100% when the fracture is at or close to the physis. Appropriate imaging orders are

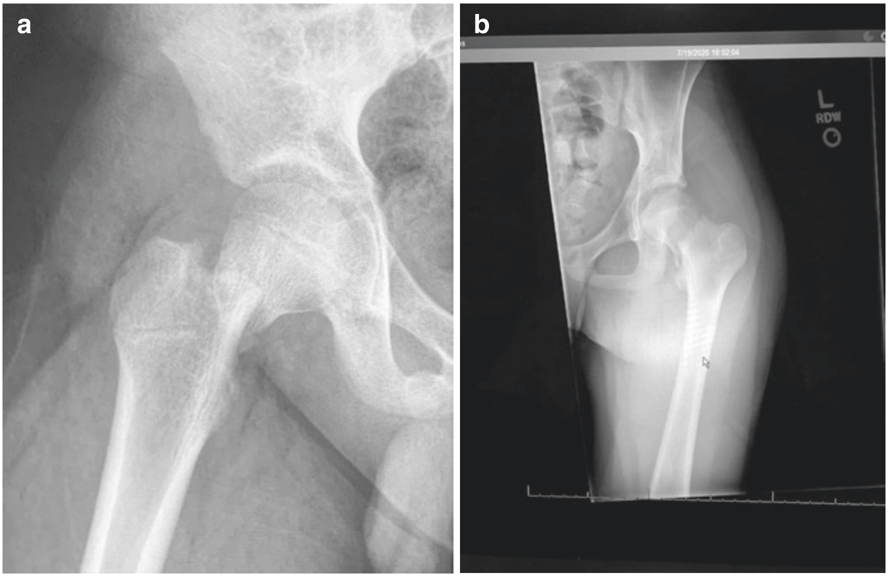

Fig. 29.5 Displaced femoral neck fracture examples in the right hip (**a**) and the left hip (**b**). These would require urgent reduction and fixation in the operating room

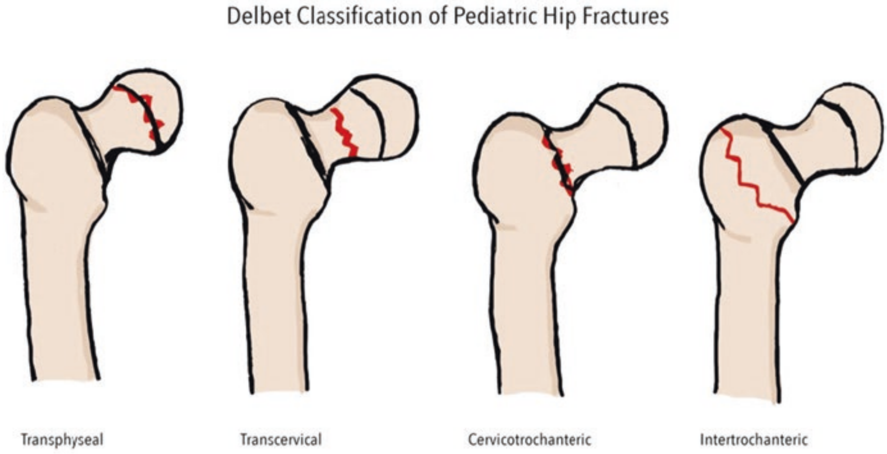

Fig. 29.6 Proximal femur fracture types based on the Delbet classification of pediatric hip fractures. Transphyseal fractures traverse the physis. Transcervical fractures are through the neck of the femur and are intra-articular. Cervicotrochanteric fractures, or basicervical fractures, are at the base of the femoral neck. Intertrochanteric fractures are between or involving the greater trochanter and lesser trochanter of the proximal femur

paramount as ordering frog-leg lateral radiographs instead of cross-table lateral x-rays can displace the fracture further.

What to look for: Inability to weight bear with a shortened, externally rotated lower extremity.

What to do: XR hip (AP and cross-table lateral), pelvis and femur.

When to consult: Urgent orthopedic consultation. Femoral neck fractures should have fixation within 24 h to optimize outcome and decrease the risk of AVN [22, 23].

Avulsion Fractures

Certain fractures surrounding the pelvis can be avulsion fractures where the bone fails, often through the weaker physis, before the tendon bone interface. Apophyseal injuries occur when the sudden force of a muscle contraction causes failure through the developing physis rather than through the relatively stronger tendon, typically during sprinting, jumping or kicking a ball [24]. These fractures are typically non-displaced and stable. Figure 29.7 shows expected extremity positions for apopyseal injuries of the pelvis. The vast majority are treated conservatively with activity and weight bearing as tolerated, using crutches as needed.

What to look for: Mechanism secondary to sports injury with avulsion fracture seen on the radiographs.

What to do: XR pelvis, management includes activity and weight-bearing restrictions.

When to consult: Outpatient consult to orthopedics.

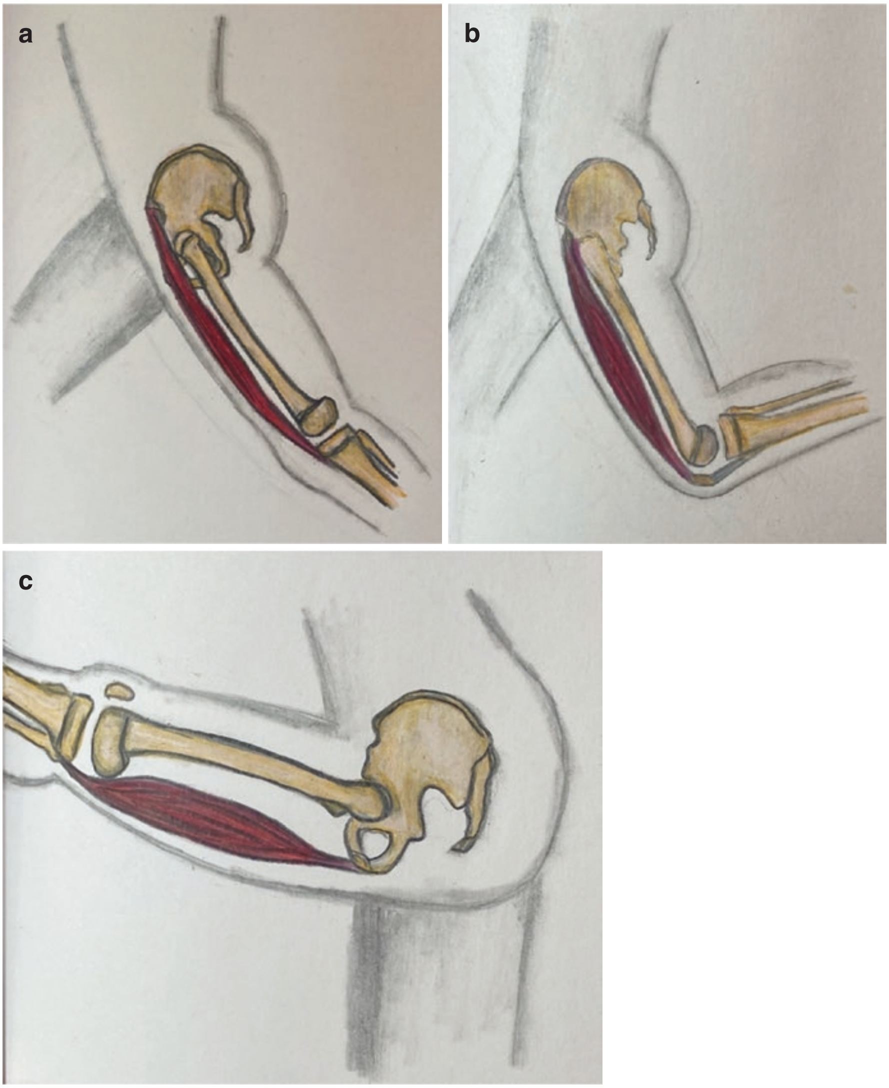

Fig. 29.7 Avulsion fractures about the pelvis are caused by eccentric load of a major tendon:origin, depicted in (**a**) sartorius:ASIS, (**b**) rectus femoris:AIIS, (**c**) hamstrings:ischial tuberosity

Outcomes

The outcomes of pediatric pelvis and hip trauma are often difficult to predict. Pediatric fractures have the capacity to quickly heal, remodel, and overgrow, but they can also shorten or deform if the physis is injured. Morbidity secondary to musculoskeletal trauma is common; thus long-term follow-up is essential [5]. It is of vital importance to recognize these injuries in a timely manner with a thorough exam and high clinical suspicion, given the energy of the injury. Adverse long-term outcomes can be high with injuries to the hip and pelvis, so appropriate and timely management is key to giving the patient the best clinical outcome.

Conclusion and Take Home Points

Pelvic fractures in children are typically due to mechanisms that exert significant force on the pelvic ring such as a pedestrian struck by a motor vehicle. The ATLS primary and secondary surveys are stressed even more to ensure that there is no missed injury as up to half of all pelvic fractures in children have an associated musculoskeletal or visceral injury. Additionally, the pelvis can hold a significant volume of blood, and children can exsanguinate due to a missed or untreated pelvic injury. Placement of a pelvic binder as described in this manuscript can be a life-saving measure and tamponade the hemorrhage associated with pelvic injuries. Identification of the pelvic injury radiographically can assist with appropriate reduction and treatment modalities. Emergent or urgent orthopedic consultation is indicated for the vast majority of pelvic injuries in the pediatric patient to ensure the best clinical outcomes.

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Chapter 30
Pediatric Extremity Injuries

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Abstract Skeletal extremity injury is a primary aspect of pediatric trauma. The intention of this chapter is to give the non-orthopedic surgeon, initial evaluating physician or healthcare provider insights into management, pearls and pitfalls for pediatric extremity trauma. We aim to provide a strategic plan for timely recognition of such injuries, obtain appropriate imaging studies, and deliver effective initial management prior to consultation with the orthopedic surgeon who provides definitive management.

Keywords Trauma · Extremity injury · Fracture · Dislocation

Key Concepts

- Mechanism of injury is important to understand the energy involved, predict fracture patterns, and guide subsequent workup and treatment.
- Children who are victims of child abuse may present with extremity fractures. Fractures in different stages of healing, long bone fractures, posterior rib fractures, metaphyseal corner fractures are suggestive of child abuse and should prompt further workup.
- Clavicular fractures are the most common fracture of the extremity in pediatric patients. The majority of these can be treated non-operatively unless there is evidence of a neurovascular compromise or skin breakdown.
- Examining the wrist and elbow can help rule out concomitant adjacent joint injury - radial head dislocation in Monteggia injuries and DRUJ instability in Galeazzi injuries.
- The 3 A's: Anxiety, Agitation, increasing Analgesic requirement, especially in a non-verbal pediatric patient, should prompt further evaluation for an underlying compartment syndrome in an extremity fracture.

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Mechanism of Injury

The mechanism of injury is important to help understand the energy involved in the fracture. Most extremity fractures are secondary to low-energy falls [1]. Fortunately, high-energy injuries are less common in children, but when trauma occurs, it is often caused by motor vehicle collisions or lawnmower accidents [1–3]. Understanding the mechanism of injury helps guide subsequent work-up and treatment.

Initial Exam

Most children will be able to identify the area of injury/pain; however, for younger children, the history and physical exam will help dictate where to image. Areas of swelling or ecchymosis can narrow the area of investigation. It can be difficult to examine a child in pain; however, a thorough exam is necessary to identify all injuries and can often be accomplished with the child held by a parent.

Non-Accidental Trauma

This is an unfortunate topic but must be addressed and forefront in the clinician's mind in the setting of specific injuries. Injuries that do not conform to the underlying mechanism of trauma or are not typical of the developmental stage of the child may suggest child abuse. For example, if there is evidence of a long bone fracture in a non-ambulatory child, particularly a femur fracture, a head-to-toe exam must be performed. The child must be fully exposed, and the skin examined for bruises or burn marks. A skeletal radiographic survey must be completed to look for other fractures, especially worrisome if they are in different stages of healing. Metaphyseal corner fractures, secondary to violent shaking by the affected limb, as well as rib fractures, are pathognomonic for non-accidental trauma, but they are less commonly present than diaphyseal fractures [4, 5]. A bone scan can facilitate the diagnosis of fractures not seen on screening radiographs [1].

What to look for: Skin bruising, burn marks, fractures in different stages of healing, long bone fractures, posterior rib fractures, metaphyseal corner fractures [5].

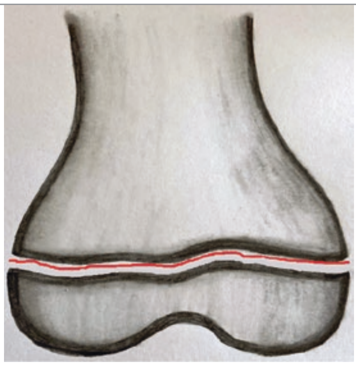
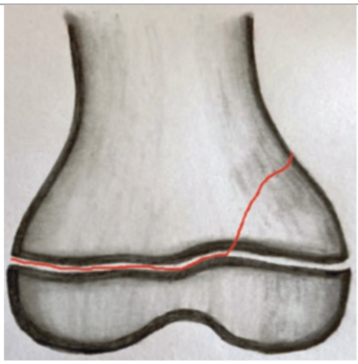
What to do: Skeletal survey, Child Protective Services (CPS) alert in the emergency department. Ophthalmology consult per institutional preference. Pediatric ward admission for further workup. Repeat skeletal survey in 10–14 days in the setting of high clinical suspicion but no definite findings on initial survey [5].

When to consult Orthopedics: Upon suspicion in the emergency department (ED) with fractures present.

Physeal Injury

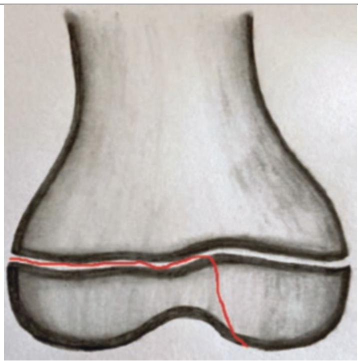
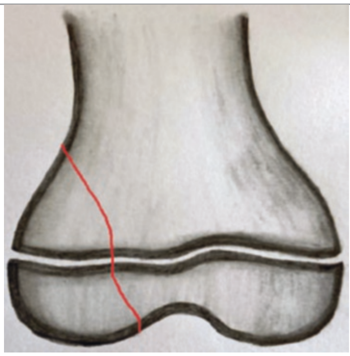
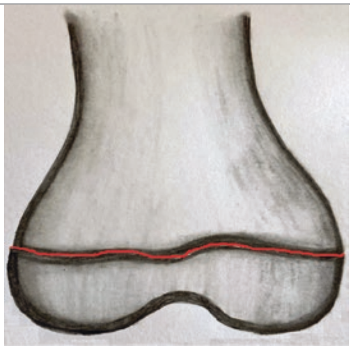
It is important to consider that pediatric patients are not just small adults. Growing children have open physes, or growth plates, that are relatively weaker than the surrounding bone and soft tissue. Injury to these vital structures can cause growth arrest, shortening, and angular deformity. Physiologic physeal closure is variable; however, the majority are closed by approximately age 14 for girls and 16 for boys [6]. Eliciting a history of menarche for girls is important in the evaluation of physeal injuries, as the period of most rapid growth is just before this time and can dictate treatment. Radiographs of the left hand are helpful in determining bone age; however, this radiograph is typically obtained in an outpatient setting rather than the trauma setting. See Table 30.1 for the Salter-Harris Classification of physeal injuries.

Table 30.1 The Salter Harris classification of physeal fractures, with correlating radiographs

SHI	Fracture through the physis, difficult to see but occasionally with physeal widening	
SHII	Fracture through the physis extending into the metaphysis	

(continued)

Table 30.1 (continued)

SHIII	Fracture through the physis extending into the epiphysis	
SHIV	Fracture through the epiphysis, physis and metaphysis	
SHV	Axial compression of the physis	

Upper Extremity Injuries

Clavicle: The clavicle is the most commonly fractured bone in the body, and accounts for 8–15% of skeletal injuries in children [6, 7]. The clavicle protects vital structures, including the subclavian vessels and the brachial plexus, so any injury warrants a neurovascular exam to ensure no associated injury. The clavicle articulates medially with the sternum, forming the sternoclavicular (SC) joint and laterally with the acromion, forming the acromioclavicular joint (AC) joint, both of which can be injured in clavicular fractures.

Fig. 30.1 Left midshaft clavicle fracture with 100% displacement, amenable for nonoperative management with sling

Post-partum neonates: During childbirth, the clavicle is commonly fractured in children with shoulder dystocia and those of higher birth weight. Treatment methods include swaddling the affected arm by wrapping a bandage around the arm and pinning the wrap to itself around the baby's torso, but not too tight! A long-sleeve T-shirt can also be pinned to itself. This immobilization is for comfort as well as to indicate to caregivers the presence of an injury.

Toddlers and adolescents: Most pediatric clavicle shaft fractures are treated nonoperatively with a sling due to great potential for remodeling. An example is shown in Fig. 30.1. Open and impending open shaft fractures, medial fractures with posterior displacement, or displaced lateral clavicle fractures often require operative management [7].

What to look for: While many clavicle fractures are treated nonoperatively, the evaluating provider needs to look for a medial, often physeal, clavicle fracture that may have posterior displacement, as these fracture dislocations can injure nearby mediastinal structures [7].

When to consult Orthopedics: Routine outpatient consult is appropriate for shaft fractures. Urgent consultation for medial clavicle fractures with concern of posterior displacement, open clavicle fractures or fractures causing tenting, or impending pressure necrosis on the skin.

What to do: Shaft fractures can be treated with a sling for 2–4 weeks, with subsequent progression of motion. Lateral clavicle fractures should have a follow-up with outpatient ortho within 1 week. Medial clavicle fractures should have a consultation on the day of presentation.

Elbow

Nursemaid's elbow: This is a common injury that occurs in patients aged 1–4 years old [6, 7]. The injury is secondary to a hyperextension event to the child's elbow, with subsequent interposition of the annular ligament. The arm is then often held against the body, with the elbow slightly flexed and pronated. Radiographs do not often show abnormality as these injuries are often fortuitously reduced during positioning in the radiology suite. Radiographs must still be obtained to rule out a fracture.

*How to reduce***:** Place your thumb on the radial head and flex the elbow while also supinating. A palpable and sometimes audible click should be appreciated. Occasionally, these injuries will require a pronation movement if supination is ineffective.

What to do: Check the range of motion. If reduced acutely, the child will begin to use the extremity within a few minutes.

When to consult Orthopedics: Consult in ED if reduction maneuvers are not successful.

Distal Humerus: The most common injury in the pediatric elbow is the supracondylar humerus fracture. This fracture accounts for 3% of all pediatric fractures and most commonly occurs between ages 5–7 [8]. Physical exam is a key component to the management of this fracture.

When evaluating a child with a supracondylar humerus fracture, it is important to have a thorough assessment of the neurovascular status. The brachial artery and the anterior interosseous nerve are the most often injured neurovascular structures with these fractures [9].

Key neurovascular exam components are detailed in Table 30.2.

There are also certain signs that give us clues to the extent of the injury, with Fig. 30.2 depicting key aspects of displaced supracondylar humerus fractures that should not be missed. The "dimple sign" is associated with the skin at risk in an unstable pediatric elbow fracture. The fracture has penetrated the brachialis fascia, with skin tenting. This requires an emergent trip (<1–2 h) to the OR for reduction and fixation [10]. An injury with the skin at risk, i.e., an impending open fracture, needs to be taken emergently to the OR to decrease the risk of progression to open fracture and to facilitate closed reduction. A thorough neurovascular exam is required to document neurovascular status and treat appropriately. Vascular compromise often requires a vascular surgeon available for exploration and repair vs. thrombectomy, as indicated.

Radiographs should include an elbow series, including AP, lateral and two oblique views. These are sometimes difficult to get in an injured child; however,

Table 30.2 Key components of the upper extremity neurovascular exam to ensure distal nerve pathways are intact

Physical exam component	Nerve tested		
	Median/anterior interosseous	Radial/posterior interosseous	Ulnar
Motor	Perform OK sign, thumb interphalangeal (IP) joint must flex	Extend index finger and thumb IP joint	Cross fingers, spread fingers apart
Sensory	Radial aspect of index finger distal phalanx	1st dorsal webspace	Ulnar aspect small finger distal phalanx
Vascular	Palpate radial pulse. The hand should be pink and perfused		

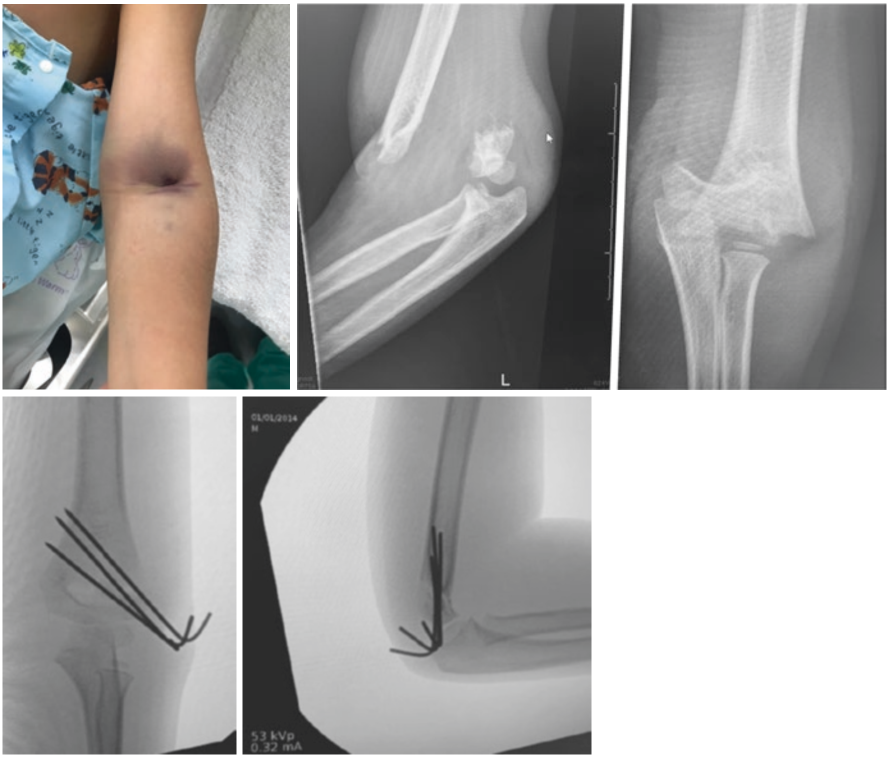


Fig. 30.2 Supracondylar humerus fracture with complete displacement, with skin at risk, characterized by the “dimple sign”. This requires an immediate trip to the operating room for reduction and fixation. A neurovascular exam before and after provisional splinting is essential, as well as postoperatively. Splint pending operative management can assist in pain control, but this should be in a position of comfort rather than at 90° as more flexion can exacerbate the skin dimpling or cause neurovascular compromise

they are important in determining the diagnosis. A posterior fat pad sign, seen on the lateral view, is pathognomonic for underlying fracture, even when occult, as it indicates hemarthrosis within the elbow joint [3, 7, 10].

What to look for: Neurovascular status as discussed, dimple sign.

When to consult Orthopedics: Consult orthopedics in the emergency department for all displaced fractures.

What to do: Splint, neurovascular check, orthopedics will definitively manage.

Forearm: Fractures of the pediatric forearm are common injuries that typically occur with a fall with an outstretched arm. There is high remodeling potential in the pediatric forearm, and the distal radial and ulnar physis account for approximately 75% and 80% of the growth of the forearm [11]. These injuries are commonly treated non-surgically with a well-molded long or short arm cast. As the child grows closer to skeletal maturity, the parameters for non-operative management become stricter, about age 11–12 for boys and 9–10 for girls [7].

Examination should include a neurovascular assessment and a skin exam to make sure there is open skin or draining wound near the site of the fracture that would increase clinical suspicion for an open fracture. The wrist should be examined for a dislocation of the distal radioulnar joint (DRUJ), termed Galeazzi injury. The elbow should be examined for a radial head dislocation with a proximal ulnar fracture termed Monteggia injury. Radiographic assessment should include orthogonal imaging of the forearm with an AP and lateral. Dedicated wrist and elbow series should be obtained to rule out elbow or wrist pathology.

When identified, orthopedics may be consulted for closed reduction and casting in the emergency department with the application of a plaster or fiberglass cast. Reduction is typically done with conscious sedation. If unavailable, these should be temporized with a splint that incorporates the elbow, forearm and wrist, demonstrated on radiographs in Fig. 30.3.

Fig. 30.3 AP and lateral radiographs of a both bone forearm fracture placed in a temporary sugar-tong splint. The splint wraps from the palm, around the wrist and elbow, and ends on the dorsal hand

When forearm fractures are open or fall out of parameters for acceptable closed reduction, surgical treatment is necessary to maintain alignment. The patient may require admission to facilitate urgent care in the setting of neurovascular compromise or skin at risk.

There are other variants of forearm and distal forearm fractures to include buckle fractures and greenstick fractures. These injuries represent incomplete fractures of the bone with some intact periosteum. The goal of management of these injuries is to address displacement to allow for optimal healing.

What to look for: Open wound, draining sinus or puncture that indicate an open injury. Physeal involvement.

When to consult Orthopedics: Consult orthopedics in the emergency department for closed reduction under conscious sedation and casting.

What to do: Neurovascular exam, radiographs of the forearm, elbow and wrist, provisional splint; call orthopedist for definitive management.

Wrist: Distal radial fractures occur in children because of a fall on an outstretched hand (FOOSH). The clinician needs to recognize common injury patterns and be cognizant of limiting reduction attempts of physeal injuries to ONE time only to decrease the risk of growth arrest secondary to iatrogenic growth plate damage [1]. Distal ulna physeal fractures have an even higher risk of physeal arrest, of up to 50% [6]. All physeal injuries should be followed for at least 5–6 months after the injury for monitoring. Distal radius buckles, or incomplete unicortical fractures, are stable injuries that can be effectively treated with non-rigid immobilization such as soft casts, splints, and braces. Alternative options may allow the child and their family greater ease with activities and facilitate hygiene, as well as decrease time off from school and work due to fewer follow-up appointments [12].

What to look for: Significant displacement, acute carpal tunnel syndrome, open fractures, Galeazzi or Monteggia-type injuries.

When to consult Orthopedics: Consult orthopedics in the emergency department prior to reduction, as physeal fractures necessitate a single reduction attempt to decrease the chance of injury to the growth plate.

What to do: Provisional splint and consult orthopedics to reduce under sedation and place in a short arm cast. Outpatient follow-up is encouraged in under 7 days.

Lower Extremity

Femoral Shaft: Femoral shaft fractures are common injuries in all ages of children, and are often the result of abuse, falls, or motor collisions. They account for almost 2% of all pediatric fractures [13]. The treatment of a femoral shaft fracture depends on the age of the child and the fracture pattern. Children under 3 years old who present with a femoral shaft fracture should be evaluated for child abuse. This is particularly important for patients who have not started walking [13]. Neonates and young children up to about age 6 months old can be treated in a Pavlik harness, with an example shown in Fig. 30.4.

Fig. 30.4 Pavlik harness placed for the treatment of bilateral femoral shaft fractures

What to look for: Thigh swelling, deformity, abnormal rotation of foot. Open wounds are concerning for higher energy trauma.

When to consult Orthopedics: Urgent consultation in the emergency department as soon as the fracture is diagnosed is required.

What to do: Splint with care to avoid iatrogenic heel pressure ulcers, radiographs of the affected femur including ipsilateral hip and knee. Monitor blood pressure; though shock is rarely due to a femoral shaft fracture in children, but evaluation for other internal hemorrhage is warranted [6].

*Distal Femu*r: The distal femoral physis accounts for approximately 9 mm of growth per year [14]. When there is an injury to the distal femur, there needs to be a high concern for a physeal injury, demonstrated by the radiograph in Fig. 30.5. The physis is the point of weakness and is often injured in the child. The extremity needs a thorough neurovascular exam and consultation with an orthopedist.

What to look for: Deformity, poke holes, oozing blood. Can sometimes mistake condylar prominence for dislocation rather than fracture, which would be rare in a pediatric patient given physes usually fail before ligamentous tissue.

When to consult Orthopedics: Urgent consultation in the emergency department as soon as the fracture is diagnosed is required.

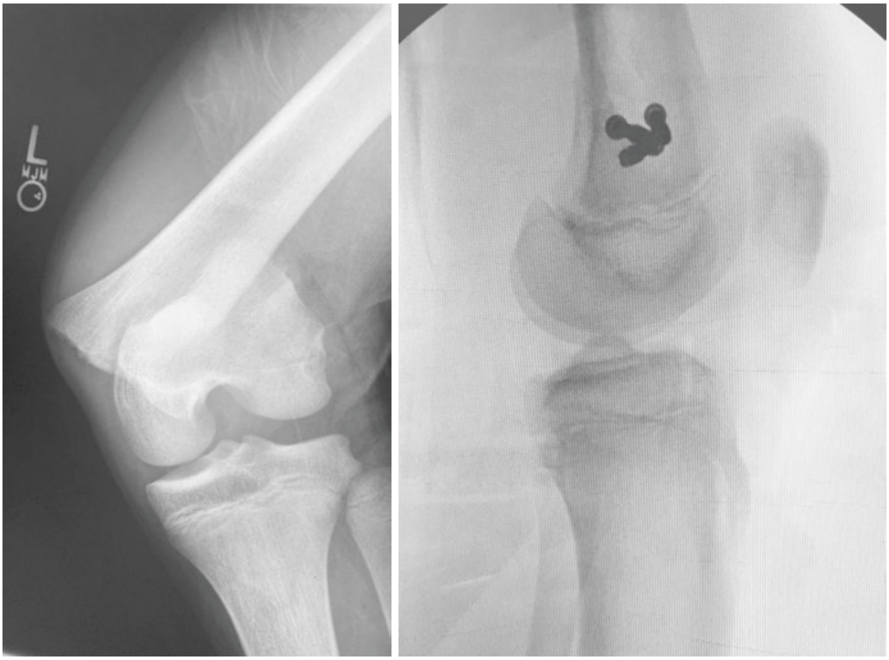


Fig. 30.5 Distal femur physeal fracture (salter harris 2 fracture), that was provisionally treated with closed reduction and splinting, followed by operative management with internal fixation of the metaphyseal fragment with screws

What to do: Place a long leg splint in a position of comfort. If there is an open wound, then remove frank debris, perform provisional irrigation, place gauze pending ortho evaluation.

Proximal tibia fractures (tibial spine and tuberosity): Tibia fractures are very common pediatric injuries, comprising 15% of all long bone fractures, following behind femur and forearm fractures. It is also a common injury in the polytrauma patient, following femur and humerus fractures [15]. An example is shown in the radiograph in Fig. 30.6. Fractures of the tibial spine are equivalent to an adult ACL tear, but often occur in adolescents aged 8–14 years old, also from a noncontact twisting mechanism. These injuries tend to occur with jumping, biking, skiing, playing soccer and football. Tibial tuberosity fractures involve the patellar tendon insertion, the proximal tibial physis, and occasionally extend intra-articularly, typically occurring in male basketball players between the ages of 12–17 years old [14]. These occur secondary to an eccentric load while jumping, from a significant quadriceps contraction. These injuries tend to have a lot of swelling given the periosteum is torn from the tibia. Elevation and ice can be big components of pain control. Initial evaluation should include ankle-brachial indices (ABI's) followed by serial examinations given up to 20% of injuries can be associated with concomitant compartment syndrome [16], which may be secondary to disruption of the anterior tibial recurrent artery.

Fig. 30.6 Right knee displaced tibial eminence fracture, an ACL equivalent injury. Rather than the ligament tearing, the force disrupted the bony insertion

What to look for: Twisting or jumping, non-contact knee injury.

When to consult Orthopedics: Consult orthopedics in the emergency department.

What to do: Place in a knee immobilizer. Admission for compartment monitoring and/or surgical management.

Tibial Shaft Fractures: Tibial shaft fractures account for 40% of tibia fractures, occur more often in boys, with an average age of injury at 8 years old [15]. There is a subset of torsional tibial shaft fractures in younger patients termed “toddler’s fracture” that occurs when the foot is planted, and the body rotates. This torsional force creates a spiral fracture of the diaphysis of the tibia. The child may present with limping and have tenderness over the diaphysis of the tibia. These fractures are typically treated nonoperatively with a long leg cast. Higher energy injuries in older children need to be evaluated with a thorough neurovascular examination, and compartment syndrome needs to be ruled out. The clinician must also look at the ankle, knee, femur, and hip of the child. Dedicated radiographs need to be done if there is any clinical concern for injury to the knee or ankle. Management of these fractures is typically non-operative with long leg cast application. Consultation of the orthopedic department is warranted for cast placement.

What to look for: Swelling, open wounds, rotational deformity.

When to consult Orthopedics: In the Emergency Department.

What to do: A thorough neurovascular exam, long leg splint pending orthopedic management.

Ankle

Physeal ankle fractures: Pediatric ankle fractures differ from adult ankle fractures in that children have an open physis that is relatively weak compared to the bones and ligaments [17]. Physeal injury needs to be evaluated, as traumatic injuries can lead to premature closure and cause shortening or angular deformity. The Salter-Harris classification is utilized to help determine the extent and prognosis of physeal injuries. Natural physeal closure occurs around 14 years for girls and 16 for boys and must be considered when evaluating these patients acutely [17]. The distal tibial physis closes from central-medially to laterally and there is a window of time where the physis is transitioning to closure. If there is an injury in this period, then there can be specific fractures (Tillaux and Triplane) that warrant a closed reduction attempt in the emergency department. These injuries need radiographic evaluation with an AP, lateral, and mortise view of the affected ankle. In some fracture patterns, a CT is warranted. The clinician should consult orthopedics prior to obtaining advanced imaging, as if a reduction is needed, advanced imaging should be delayed until after the reduction is performed. Displaced articular fractures need to be reduced and stabilized surgically. After a thorough exam and radiographic evaluation, the clinician should consult orthopedics in the emergency department for further management.

What to look for: Open physes and physeal involvement.

When to consult: Consult ortho in the emergency department prior to reduction.

What to do: Neurovascular exam, well-padded three-sided splint, elevation of the extremity.

Ankle sprain: These are common injuries in older children that occur from an inversion and axial load to the ankle. The two ligaments that are injured are the anterior talofibular ligament (ATFL) and the calcaneofibular ligament (CFL). In children with an open physis, the clinician must have a high suspicion for a physeal injury or fibular fracture. Children with ankle sprains present with tenderness to palpation and bruising over the anterolateral ankle. These injuries need to be evaluated and radiographic examination determined based on the severity of the injury. Treatment is determined based on the severity of injury. If there is a mild injury, then it can be treated with a removable brace. If it is more severe, a CAM boot or aircast may be appropriate with limited weight bearing. Physical therapy is often helpful at restoring ankle and peroneal strength, stability, and motion.

What to look for: Ankle fracture or distal tibial physeal injury.

When to consult Orthopedics: Routine outpatient orthopedic consult.

What to do: Provide the patient with support and immobilization based on grade and instability. May use CAM boot, aircast, short leg splint, short leg cast.

Foot: The majority of hindfoot, midfoot, and forefoot injuries can be treated nonoperatively unless open, dislocated or grossly displaced. If the injury is found on radiographs, and short leg splint, non-weight bearing status with crutch use, and routine orthopedic follow-up is warranted.

What to look for: Open fractures, dislocations, or grossly displaced fractures.

When to consult Orthopedics: Routine, unless the above-mentioned injuries.

What to do: Short leg splint, non-weight bearing with crutches and orthopedic follow-up.

Tarsometatarsal injuries (Lisfranc injuries): These injuries are fracture/dislocation injuries to the midfoot. Three mechanisms of injury have been described: an indirect injury with an axially directed force on a plantar-flexed foot, a fall backward with a fixed foot position, or a direct injury with heel-to-toe compression. In children, the most common is the axially directed force from a fall from height (56%), followed by a fall backward (22%), and then heel-to-toe compression (18%) [18]. The eponym of "Lisfranc" injury is from the Napoleonic surgeon Jacques Lisfranc de St. Martin, who noticed an injury pattern of soldiers that fell off the horse with the foot still in the stirrup [2]. These patients can present on exam with plantar ecchymosis, significant swelling and/or pain with weight bearing. Diagnosis is made by clinical exam and foot radiographs. If there is still a concern for occult injury, then weight-bearing stress view radiographs with the contralateral foot are obtained. This can give a good reference for the evaluation of the spacing of the first tarsometatarsal joint. The diagnostic radiographic evaluation looks at multiple radiographic findings, some of which are depicted in Fig. 30.7 [4].

Prior to obtaining advanced imaging, such as a CT, consult orthopedics to ascertain if this is appropriate. Emergency department management should consist of appropriate imaging, a short leg splint, and consultation with orthopedics. Definitive orthopedic treatment can consist of non-operative or operative management. Non-operative management occurs with non or minimally displaced fractures. Operative

Fig. 30.7 AP, oblique and lateral views of a left foot demonstrating a lisfranc injury, which is characterized by widened space between the medial cuneiform and 2nd metatarsal base. There is also disruption of the intercuneiform joint. The lateral view shows moderate soft tissue swelling

management is indicated with displacement and utilizes hardware to maintain a closed joint or a fracture if present.

What to look for: Plantar ecchymosis and swelling; specific radiographic signs; weight-bearing radiographs if occult injury.

When to consult Orthopedics: Routine consultation in the emergency department if no gross dislocation is present.

What to do: Short leg non-weight bearing cast, elevation, pain control.

Puncture wounds: As most children play outside, it is inevitable that one could step on a rusty nail or sharp object. This raises concern for bacteria on the penetrating object, which is then transported deep into the foot. The most concerning organism is *pseudomonas*, with antibiotic coverage typically consisting of ciprofloxacin or levofloxacin [6].

What to look for: Puncture wound in the shoe.

When to consult: Routine in the emergency department.

What to do: Antibiotic coverage for pseudomonas, update tetanus.

Compartment syndromes: Pediatric acute compartment syndrome is most commonly secondary to trauma, with or without an associated fracture [19]. It is a significant complication of extremity injuries that necessitates urgent recognition and subsequent treatment. Pediatric patients present similarly to adults, but pain may present as anxiety, agitation or increasing analgesic requirement, especially in a child who is nonverbal.

What to look for: The 3 A's: Anxiety, Agitation, increasing Analgesic requirement. Tense, firm muscle compartments.

When to consult: Upon suspicion. Constitutes an orthopedic emergency.

What to do: Exam, imaging of affected limb. The diagnosis is made based on physical exam; compartment pressure testing is reserved for obtunded patients.

Conclusion

Extremity fractures are not uncommonly seen in pediatric trauma patients. The mechanism of injury is important to understand the kinetics and predict fracture patterns. In children, attention must be paid to potential injuries to the open physes, or growth plate, as this may have long lasting consequences due to growth arrest, shortening or angular deformities affecting function later in life. Children are also at risk of child abuse, and the clinician must have a high index of suspicion especially in children who have fractures not appropriate for their developmental age, multiple fractures in different stages of healing, or areas where the injury is not routinely seen such as posterior rib fractures. Many fractures in children can be treated non-operatively; however, consultation with orthopedic surgery to assure appropriate stabilization and reduction is important.

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Chapter 31
Injuries to the Hand

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Abstract Traumatic injury to the pediatric hand is an increasingly common presentation. The initial physical examination of the hand is the single most important aspect of acutely managing these patients. However, the exam can be quite challenging in the very young or uncooperative pediatric patients. Emergent conditions, such as compartment syndrome or acute carpal tunnel syndrome, must be quickly diagnosed and hand surgery should be consulted. In all cases of bleeding, tamponade will provide hemostasis and a tourniquet should not be applied. Prompt radiographic imaging allows for the assessment of bony injuries. In general, most fractures of the hand in children can be treated nonoperatively with appropriate immobilization. Nearly all bony and soft tissue injuries to the hand can be splinted in an intrinsic-plus position. Outpatient follow up with hand surgery should occur within 1 week for all acute injuries.

Keywords Hand · Wrist · Finger · Tendon · Nailbed · Metacarpal · Phalanx · Scaphoid · Fracture · Dislocation · Amputation

Key Concepts/Clinical Pearls/Learning Objectives

- Physical examination of the pediatric hand in the acute traumatic setting
- Radiographic recognition of fractures
- Diagnosis of compartment syndrome of the hand and acute carpal tunnel syndrome
- What type of splint or immobilization is required for specific injuries
- When to perform bedside reductions and procedures
- When to consult or refer to hand surgery

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Initial Management of Trauma Patient

- Obtain thorough history
  - Mechanism of injury
  - Time of injury
  - Hand dominance
- Perform comprehensive physical exam of the hand/wrist
  - Examination of the injured hand is challenging in a child, particularly in the anxious or nonverbal patient

    It is essential to compare the exam to contralateral, uninjured hand
  - Hold pressure to stop bleeding
  - Inspection

    Resting posture of hand and digital cascade

    Rotational deformity of the digits, best evaluated with attempted composite fist

    Wounds, lacerations, open fractures

    Swelling, ecchymosis
  - Localize sites of pain
  - Test active and passive range of motion of the wrist and all digits

    Tenodesis

    - Passive flexion of the wrist should extend the digits
    - Passive extension of the wrist should flex the digits

    Test flexion and extension at each joint in all digits in isolation against resistance when concern for tendon injury
  - Test median, radial, ulnar, anterior interosseous (AIN), posterior interosseous (PIN) motor and sensory function
  - Test digital nerve sensory function

    2-point discrimination on the ulnar & radial aspect of each digit pulp

    - Normal <5 mm

    Wrinkle test

    - Wrap all digit pulps with wet towel and leave for 15 min
    - Digits with intact nervous structures will exhibit wrinkling, those with nerve injuries will not
    - Easier to perform than 2-point discrimination in the very young or uncooperative child

- Assess perfusion

  Color and temperature of each digit
  Capillary refill
  Doppler on palmar arch and digit pulp
  Allen's Test
  Doppler Allen's test (preferred)

  - Manually compress both the radial and ulnar arteries at the wrist
  - Have an assistant place a doppler ultrasound over the deep palmar arterial arch
    - Located in the midline of the proximal 1/3 of the palm
    - Should not have a signal at this point
  - Release the ulnar artery (keeping the radial artery compressed) and listen for return of a signal
  - Repeat with release of the radial artery
  - Return of signal indicates intact collateral circulation through the palmar arterial arch

- Order appropriate imaging studies
- Consult hand surgery immediately if concern for compartment syndrome or acute carpal tunnel syndrome

Initial Radiographic Studies

- X-ray
  - AP view of the hand and/or wrist
  - Lateral view of the hand and/or wrist (with digits fanned)
  - Oblique view of the hand and/or wrist (with digits fanned)
  - AP view of the wrist with maximum ulnar deviation

    Scaphoid fracture

  - True AP view (Roberts) of the thumb

    Thumb fracture

  - True lateral view of the thumb

    Thumb fracture

  - Imaging of the contralateral, uninjured hand/wrist helpful to identify subtle injuries
- CT of hand and/or wrist
  - Defer to hand surgery first
  - Occasionally indicated, often deferred to the outpatient setting

Compartment Syndrome of the Hand

When the tissue pressure within a fascial compartment rises to levels that constrict arterial inflow causing diminished arterial perfusion, cellular necrosis, and progressive tissue ischemia. There are ten compartments within the hand. Compartment syndrome often occurs with closed soft tissue trauma or fracture. This is an orthopedic emergency and the evaluating clinician must have a high index of suspicion. If undiagnosed, can lead to permanent contracture (Volkmann's) and functional deficits. Irreversible tissue ischemia can occur 8 h after onset.

- Presentation
  - Clinical diagnosis relying on serial physical exams
  - Severe, progressively worsening pain out of proportion

    Increasing pain medicine requirement is the most sensitive indicator in children

  - Tense, swollen compartments of the hand
  - Pain with passive extension of the digits
  - Paresthesias and neurologic dysfunction (late)
  - Signs of poor perfusion or pulselessness (missed diagnosis)
  - Compartment pressure measurement helpful in obtunded patients

    Record a diastolic blood pressure (DBP)
    Measure interstitial tissue compartment pressure using a needle manometer in each compartment
    Delta Pressure < 30 mmHg confirms the diagnosis

    - Defined as the difference between the DBP and the measured compartment pressure

- Management
  - Consult hand surgery immediately if suspected
  - Remove constrictive dressings, splints, or casts
  - Elevate the hand to the level of the heart
  - If diagnosis not confirmed but remains a concern, perform serial physical exams and/or compartment pressure measurements
  - Definitive treatment consists of fasciotomies of each compartment of the hand

    Goal to perform fasciotomies within 6 h of onset
    Prophylactic carpal tunnel release often concomitantly performed

- Medical considerations
  - Severe muscle damage can cause rhabdomyolysis, acute kidney injury, electrolyte abnormalities and coagulopathy
  - Obtain CBC, BMP, and urinalysis

Hyperkalemia, hyperphosphatemia, hyper/hypocalcemia
Myoglobinuria

– Resuscitate with IV fluids and treat electrolyte abnormalities

Acute Carpal Tunnel Syndrome

Acute carpal tunnel syndrome is analogous to compartment syndrome of the carpal tunnel. It is defined as a rapid rise in pressure within the carpal tunnel that compromises median nerve epineural blood flow leading to unrelenting pain and dysesthesias in the median nerve distribution. The carpal tunnel is located 1 cm distal to the volar wrist crease. The median nerve is the most important structure that passes through the carpal tunnel. This condition must be treated as an orthopedic urgency and the clinician must have a high index of suspicion. If undiagnosed, it can lead to permanent median nerve injury. The clinician must differentiate acute carpal tunnel syndrome from a **median nerve neuropraxia**, which is characterized by:

- Symptoms present at time of initial injury
- Symptoms will not progress or worsen
- Symptoms will resolve with either time or reduction of fracture

- Presentation of Acute Carpal Tunnel Syndrome
  - Clinical diagnosis relying on serial physical exams
  - Symptoms not present at time of initial injury
  - Progressive, severe pain and paresthesias in the median nerve distribution
  - Symptoms will not resolve with time or reduction of fracture
  - Loss of 2-point discrimination in median nerve distribution

    >15 mm indicated 100% sensory loss

  - Motor dysfunction in median nerve distribution (late)

- Management
  - Remove constrictive dressings, splints, or casts
  - Elevate the hand to the level of the heart
  - Reduce displaced fractures (i.e. distal radius)
  - Perform serial physical exams to monitor for improvement

    If symptoms improve the patient has a median nerve neuropraxia, not acute carpal tunnel syndrome
    This can be further observed and no urgent surgical intervention is needed

  - If persistent and progressive symptoms, consult hand surgery immediately
  - Definitive treatment consists of surgical carpal tunnel release

    The earlier the release, the earlier and more complete return of function

High Velocity Injection Injury

This is an orthopedic emergency caused by injection of material at sufficient pressure to breach the skin. These are typically occupational injuries and can be seen in young men. The injected material can cause significant issue destruction and can spread along they fascial planes. They can cause compartment syndrome and/or acute carpal tunnel syndrome. Common types of injected materials include: water, oil or latex-based paints or paint thinner, and automobile grease and hydraulic fluid. These injuries may appear innocuous but a missed diagnosis can lead to permanent hand dysfunction. As noted previously, the material injected will disperse from injection site along fascial planes. Digit injections produce a worse outcome than injections more proximal on the hand. The longer the material remains within the tissue, the worse the outcome typically is. The amount of inflammatory response depends on material injected.

- Presentation
  - Small, subtle puncture wound

    Discoloration can be present depending on type of material
  - Initially only mild pain and swelling
  - Rapidly worsening symptoms within hours

    Severe pain that tracks proximally
    Streaking erythema
    Signs and symptoms of compartment syndrome
- Management
  - Consult hand surgery immediately
  - Broad-spectrum antibiotics
  - Definitive treatment consists of surgical decompression and debridement

Fractures & Dislocations

Open Fractures

- The most common open fractures in children involve the hand and upper extremity
- Gustilo & Anderson Classification (Types I-III)
- Management
  - Immediate IV antibiotics

    Time to antibiotics is the single most important factor in reducing infection rate

- Tetanus prophylaxis
- Thorough bedside irrigation with saline and removal of gross contaminant
- Appropriate splinting of fracture site
- Consult hand surgery

- Type I open fractures of the proximal phalanx and distal can be definitively treated as an outpatient and can safely be discharged from the acute setting
  - Injuries proximal to the proximal phalanx are controversial and hand surgery should be consulted
  - Discharge on 5 days of PO antibiotics effective against skin flora

Carpal Fractures

- Fractures of carpal bones other than the scaphoid are exceedingly rare in the pediatric population
  - Apply an intrinsic-plus splint
  - Generally treated nonoperatively
  - Outpatient referral to hand surgery in 1 week

Scaphoid Fractures

- Rare in the pediatric population
- Anatomy
  - Begins to ossify at the age of 4 years with complete ossification by age 15 years
  - Risk of nonunion and avascular necrosis secondary to tenuous blood supply
- Result of a fall onto an outstretched hand, typically in the adolescent athlete
- Frequently a missed injury due to negative initial imaging
- Presentation
  - Swelling, ecchymosis at the wrist
  - Painful range of motion at the wrist
  - Tenderness and swelling over the anatomic snuffbox or volar scaphoid tubercle
- Imaging
  - Standard wrist X-rays
  - AP view of the wrist in maximum ulnar deviation ("scaphoid view")
  - Consider X-ray views of the contralateral wrist for comparison

    Up to 30% of initial radiographs are negative
  - Advanced imaging (CT, MRI) is deferred to the outpatient setting

- Management
  - Concern for fracture with negative X-ray

    Apply Velcro thumb spica splint to be worn at all times
    Outpatient referral to hand surgery in 2 weeks

    - If subsequent X-rays are negative and pain improved, no further immobilization required
  - Nondisplaced fractures

    Apply thumb spica splint
    Outpatient referral to hand surgery in 1 week

    - Nonoperative management with a thumb spica cast is generally acceptable
  - Displaced fractures

    Do not attempt reduction, can further compromise vascularity
    Apply thumb spica splint
    Universally treated surgically with screw fixation
    Outpatient referral to hand surgery in ASAP

Metacarpal Fractures.

- Presentation
  - Pain over dorsal and volar hand
  - Swelling and ecchymosis
  - Pain and difficulty making a composite fist
  - Malrotated fractures can cause overlapping digits while attempting to make fist
- Imaging
  - Standard hand X-rays
  - Evaluate for:

    Angulation

    - Neck fractures have apex dorsal angulation

    Shortening
    Malrotation

Metacarpal Shaft Fractures

- Have inherent stability from the intermetacarpal ligaments and interosseous muscles

- Management
  - Nondisplaced fractures

    Apply an intrinsic-plus splint (ulnar gutter for ring and small finger metacarpals)
    Treated nonoperatively

  - Displaced fractures

    Consult hand surgery, often require reduction
    Surgical treatment reserved for fractures outside acceptable alignment, clinical malrotation of the digit and multiple fractures

  - Outpatient referral to hand surgery within 1 week

Metacarpal Neck Fractures ("Boxer's Fractures")

- Account for up to 70% of all pediatric metacarpal fractures
- Most common at the small finger
- Result of an axial force applied to a clenched fist
- Vast majority are treated nonoperatively regardless of displacement
- Delayed presentations are common
  - Attempts at reduction are futile if injury >7–10 days old
- Management
  - Nondisplaced fractures

    Apply an intrinsic-plus splint (ulnar gutter for ring and small finger metacarpals)
    Treated nonoperatively

  - Displaced fractures

    Reduce fracture into best anatomic alignment possible

    - Begin with longitudinal traction to disimpact the fracture
    - Flex the MCP, PIP joints while applying dorsally directed pressure to the metacarpal head
    - Correction of malrotation is of utmost importance

    Apply an intrinsic-plus splint (ulnar gutter for ring and small finger metacarpals)
    Surgical treatment is rare and reserved for clinical malrotation of the digit
  - Outpatient referral to hand surgery in 1 week

Phalangeal Fractures.

General

- Presentation
  - Pain at involved digit/joint
  - Swelling and ecchymosis
  - Angular deformity secondary to displacement
  - Limited range of motion at adjacent joints
  - Malrotated fractures can cause overlapping of digits while attempting to make a composite fist
- Imaging
  - Standard hand and digit X-rays
  - Evaluate for:

    Angulation
    Shortening
    Malrotation

Intraarticular Condylar Split Fractures

- Defined as an intraarticular fracture of any phalanx with a longitudinal split between the condyles
- Frequently missed with delayed presentation
  - Can result in malunion and angular deformity at the joint leading to stiffness
- Imaging
  - Often appears normal on AP view
  - Lateral view will show displacement and "double density" sign
- Management
  - Nondisplaced fractures

    Apply an intrinsic-plus splint (ulnar gutter for small or ring fingers)
    Treated nonoperatively
    Outpatient referral to hand surgery in 1 week
  - Displaced fractures

    Apply an intrinsic-plus splint (ulnar gutter for small or ring fingers)
    Require surgical pinning for restoration of the joint surface
    Outpatient referral to hand surgery in 3–5 days

Phalangeal Neck Fractures

- Defined as an extraarticular fracture of the proximal or middle phalanx neck
  - Most common in the border digits
- Missed injuries or unreduced fractures carry risk of:
  - Volar bone spike preventing joint flexion
  - Nonunion
  - Malunion with angular deformity
  - Avascular necrosis of the distal fragment
- Often result of a “doorjamb” injury where the digit is crushed in a door and forcefully withdrawn
- Imaging
  - AP view: often mistaken for a physis despite the physis being located at the base of the phalanx
  - Lateral view is essential and shows dorsal displacement of the distal fragment
- Management
  - Nondisplaced fractures

    Apply a dorsal intrinsic-plus splint (ulnar gutter for small or ring fingers)
    Treated nonoperatively
    Outpatient referral to hand surgery in 1 week
  - Displaced fractures

    Must reduce back into anatomic alignment

    - Longitudinal traction with volarly directed pressure over the distal fragment

    Apply a dorsal intrinsic-plus splint (ulnar gutter for small or ring fingers)
    Most do not maintain reduction and will require surgical pinning
    Outpatient referral to hand surgery in 3–5 days

Phalangeal Shaft fractures

- Proximal phalanx shaft fractures will displace apex volar
  - Unreduced, volarly displaced malunion will cause loss of PIP joint extension

- Management
  - Nondisplaced fractures

    Buddy tape to adjacent digit
    Treated nonoperatively
    Outpatient referral to hand surgery in 1 week

  - Displaced fractures

    Must reduce back into anatomic alignment

    - Longitudinal traction with pressure over the fracture site to correct angulation
    - Malrotated fractures require correction of rotation during traction

    Apply a volar intrinsic-plus splint (ulnar gutter for small or ring fingers)
    Surgical treatment reserved for fractures outside acceptable alignment and clinical malrotation of the digit
    Outpatient referral to hand surgery in 3–5 days

Proximal Phalangeal Base fractures

- Result of abduction force to the MCP joint
- Most common in the small finger, known as “extra-octave” fractures
- Imaging
  - Can be through the physis or just distal to it
  - Displaces into abduction
- Management
  - Nondisplaced

    Apply an intrinsic-plus splint (ulnar gutter for small or ring fingers)
    Universally treated nonoperatively
    Outpatient referral to hand surgery in 1 week

  - Displaced

    Must reduce into anatomic alignment

    - Flex the MCP joint to stabilize the proximal fragment
    - Use a pen or pencil as a fulcrum in the adjacent webspace to gain control of the distal fragment
    - Irreducible fractures can be blocked by flexor tendon entrapment, disruption of the collateral ligaments or comminution

    Apply an intrinsic-plus splint (ulnar gutter for small or ring fingers)
    Residual displacement requires surgical pinning
    Outpatient referral to hand surgery in 3–5 days

PIP Joint Fracture-Dislocations

- Most commonly injured joint of the hand
- Often overlooked as a "jammed" finger
- Result of an avulsion or direct axial impaction force
- When fracture is present, the amount of articular involvement predicts stability
- Identifying difference between a dorsal or volar dislocation is paramount
  - Dorsal dislocation: injury to the volar plate

    Heals with minimal intervention
  - Volar dislocation: injury to the extensor central slip

    If untreated can lead to a difficult to treat boutonniere deformity
- Presentation
  - Obvious volar or dorsal dislocation
  - Puckering of the skin may indicate interposed soft tissue
  - Will often spontaneously reduce, or the patient will self-reduce prior to examination
- Imaging (Fig. 31.1)
  - Always obtain post-reduction X-rays
  - Lateral view will show:

    Direction of dislocation (volar or dorsal)

Fig. 31.1 (**a**) is a lateral X-ray of a dorsal PIP joint dislocation of the small finger. (**b**) is a lateral X-ray of a volar PIP joint dislocation

Fracture of the middle phalanx base and percentage of articular involvement

- Dorsal dislocation: fracture of the volar lip
- Volar dislocation: fracture of the dorsal lip

- Management
  - Reduce the dislocation

    Traction and either volar or dorsal directed pressure
    Rarely, can be irreducible secondary to interposed soft tissue
    If irreducible, consult hand surgery for surgical open reduction

  - Dorsal fracture-dislocation

    Simple (no fracture)

    - Buddy tape to adjacent digit
    - Universally treated nonoperatively
    - Outpatient referral to hand surgery in 1 week

    Complex (fracture)

    - Apply dorsal extension-blocking splint keeping the PIP joint in approximately 50 degrees of flexion
    - Can be treated nonoperatively or surgically depending on amount of joint involvement
    - Outpatient referral to hand surgery in 3–5 days

  - Volar fracture-dislocation

    Simple (no fracture)

    - Apply volar splint with the PIP joint locked in full extension leaving DIP joint free
    - Treated nonoperatively with extended period of immobilization

    Complex (fracture)

    - Apply volar splint with the PIP joint locked in full extension leaving DIP joint free
    - Can be treated nonoperatively or surgically depending on amount of joint involvement

    Outpatient referral to hand surgery ASAP

Mallet Finger

- Defined as an avulsion fracture of the dorsal distal phalanx (extensor tendon injury)
  - Extensor tendon is attached to the avulsed fragment

- Result of flexion force onto an actively extended finger
- Presentation
  - Extensor lag to the DIP joint, lacking active DIP extension
- Management
  - Splint with DIP joint in extension (leave PIP joint free)
  - Vast majority treated nonoperatively
  - Outpatient referral to hand surgery in 1 week

Jersey Finger

- Defined as an avulsion fracture of volar distal phalanx (flexor tendon injury)
  - Flexor tendon is attached to the avulsed fragment
- Result of extension force onto an actively flexed finger
- Presentation
  - Loss of normal resting cascade of the digit

    Affected digit will be held in slight extension
  - Loss of tenodesis

    Affected distal phalanx will not flex with passive extension of the wrist
  - Loss of strength or inability to flex affected digit
- Management
  - Apply an intrinsic-plus splint
  - Requires surgical repair within 1 week
  - Outpatient referral to hand surgery ASAP

Nailbed Injuries and Amputations

Nailbed Injuries/Tufts Fractures

- Defined as an open fracture of the distal phalanx with associated nailbed injury
- Fingertip and nailbed injuries account for up to 2/3 of all pediatric hand injuries
- Result of a crush injury or sharp laceration to the fingertip, commonly door-related
- Anatomy
  - The nail itself is referred to as the nail plate, bordered distally by the hyponychium and proximally by the eponychium

- The nailbed is comprised of the sterile matrix (distal) and the germinal matrix (proximal)
- The germinal matrix houses regenerative cells for nail growth

- Presentation
  - Obvious injury to the nail with exposed nailbed
  - Can be more subtle with only subungual hematoma
  - Removal of nail will reveal nailbed injury pattern
- Imaging
  - Standard hand and digit X-rays
- Management
  - See nailbed repair section below
  - Subungual hematoma

    If tufts fracture is displaced, remove the nail for exploration of the nail bed
    If tufts fracture is nondisplaced or there is no associated fracture, management depends on the size of the subungual hematoma

    - Involving >50% of the nail without a fracture, or > 25% in presence of a fracture: remove the nail for exploration of the nail bed
    - Hematomas smaller than the above criteria can be treated with simple nail plate trephination

    If there is any question, remove the nail plate and fully explore the nail bed

  - Nailbed avulsion

    The avulsed nailbed will be attached to the undersurface of the nail plate
    Treat by suturing the avulsed tissue back into place

  - Can be treated definitively in the emergency department

    Fracture is always treated nonoperatively

  - Outpatient referral to hand surgery in 1 week

Seymour fracture

- Defined as an open fracture of the distal phalanx physis with associated nailbed injury
  - Soft tissue (germinal matrix) entrapped within the fractured physis
- Result of a hyperflexion force to the distal phalanx
- Easily overlooked, must have high index of suspicion
- Delay in treatment can lead to

  - Nail dystrophy
  - Infection or osteomyelitis
  - Physeal growth arrest with flexion deformity

- Presentation

  - Similar in appearance to mallet finger
  - Blood at the nail fold or subungual hematoma
  - Proximal nail plate may rest on top of the eponychial fold (rather than beneath)

    Nail will appear longer compared to uninjured digits

- Imaging (Fig. 31.2)

  - Standard hand and digit X-rays
  - True lateral view of the DIP joint must be used to confirm the diagnosis

    Widening of the dorsal distal phalanx physis

Fig. 31.2 The figure shows a lateral X-ray of a Seymour fracture with interposed soft tissue within the physeal fracture causing widening of the dorsal distal phalanx physis

- Management
  - Remove nail bed and repair
  - Apply an intrinsic-plus splint to involved digit
  - Displaced fractures

    Widening and/or flexion deformity at the physis
    Entrapped soft tissue within the physis requires surgical debridement and pinning

  - Outpatient referral to hand surgery in 3–5 days

Amputations

- Any amputated digit or extremity in a child should be considered for replantation
  - Typical contraindications to adult replantation do not apply
  - Increased capacity for vasogenesis and healing of replant compared to adults
  - Outcomes are vastly superior to adult replantation
- Imaging
  - Standard hand X-rays
- Management
  - Hold continuous pressure to stop bleeding
  - Place amputated part in moist, sterile gauze inside a waterproof bag that is placed in a bucket of ice

    Do not place amputated structure directly onto ice due to risk of frostbite or thermal necrosis

  - Consult hand surgery immediately

Tendon and Neurovascular Injuries

Extensor Tendon Injuries

- Extensor tendons cross the dorsal wrist and hand in a predictable anatomic pattern
- Injuries can be subtle, thus a detailed physical exam is necessary
- Missed injuries can lead to a dysfunctional hand with inability to extend the digits and/or wrist
  - Untreated injuries over the PIP joint of the central slip lead to boutonniere deformity
  - Untreated injuries over the MCP joint (“fight bite”) can lead to osteomyelitis

- Presentation
  - Can have visible tendon through wound
  - Loss of normal resting cascade of the digits

    Affected digits will be held in slight flexion

  - Loss of tenodesis

    Affected digits will not extend with passive flexion of the wrist

  - Loss of strength or inability to extend affected digits

    Must test each extensor tendon individually with and without resistance (juncturae tendinum inter-tendon connections can mask injuries)

    If confounding pain, consider local anesthesia with digital block

- Imaging
  - Standard hand and wrist X-rays
- Management
  - Suture wound closed
  - Apply an intrinsic-plus splint

    For thumb, apply a spica splint

  - Can be treated nonoperatively with immobilization or surgically depending on the location of injury
  - Outpatient referral to hand surgery ASAP

Flexor Tendon Injuries

- Flexor tendons cross the volar wrist and hand in a predictable anatomic pattern
- Injuries can be subtle, thus a detailed physical exam is necessary
- Missed injuries can lead to a dysfunctional hand with inability to flex the digits and/or wrist
  - High risk of associated neurovascular damage with open injury given close anatomic relationship
- Presentation
  - Can have visible tendon through wound
  - Loss of normal resting cascade of the digits (Fig. 31.3)

    Affected digits will be held in slight extension

  - Loss of tenodesis

    Affected digits will not flex with passive extension of the wrist

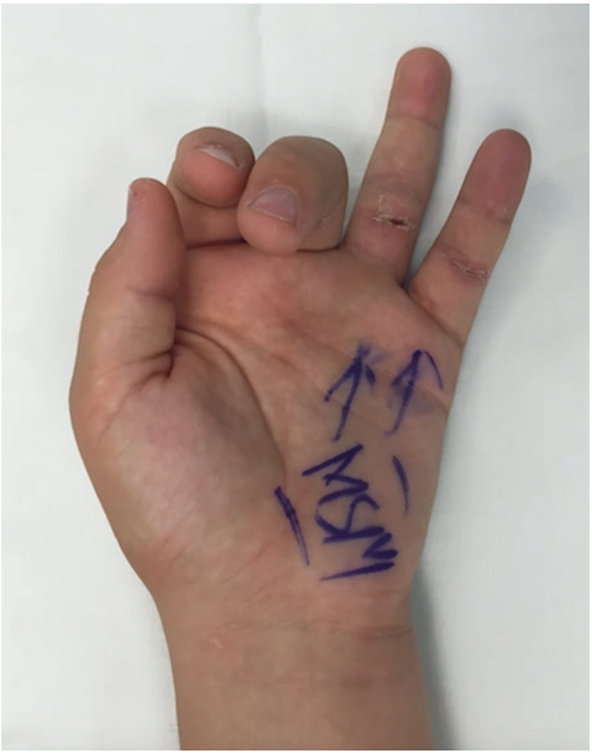

Fig. 31.3 The figure shows the resting posture of a hand with a flexor tendon injury to the ring and small fingers. The resting posture of the digits is held in extension and unable to flex

- Loss of strength or inability to flex affected digits

  Must test each flexor tendon individually with and without resistance

- Imaging
  - Standard hand and wrist X-rays
- Management
  - Suture wound closed
  - Apply an intrinsic-plus splint

    For thumb, apply a spica splint

  - Universally requires surgical repair within 1 week
  - Outpatient referral to hand surgery ASAP

Neurovascular Injuries

- Nerves and arteries cross the volar wrist and hand in a predictable anatomic pattern
- Injuries can be subtle, thus a detailed physical exam is necessary
  - High risk of associated flexor tendon injury given close anatomic relationship

- Anatomy
  - The palmar arterial arches are in parallel with the middle crease of the palm
  - In the palm, the digital artery is more volar
  - In the digits, the digital nerve is more volar
- Presentation
  - Can have visible nerve or vessel within wound
  - Signs of a poorly perfusion
    - Pale, blue discoloration
    - Cool temperature
    - Sluggish capillary refill
  - Doppler Allen's Test
  - Doppler palmar arch or finger pulp
  - Two-point discrimination or Wrinkle test
- Management
  - Hold continuous pressure to stop bleeding
    - Tamponade will stop all bleeding
    - Do not attempt to tie off bleeding vessels with suture due to risk of injuring accompanying nerves
    - Placement of a tourniquet indicates a limb threatening emergency and is strongly discouraged
      - Can cause global nerve palsy and permanent hand dysfunction
  - Suture wound closed
  - Apply an intrinsic-plus splint
    - For thumb, apply a spica splint
  - Definitive management requires surgical exploration and repair
    - Nerve injuries are typically repaired
    - Arterial injuries do not typically require surgical repair unless there is an ischemic digit
  - Outpatient referral to hand surgery ASAP

Miscellaneous

Animal Bites

- Most common site of bite injury is the upper extremity, and the hand is often involved
- Dogs and cats are the most common offenders

- If not managed appropriately can lead to wound infection, septic arthritis and osteomyelitis
  - Most infections are polymicrobial
  - Most common organism is *Pasteurella* followed by *Staph Aureus*
  - Increased risk with delayed presentation
- Presentation
  - Dog bites

    Can range from small penetrating wounds to large crush or avulsion wounds
    Higher risk of structural damage to hand
  - Cat bites

    Typically small puncture wounds
    Higher risk of penetration into bone, joints and tendons
  - Must perform meticulous examination of the hand to identify any tendon or neurovascular injuries
- Imaging
  - Standard hand and wrist X-rays

    Rule out concomitant fracture or retained foreign body
- Management
  - Remove foreign bodies (such as animal teeth) as they increase risk of infection
  - Do not suture wound closed, leave open to heal by secondary intention
  - If large crush injury or soft tissue defect, consult hand surgery

    Requires surgical debridement
  - One dose of IV ampicillin-sulbactam acutely followed by 5 days of PO amoxicillin-clavulanate
  - If any concern for rabid animal, urgently administer rabies vaccine and rabies immunoglobulin
  - Apply an intrinsic-plus splint if fracture or tendon injury present
  - Outpatient referral to hand surgery within 1 week

Bedside Procedure Techniques

- Bedside procedures in children often require a conscious sedation
- <u>Local anesthesia with digital block</u>
  - Extremely valuable for procedures involving the digits

    Reductions
    Wound closure
    Nailbed repairs

  - Do not anesthetize digit prior to obtaining a detailed sensory examination
  - We recommend using 1% lidocaine

    Epinephrine can be safely added for wound closures without risk of digital ischemia

  - Technique

    Single injection at the volar distal palmar crease in the midline of the desired digit
    Directed at the common digital nerves prior to branching into the radial and ulnar proper digital nerves

- Fracture reduction

  - When performing reductions of phalanx fractures, digital blocks can be very valuable for pain control
  - Have all splint materials at the bedside to swiftly immobilize newly reduced fractures
  - Best if performed with an assistant to provide counter-traction to the limb
  - Using a mobile C-arm will provide real-time radiographic evaluation of fracture alignment
  - Reduction techniques for specific injuries are described in their associated sections

- Splinting

  - *Intrinsic-plus splint* (Fig. 31.4)

    Indications

    - Nearly all injuries to the hand and digits
    - Flexor and extensor tendon injuries
    - Neurovascular injuries
    - Index, middle, ring metacarpal and phalangeal fractures

    Apply splint material volarly and dorsally, from the forearm to the end of all the digits (except thumb)
    Mold with wrist in extension, MCP joints flexed at 90 degrees, PIP joints fully extended
    Prevents contracture of intrinsic muscles of the hand

  - *Ulnar gutter splint*

    Indications

    - Small finger metacarpal and phalangeal fractures

    Apply splint material from the ulnar aspect of the forearm to the end of the small finger
    Mold with wrist in wrist in extension, MCP joints flexed at 90 degrees, PIP joints fully extended

Fig. 31.4 The figure shows the proper application of an intrinsic-plus splint. **a** shows both volar and dorsal plaster. **b** demonstrates proper positioning with extension at the wrist, flexion at the MCP joints, and extension at the PIP joints

– *Thumb spica splint*

Indications

- Thumb metacarpal and phalangeal fractures
- Thumb flexor or extensor tendon injuries

Apply splint material from the radial aspect of the forearm to the end of the thumb

Circumferentially wrap the thumb with splint material

Mold with the thumb slightly abducted in resting posture

- Wound Management
  - When closing a digital wound, digital blocks are essential for management of pain control

    Must perform a detailed sensory examination of the digit prior to block
  - Always irrigate the wound with sterile saline and manually debride gross contaminant prior to closure

    Decontaminate the skin using a sterile prep solution
  - Do not close open fracture wounds, gunshot wounds, or foreign body wounds

    Simply apply a nonstick dressing after adequate irrigation and bedside debridement
    Exception: type 1 open fractures of the proximal phalanx and distal can be safely closed
  - Use absorbable suture (such as chromic gut) with a tapered needle

    Size 5–0, 4–0, or 3–0 is appropriate depending on the size of the patient
    A cutting needle poses a higher risk of damaging surrounding structures
  - We recommend a simple, interrupted technique for nearly all acute wounds

    If a wound requires more advanced suture technique, hand surgery should be consulted
  - Do not over-tighten the suture

    Can lead to ischemic skin edges
    A loose approximation of the skin edges in the hand is preferred for viable healing
    If there is an area with a large amount of soft tissue loss where skin edges are not able to be approximated, leave open to allow for healing by secondary intention
  - Apply a nonstick dressing (such as Vaseline or antibiotic coated gauze) with a bulky soft dressing overtop

    Dry dressings can cause poor cosmetic scar formation and are painful to remove
  - Tetanus prophylaxis
  - One dose of IV antibiotics acutely followed by 5 days of PO antibiotics effective against skin flora
- Nailbed repair
  - Digital blocks are essential for management of pain control

    Must perform a detailed sensory examination of the digit prior to block

- Trephination for subungual hematoma evacuation

  Using a 15-blade scalpel or 18-guage needle (for the very young child), make a sufficiently large hole in the nail to allow drainage of the hematoma

- Remove nail for exploration of the nailbed

  Use a freer elevator to atraumatically separate remaining attachments of the nail plate from the underlying nailbed
  Orient the scalpel horizontally, directing the tip of the blade dorsally
  Once the nail plate is separated from the underlying nailbed, it is helpful to clamp a hemostat or needle driver onto the distal aspect of the nail and provide tension to the underlying soft tissue attachments when separating the nail plate

- Irrigate the wound with sterile saline and manually debride gross contaminant

  Decontaminate the wound using a sterile prep solution

- Use absorbable suture (such as chromic gut) with a tapered needle

  Size 5–0 or 4–0 suture is appropriate depending on the size of the patient

- We recommend a simple, interrupted suture technique
- Do not over-tighten the suture

  A loose approximation of the wound edges is preferred for viable healing
  In areas of complex injuries (stellate wound) where wound edges are not able to be approximated, leave open to allow for healing by secondary intention

  - The nailbed has an abundant blood supply and will heal expediently

- Splinting the repaired nailbed

  Prevents scar formation between the eponychium and germinal matrix

  - If this occurs it will result in a permanently split, dystrophic nail

  Replacing the removed nail plate versus using a nonstick material (foil from the suture packaging or Vaseline gauze) is controversial

  - If the nail plate is intact, we recommend replacing the nail
  - If the nail plate is too damaged, we recommend replacing with a non-stick material

  The nail plate or nonstick material should be situated underneath the eponychium and sutured into place

  - We recommend a single suture on both the ulnar and radial aspect of the fingertip through the material

- Apply a nonstick dressing (such as Vaseline or antibiotic coated gauze) with a bulky soft dressing overtop

– Tetanus prophylaxis
– One dose of IV antibiotics acutely followed by 5 days of PO antibiotics effective against skin flora

Conclusions and Take Home Points

The initial physical examination of the hand is the single most important aspect of acutely managing trauma to the pediatric hand. Emergent conditions, such as compartment syndrome or acute carpal tunnel syndrome, must be quickly diagnosed and hand surgery should be consulted. In all cases of bleeding, tamponade will provide hemostasis and a tourniquet should not be applied. In general, most fractures of the hand in children can be treated nonoperatively with reduction and appropriate immobilization. Nearly all bony and soft tissue injuries to the hand can be splinted in an intrinsic-plus position. Outpatient follow up with hand surgery should occur within 1 week for all acute injuries.

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Chapter 32
Vascular Injuries to the Heart and Great Thoracic Vessels

Shalimar Andrews and Obie Powell

Abstract Injury to the heart and great vessels in children is rare but is associated with a disproportionately high morbidity and mortality, and it is often associated with polytrauma. This chapter will outline the initial evaluation and management of the pediatric patient with thoracic injuries, including helpful laboratory and radiographic studies. It will cover blunt and penetrating injuries to the heart, including pertinent anatomy, incidence, physical exam findings, pertinent radiographic studies, trauma bay resuscitation, operative and non-operative management strategies. It will also cover blunt and penetrating injuries to the aorta and great vessels, including pertinent anatomy, incidence, physical exam findings, pertinent radiographic studies, trauma bay resuscitation, operative and non-operative management strategies. Also included is a discussion of open versus endovascular techniques for blunt aortic injuries in children.

Keywords Cardiac trauma · Great vessel trauma · Thoracotomy · Endovascular management

Key Concepts/Clinical Pearls

- Initial evaluation and management of the child with heart or great vessel injury should follow ATLS guidelines, with a high degree of suspicion for these injuries in the polytrauma patient with evidence of thoracic trauma.
- All trauma practitioners should be familiar with the performance and interpretation of the eFAST exam as it is tremendously useful in aiding decision making.
- In the event of these cardiac or great vessel injuries, chest tube thoracostomy is often diagnostic and therapeutic.

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- Once the decision to proceed to the operating room is made, positioning and incision should be dictated by suspected injuries, but a generous anterolateral thoracotomy provides excellent initial exposure. It can be easily extended across the midline to the contralateral side to provide unparalleled exposure to the chest.
- A multidisciplinary approach should be employed, as there are emerging endovascular techniques that may be appropriate for the severely injured child.

Initial Evaluation and Management

Initial in hospital evaluation and management of the child with chest trauma should follow the basic principles of Advanced Trauma Life Support (ATLS), and it should start with a primary survey looking for life-threatening injuries following the ABCDEs. Keep in mind that some procedures may be required to stabilize or temporize life-threatening injuries prior to proceeding with the assessment, and many of these steps occur simultaneously.

A general algorithm for evaluation and management of both blunt and penetrating chest trauma with injuries to the heart and great vessels is listed below (Fig. 32.1). Chest wall, tracheobronchial, pulmonary, esophageal and diaphragmatic injuries are discussed elsewhere in this book, but should be evaluated and managed simultaneously with injuries to the heart and thoracic blood vessels.

Physical exam findings which indicate the possibility of thoracic injuries include abnormal respiratory rate, hypoxemia, nasal flaring/retractions, distended neck veins, diminished/absent breath sounds, muffled heart sounds, arrhythmias, asymmetric, diminished/absent peripheral pulses, crepitus over the neck/chest wall, focal bony tenderness of the chest wall, paradoxical chest wall movement, abrasion, ecchymosis, or lacerations of the chest wall, or obvious open wounds.

Chest X-ray is often the first and most easily obtained study, and can be used to evaluate for the presence of hemo/pneumothorax (HTX/PTX), widened mediastinum, or chest wall injuries. Extended Focused Sonography for Trauma (eFAST) is now standard practice in most emergency departments, and it can help diagnose pericardial effusion and PTX. Computed tomography scans (CT) remain the most detailed imaging study. They should be used to evaluate the pediatric patient in whom the significant injury is suspected but not confirmed in other studies.

With regards to injuries to the heart and great vessels, life-threatening injuries include cardiac tamponade, myocardial contusion, aortic transection, injury to the intrathoracic blood vessels. Immediate management may include fluid and blood product resuscitation, needle decompression, chest tube thoracostomy, or pericardiocentesis. Specific injuries and their management will be discussed later in this chapter.

Children with asymptomatic isolated thoracic trauma, normal vital signs, Glasgow Coma Scale (GCS) of 15, and no physical exam abnormalities can safely be managed in an outpatient setting. Isolated rib fractures with normal vital signs with good pain control on oral medications can also safely be discharged with outpatient follow-up.

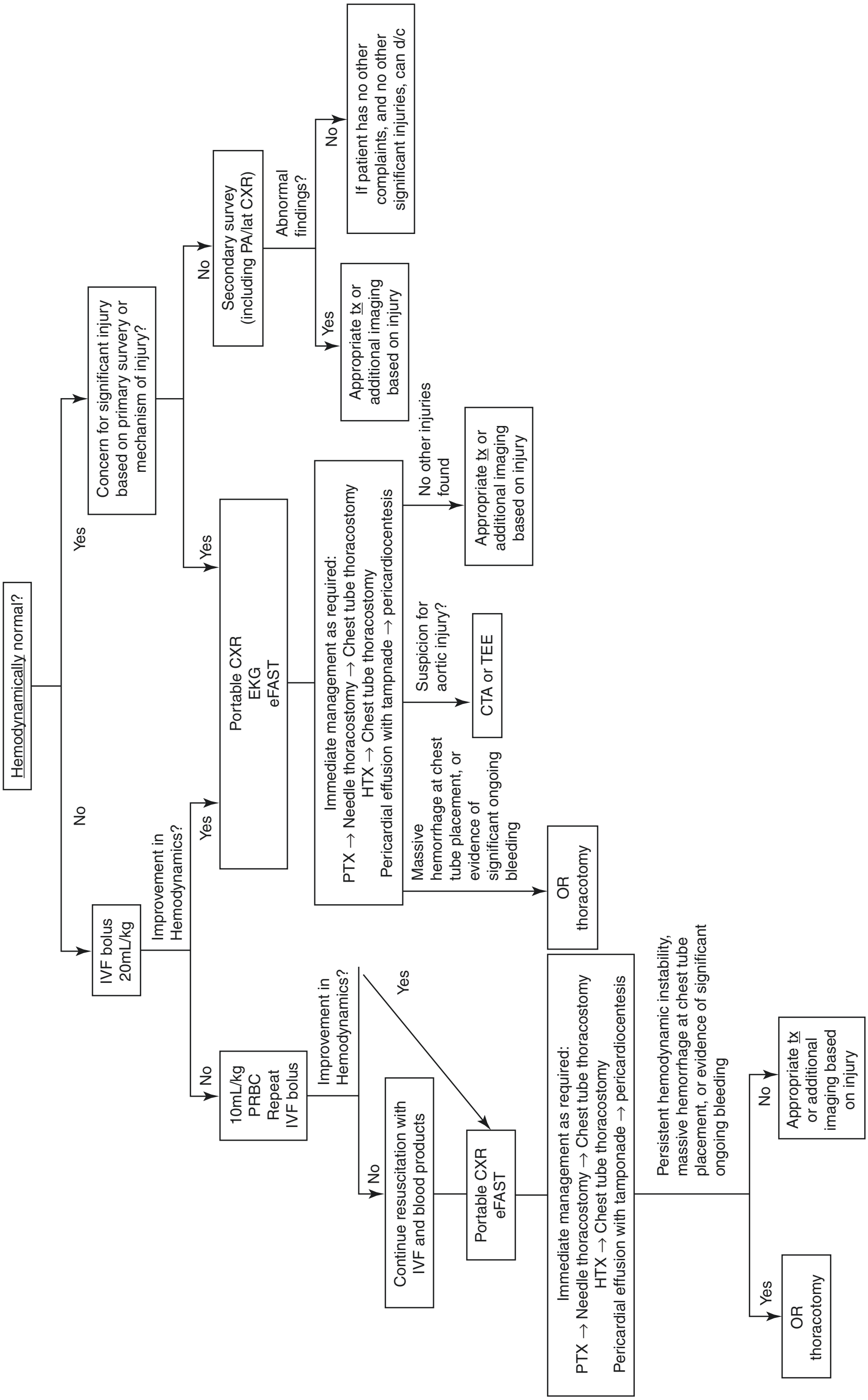

Fig. 32.1 Stepwise algorithm for evaluation and management of both blunt and penetrating chest trauma with injuries to the heart and great vessels

Any child with abnormal vital signs, severe pain, abnormal chest radiograph, high impact mechanism of injury, or suspicion of non-accidental trauma should be admitted for observation.

The majority of chest injuries resulting in HTX require only a tube thoracostomy for successful treatment. Indications for emergent surgical intervention for injuries to the heart and great vessels include massive hemorrhage identified at the time of chest tube thoracostomy (>10–15 mL/kg), or evidence of ongoing hemorrhage (>2–3 mL/kg/h over 4 h), or evidence of cardiac tamponade.

If there is suspicion for cardiac or great vessel injury, the child is best treated at a Level 1 Trauma Center, as they will have the necessary specialist and subspecialists to care for these complex injuries, and transfer should be arranged expeditiously.

For the child in extremis, an emergency department thoracotomy may be required. This procedure should only be performed by experienced clinicians such as a general, trauma, or thoracic surgeon who is immediately available to take the patient to the operating room to perform definitive stabilization. Survival rates for patients 18 years of age or less have been quoted around 3%, with the best survival rates in adolescents who suffer penetrating injuries [1]. Firm indications in children are not well defined, but if we extrapolate from adult data, resuscitative thoracotomy is indicated in patients with penetrating thoracic trauma who have a witnessed arrest in the emergency department or in patients who have been pulseless and receiving cardiopulmonary resuscitation (CPR) for less than 15 min. For patients with blunt injuries, a small subset may benefit from ED thoracotomy. Those include patients with witnessed arrest without other obvious nonsurvivable injuries [2].

Initial Radiographic/Ancillary Studies

All children with suspected heart or thoracic vascular injuries should have initial laboratory evaluation, including an arterial blood gas, CBC, BMP, coagulation studies (PT/PTT/INR) and thromboelastogram (TEG or ROTEM) if available at your institution. These labs should be used to help guide your resuscitation.

If concern for blunt cardiac injury is present, specifically those children who have sustained anterior compressive chest trauma, have evidence of a sternal fracture, or any cardiac arrhythmia, we recommend cardiac troponin levels and electrocardiography [3, 4]. Echocardiogram should be reserved for patients with clinical suspicion of cardiac injury who also have elevated troponins or abnormal EKGs.

A portable chest X-ray should be obtained only in a patient with an abnormal respiratory rate, tenderness to palpation of the chest wall, or abnormal, decreased or absent breath sounds. Multiple observational studies have shown that children with isolated minor thoracic trauma who have a Glasgow coma scale score of 15, normal blood pressure, and no abnormal findings on examination of the thorax are unlikely to have abnormal plain chest radiographs [5–7].

The cardiac and pulmonary portions of the eFAST can be used to rapidly identify the presence of a pericardial effusion, PTX, or HTX. Please keep in mind that this test is very operator dependent, and a negative exam does not preclude these injuries [8, 9].

CT angiogram (CTA) of the chest is primarily indicated to evaluate for vascular injuries in the chest; however, two large observational studies found that CTA rarely resulted in an alteration of management in children with major thoracic injuries compared with chest radiograph alone [10, 11]. In the pediatric population, great vessel injuries are infrequent, and as such, the clinician may find that the risk of missed injury is less than the risk of radiation exposure from a CT scan [12]. In a hemodynamically stable patient with high suspicion for thoracic vascular injury, CTA may be helpful for operative planning, especially if endovascular techniques are to be considered [13].

Overview

Thoracic trauma accounts for only 4–8% of pediatric injuries but may be a marker of a more severe overall injury pattern [14–17]. Blunt trauma accounts for most chest injuries, accounting for roughly 85%, with pedestrian injuries and motor vehicle crashes as the leading mechanisms [14]. The child's smaller body size, decreased adiposity, closer proximity of vital organs, and increased compliance of their thorax can lead to significant injuries in the absence of obvious injury to the chest wall. Additionally, given the relatively small chest to abdomen/head ratio, blunt thoracic trauma is frequently seen in a multisystem injury pattern and is a marker of injury severity. In fact, most children who die following blunt trauma that includes thoracic injuries do so as a result of their associated abdominal or head injuries. In the United States, gunshot wounds are the most common cause of penetrating injuries to the chest, and in those cases that result in mortality, the thoracic injury is often the cause of death [14–16]. Regardless of the mechanism, injuries to the heart and intrathoracic blood vessels resulted in the highest mortality [15].

The pediatric and adult hearts are generally very similar anatomically but differ physiologically. The adult heart can increase stroke volume by increasing inotropy and chronotropy; however, the pediatric heart can only increase chronotropy. Additionally, it has poor compliance as it relates to volume, and therefore cannot compensate as well by increasing stroke volume. As such, heart rate should be seen as a significant clinical marker when performing the initial evaluation of the pediatric trauma patient. Additionally, the child's increased physiologic reserve means that pediatric patients can tolerate up to a 30% loss in circulating blood volume before manifesting with hypotension. Tachycardia and poor capillary refill are often the most reliable early markers of hypovolemia [16].

If concern for hypovolemia exists, resuscitation should begin with a weight-based fluid bolus of 20 mL/kg. If the child's hemodynamics fail to improve and there is suspicion of ongoing hemorrhage, 10 mL/kg of type-specific or O negative packed red blood cells should be given. Ongoing resuscitation should be in a balanced fashion. If a major thoracic heart or vascular injury is identified, permissive hypotension should be allowed in order to limit blood loss [17].

In the case of great vessel injury due to gunshot wounds, an evaluation of the peripheral vasculature for bullet embolus should also be pursued after treating all life-threatening injuries.

Cardiac Injuries

Penetrating Cardiac Trauma (Image 32.1)

Penetrating cardiac injury is a rare entity in the pediatric population, but the mortality is high [18, 19]. You should have high suspicion for cardiac injury in any patient with penetrating wounds to the "cardiac box," anywhere from the clavicles to the epigastrium between the right and left midclavicular line. Based on its anterior position, the right ventricle is most commonly injured, followed by the left ventricle, right atrium, and finally the left atrium [18–20].

Initial evaluation and stabilization should follow the ATLS algorithm. Following the primary survey, adjuncts in the hemodynamically stable patient should include:

- Chest X-ray to evaluate for HTX or widened mediastinum
- eFAST cardiac window to evaluate for a pericardial effusion or evidence of tamponade.
  - Remember that a negative FAST does not rule out cardiac injury, as the blood may be decompressing into the pleural cavity.

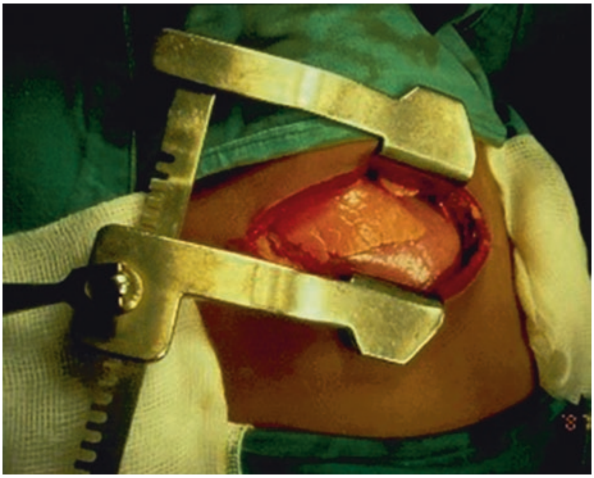

Image 32.1 Thoracotomy in a child

  - Pericardiocentesis has NO ROLE for the DIAGNOSIS of tamponade for penetrating injury as the false positive and false-negative rates are high.

- Impaled objects should be left in place as long as possible and removed in the operating room.

Trauma bay management of cardiac tamponade—The classic Beck's triad of hypotension, distended neck veins, and muffled cardiac sounds are present in only a portion of patients with tamponade. In the early post-injury period, tachycardia and anxiety with a reluctance to lie flat may be the only physical exam finding. Ultrasound is the most reliable method of identifying a pericardial effusion in the trauma bay.

- When no surgeon is immediately available, and the child has a pericardial effusion significant enough to cause cardiac compromise, there is a role subxiphoid needle pericardiocentesis, ideally under ultrasound guidance, as drainage of even 5 mL in a child can improve hemodynamics. Please note, the patient should be taken immediately to the operating room for exploration as given the mechanism of injury, the effusion is likely to rapidly accumulate. If the operating room is immediately available, do not delay transport to perform pericardiocentesis
- If tamponade is known or suspected, large volume resuscitation should be avoided as it will increase preload and could worsen tamponade
- Technique
  - The patient should be monitored using continuous EKG throughout the procedure.
  - If time allows, the skin should be prepped using betadine, and an aseptic technique should be adhered to throughout the procedure, including the use of a sterile ultrasound probe cover and sterile gel.
  - Position the ultrasound probe 3-5 cm from the left parasternal border to identify the location of the heart, the area of maximal effusion, as well as to survey the prospective path of the needle to reduce the risk of intra-abdominal injuries. If the stomach is very distended, a nasogastric tube should be placed for decompression.
  - If time allows, inject local anesthetic in the area of your proposed puncture.
  - Attach a 3 way stop cock and at least 35 mL syringe to an 18G 6in needle or similarly sized needle catheter. Insert the needle 1–2 cm inferior and on the left side of the xiphochondral junction.
  - The distance between the skin and the pericardium is about 5 cm in children, so the needle should be directed at a 15–45-degree angle (depending on US findings) in a cephalad direction towards the left scapula.

  Continuous aspiration should be performed until fluid is obtained. The needle should not be advanced any further once blood is aspirated.

    - The awake child may experience a sharp chest pain when the pericardium is punctured.

  If you note extreme ST-T wave changes or premature ventricular contractions on the monitor, most likely the needle has been advanced into the myocardium, and the needle should be withdrawn until the EKG returns to normal.

   – After aspiration, the stop cock can be closed, and the syringe removed. The patient should then be transported to the operating room for exploration. If tamponade physiology returns, the syringe can be reattached and repeat aspiration performed.

Hemodynamically unstable patients, those with evidence of massive hemorrhage identified at the time of chest tube placement (>10–15 mL/kg), or significant ongoing hemorrhage (>2–3 mL/kg/h over 4 h) should undergo emergent surgical exploration. Caveat—the patient must be stable enough to make it to the operating room; otherwise, resuscitative thoracotomy should be performed.

- Choice of incision depends on the stability of the patient as well as the anticipated injuries
   – Median sternotomy provides excellent exposure to all chambers of the heart, but it requires more time and equipment to perform.

   Place the patient in the supine position with the arms out and prep from chin to mid-thigh.
   Make a vertical midline incision centered over the sternum from just superior to the sternal notch to the tip of the xiphoid process.
   Divided the interclavicular ligament and bluntly clear the tissue deep to the manubrium, moving the innominate vein and surrounding tissue posteriorly .
   Clear the xiphoid of fat and adjacent peritoneum, and again bluntly separate the posterior tissue.
   Divide sternum in the midline. This can be done with a sternal saw, Lebsche knife and mallet, or trauma sheers if neither of those items are available. Take care to avoid deviating to the side and simply removing the ribs from the sternum.

      - If using the saw, place the saw under the manubrium and proceed inferiorly, maintaining constant upward pressure
      - If using the Lebsche knife, start at the xiphoid and proceed superiorly in order to most efficiently swing the hammer without the risk of injury to the patients face

   A chest spreader (commonly Finochietto retractor) should be placed with the bar towards the abdomen to allow for a cervical extension if necessary.

      - As the retractor is opened, the adventitial tissue should be bluntly dissected from the underside of the sternum to expose the pericardium

   If tamponade is present, the pericardium should be opened with a scalpel, as the tough bulging pericardium is often difficult to grasp and cut with scissors.

      - The pericardiotomy should be opened from the top to the base of the heart, and then extended horizontally for a short distance on either side, making an inverse "T" → remember to take care to avoid the phrenic nerve.

- The edges of the pericardium can be sutured to the skin in order to provide better exposure and raise the heart slightly to facilitate the repair.

– If additional left-sided thoracic injuries are suspected, a left anterior thoracotomy provides better access to the lungs and descending aorta, while still providing excellent exposure of the heart.

With the patient in the supine position with the arms out, prep from chin to mid-thigh.

An incision should be made overlying the fifth rib, extending from the sternum to the posterior axillary line. The nipple in males and young females, and the inframammary crease in adolescent females correlates with the 4th interspace.

This should be extended down through the subcutaneous tissues using electrocautery until the bone is encountered, and then the intercostal space should be entered just above the rib in order to avoid injury to the intercostal neurovascular bundle.

The incision should be extended posteriorly as far as possible, retracting rather than dividing the latissimus muscle.

The rib spreader should be inserted with the handle towards the bed in order to facilitate extension across to the right chest if necessary.

Evaluate the pericardium for evidence of effusion, and if necessary, open sharply anterior to the phrenic nerve and extend the pericardiotomy the length of the heart to allow the heart to be delivered and fully evaluated.

The lungs and great vessels can also be evaluated through this incision

– A thoracotomy may be extended across the sternum in a clamshell bilateral thoracotomy, which provides an unparalleled view of the mediastinum and great vessels, allowing for identification and repair of nearly all thoracic injuries.

After performing a left anterolateral thoracotomy, if additional exposure is deemed necessary, a right anterolateral thoracotomy can be made as described above, and then the sternum is transected with the Lebsche knife or heavy scissors.

If a second rib spreader is available, it should be positioned in a similar manner as above. If no additional retractor is available, the initial Finochietto can be re-positioned at the sternum and fully expanded.

The internal mammary arteries and ligated.

- Repair of cardiac injuries
  – In general, the patient should be placed in Trendelenburg position to avoid air embolism.
  – A hand can be placed behind the heart into the oblique pericardial sinus, and then the heart can be gently elevated into the wound, allowing for visualiza-

tion of the posterior walls of the left ventricle as well as the evaluation of the diagonal, circumflex, and obtuse marginal arteries. The patient may need to be placed in severe Trendelenburg position, and you should allow the heart to fall into the right pleural space when performing this maneuver in order to improve hemodynamics. Extension of a sternotomy into a left anterolateral thoracotomy can also improve exposure of the posterior heart

If extreme cardiac instability or asystole occurs when attempting to lift the heart to perform posterior repair, cardiopulmonary bypass is indicated. The techniques for bypass are beyond the scope of this chapter. If you are unfamiliar with that technique, or bypass is not available, temporary total inflow occlusion should be performed. This is done by cross clamping the inferior and superior vena cava at their intrapericardial location, which will empty the heart (likely resulting in cardiac arrest) and allow for expeditious repair. This should be limited to 1-3 min. Once the injury is repaired, expeditiously restart the heart with defibrillation and cardiac medications.

– If the heart is not beating, your priority should be to restart the heart. Continue resuscitation with blood products, cardiac drugs, open heart massage, and cardioversion if indicated. Do not delay attempts to achieve return of spontaneous circulation to repair cardiac wounds as this often takes longer than anticipated. Most injuries can be controlled with finger occlusion.

After restoration of circulation, wait a few minutes prior to attempting sutured repair of cardiac muscle as it will be very irritable.

– Missiles and fragments should be removed at the primary operation to avoid embolization, endocarditis, and erosion, which can result in a secondary injury.
– Atrial wounds can be occluded by digital pressure or a vascular clamp and then over sewn with a simple running 2-0 or 3-0 PDS suture. Pledgets may be required if the atrium is very thin walled.

For injuries to the atrial appendage, a linear cutting stapler can be used to repair the injury. The atrial lumen can be significantly narrowed without significant compromise as long as inflow and outflow are preserved.

– Myocardial free wall injuries should be closed primarily with 2–0 or 3–0 polypropylene pledgeted horizontal mattress sutures. Teflon pledgets are generally used, but if unavailable, small segments of the patient's pericardium make an excellent substitute.

If an injury is adjacent to a coronary artery, the mattress suture should be placed under the artery. The distal myocardium should be monitored to evaluate for any ischemia.

– Large coronary artery injuries should be primarily repaired with 6–0 polypropylene if possible, without causing significant stenosis, or bypassed with vein grafts. DO NOT waste time dissecting out the internal mammary artery.

If the injury is to the distal third of a major coronary artery (and distal to any major branches), or in a small branch, the artery may be ligated.

Pericardial Window—the subxiphoid trans-diaphragmatic pericardial window is an excellent diagnostic adjunct in a hemodynamically stable patient with suspected cardiac injury when the FAST exam is not available or equivocal. It can also be helpful in hemodynamically unstable patients with known intra-abdominal injuries who are undergoing laparotomy with possible but low suspicion for cardiac injury. It SHOULD NOT be performed in a hemodynamically unstable patient with known or high suspicion for cardiac injury, as these patients should undergo emergent exploration through one of the above incisions.

- Technique
  - Under general anesthesia in the operating room, an incision is made over the midline of the xiphoid process and extended a few centimeters down onto the abdominal wall.
  - Using blunt dissection, separate the peritoneum and develop a plane posterior to the xiphoid.
  - The xiphoid may be excised using heavy scissors to aid in visualization.
  - Palpate the transmitted inferior cardiac impulse to locate the pericardium, and then grasp it with two Allis clamps.
  - Make a 1 cm longitudinal incision into the pericardium sharply.

  If the field becomes flooded with blood, that is indicative of a cardiac injury, and you should proceed with operative exploration.

    - The window may be falsely positive if the peritoneum is accidentally opened in a patient with hemoperitoneum, or if there is excessive bleeding from the dissection behind the xiphoid.

Resuscitative thoracotomy—Again, firm indications for resuscitative thoracotomy in children are not well defined, but based on adult data, we recommend this procedure for a child who presents with a history of penetrating thoracic trauma with witnessed arrest in the emergency department, in patients who have been pulseless and receiving cardiopulmonary resuscitation (CPR) for less than 15 min. Or for children with blunt injuries with a witnessed arrest without other obvious nonsurvivable injuries. It may also be indicated for patients with thoracic trauma who are so hemodynamically unstable or decompensating rapidly, and you do not feel they will make it to the operating room exploration. It is imperative that this procedure should only be performed by experienced clinicians when a trauma or thoracic surgeon is immediately available to take the patient to the operating perform definitive stabilization. This is the absolute definition of controlled chaos.

- All team members should be aware that the procedure is taking place in order to limit inadvertent injury from sharp instruments or broken ribs.

- Other members of the team should be simultaneously securing the airway, obtaining IV access, and initiating resuscitation with crystalloid and blood products in a balanced fashion.
- A right chest tube thoracostomy should also be performed at the same time.
- Technique
  - Position the patient with the left arm above the patient's head.
  - Splash the chest with betadine.
  - Using a scalpel, make a bold incision in the 4th interspace just above the rib (just below the nipple in males and pre-pubescent females, and in the inframammary crease in females whose breasts have formed) from the sternum to the posterior axillary line, aiming for the tip of the scapula which will help you follow the curve of the rib
  - Open the intercostal space sharply ABOVE the rib, taking care to avoid injury to the neurovascular bundle. Use mayo scissors or trauma sheers to divide the intercostal muscles.
  - The incision should be extended posteriorly as far as possible, retracting rather than dividing the latissimus muscle.
  - The rib spreader should be inserted with the handle towards the bed in order to facilitate extension across to the right chest if necessary.
  - Open the pericardium sharply anterior to the phrenic nerve and extend the pericardiotomy the length of the heart to allow the heart to be delivered and fully evaluated. This should be done using a scalpel, as any pericardial effusion will make the pericardium extremely difficult to grasp or cut with scissors. Scissors can then be used to extend the incision longitudinally from the aortic root to the apex of the heart.

    Evacuate any clot and evaluate for presence or abscess of any cardiac activity.

    Deliver the heart to allow for examination for injuries.

    If no cardiac activity is present, or if there is a lethal arrhythmia, perform manual massage. This should be performed by compressing the heart between the palms of both hands.

    If the heart is flaccid or there is air noted in the coronary arteries, the likelihood of success is exceeding low.

    Digital control of penetrating ventricular injuries is usually sufficient to allow transport to the operating room. Atrial injuries should be controlled with clamps.

    Advance cardiac life support cardiac medications combined with directly delivered shocks of 20 to 50 joules is frequently needed to obtain a perfusing rhythm.
  - Mobilize the lung by taking down the inferior pulmonary ligament (which is not a true ligament but an extension of the parietal pleura).

    Retract the lung superiorly and laterally and make a small incision in the pleura tethering the lung to the diaphragm.

Using blunt dissection, separate the lung from the mediastinum to the level of the inferior pulmonary vein.
Elevate the lung medially, exposing the descending thoracic aorta

– The next step is to cross clamp the descending aorta to limit distal blood loss and improve perfusion to the heart and brain.

Palpate the aorta to assess the patient's remaining blood volume. It can be temporarily digitally occluded against the spine until clamping can be performed.
Place scissors against the spine just posterior to and parallel with the aorta, and use a spread, cut, spread technique to open a window in the pleura posterior to the aorta. This tissue is often much more robust than anticipated. This process should be repeated anterior to the aorta to create the space between the aorta and the esophagus. Placement of a nasogastric tube can facilitate identification of the esophagus and avoid injury.
Blunt dissection should then be used to further develop the plane so that a non-crushing aortic clamp can be placed horizontally across the aorta.

Blunt Cardiac Trauma (Image 32.2)

Data regarding blunt cardiac injury in children is limited as the injury is uncommon, occurring in less than 5% of children with blunt thoracic trauma. Myocardial contusion accounts for the majority of these injuries. Other injuries include traumatic ventricular septal defects and papillary muscle ruptures. Ventricular free wall rupture is exceedingly rare in children. Blunt injury usually results from high-energy mechanisms, such as motor vehicle collisions [18–20]. Due to the pliable nature of the child's chest wall, injuries can occur without associated chest wall injuries. Additionally, they often have few if any presenting signs or symptoms, and thus

Image 32.2 Polytrauma in a child

elicitation of mechanism of injury is even more important in these cases in order to raise suspicion for blunt cardiac injury.

Initial evaluation and resuscitation should follow the general principles of ATLS. Findings on the primary survey that should raise suspicion for blunt cardiac injury include:

- Complaint of angina like chest pain
- Chest wall deformities, abrasions, ecchymosis
- Focal tenderness over the superior ribs, sternum, or scapula
- Paradoxical chest wall motion
- Muffled heart tones or a new heart murmur
- The presence of an arrhythmia, or acute heart failure
- Unequal upper and lower extremity pulses

Following the primary survey, adjuncts in the hemodynamically stable patient with blunt thoracic injury should include:

- Chest X-ray to evaluate for rib fractures, HTX/PTX, or widened mediastinum
- eFAST cardiac window to evaluate for a pericardial effusion of evidence of tamponade.
- Cardiac troponin levels
  - Non-specific, but can be helpful in conjunction with the rest of the evaluation
- Electrocardiography
  - May show sinus tachycardia, a new arrhythmia, new bundle branch block, or ST changes. None of these are specific for blunt cardiac injury, but should raise suspicion in the right clinical setting.
- In an asymptomatic child with a normal cardiac troponin at presentation and again 6 h later, who also has a normal EKG, you can essentially rule out blunt cardiac injury [3, 21].
- If troponins are elevated or EKG is abnormal, the child should be admitted for at least 24 h of observation with telemetry monitoring, and a formal echocardiogram should be obtained.

Specific injuries and their management

- Myocardial contusion should be treated with supportive care, and the child should follow up with a pediatric cardiologist after discharge. If significant arrhythmia develops, or there is evidence of ischemia, cardiology consultation should be obtained while inpatient.
- Cardiac rupture or tamponade should be treated with surgical exploration similar to penetrating cardiac trauma as described above.
- Ventricular septal defects or valvular injuries should be repaired in a controlled setting with the assistance of a cardiothoracic surgeon and cardiopulmonary bypass.

Great Vessel Injuries

Historically, most patients with significant great vessel injuries died at the scene; however, with recent improvements in pre-hospital care, more of these patients are being seen in the trauma bay [18]. The National Trauma Registry still reports a mortality rate of 50–60% in patients with traumatic aortic disruption. Children with great vessel injuries often present in extremis, and these injuries will often prove fatal if not identified early and managed appropriately. A multidisciplinary approach including cardiothoracic or vascular surgeons and interventional radiologists is often best.

In isolated thoracic vascular injuries, therapeutic anticoagulation should be initiated prior to cross clamping and maintained until reconstruction or repair is complete and normal flow reestablished. Postoperatively these patients should receive a short course of antiplatelet therapy with low-dose aspirin. Unfortunately, the use of systemic anticoagulation and antiplatelet therapy is often contraindicated due to polytrauma and the concern for hemorrhage, specifically in patients with intracranial injuries or abdominal solid organ injuries. In these cases, the proximal and distal vessels should be flushed with heparin prior to clamping and again prior to completion of the repair/anastomosis [22].

The use of temporary vascular shunts can be particularly useful in the case of a child with multiple life-threatening injuries including a thoracic vascular injury. Shunts are more typically described in peripheral vascular trauma, but it can be used as a temporizing measure in the thorax as well, allowing for resuscitation and operative intervention for injuries in the head, abdomen, and extremities prior to definitive repair of vascular injuries. An appropriately sized shunt should allow for distal perfusion while avoiding intimal damage. Balloon catheter thrombectomy and local heparin saline infusion should be performed before placement and after removal of the shunt [22].

Penetrating Great Vessel Injuries

The majority of thoracic great vessel injuries are caused by penetrating trauma. Trauma bay evaluation and resuscitation should once again follow ATLS guidelines as described elsewhere in this book. If time permits, attempt to ascertain the type of instrument used, as the caliber of the gun or length of the knife may increase the likelihood of great vessel injury.

Indicators of Possible Penetrating Thoracic Vascular Injury

- Massive HTX and/or massive bleeding from external wounds, specifically those near the thoracic outlet, should raise suspicion for great vessel injury.
- Thoracic outlet hematoma

- Diminished and asymmetric peripheral pulses in the presence of penetrating thoracic injury should significantly increase suspicion of great vessel injury.
  - However, even penetrating vascular injuries can be completely contained by the perivascular adventitia, which can allow for persistent flow past the injury, and thus the child may still have a normal pulse exam.

Adjuncts to the primary survey should include

- Chest X-ray to evaluate for HTX/PTX, obliteration of the aortic knob, widened mediastinum, depression of the left main bronchus, left apical pleural cap
  - Marking the entry and exit wound can help you postulate as to the path of a missile, but keep in mind that once inside the body, the projectile trajectory is unpredictable.
- eFAST cardiac window to evaluate for a pericardial effusion of evidence of tamponade.

In a hemodynamically stable patient, CTA is the best imaging study to evaluate for a suspected thoracic vascular injury. This can be especially helpful in determining the best incision for optimal exposure of the injured vessel. CTA is somewhat limited in its evaluation of the aortic root and ascending aorta, and if suspected, a cardiac gated CTA should be performed. Be mindful that ductus bumps, the infundibulum of the superior intercostal artery, a diverticulum of Kommerell may mimic aortic injury but do not, in fact, require treatment. If the patient remains hemodynamically stable, formal angiography should be performed to confirm a vascular injury.

Indications for operative repair of penetrating thoracic great vessel injuries

- Hemodynamic instability with evidence of thoracic injury
- Chest tube thoracostomy with initial output >10–15 mL/kg, or evidence of ongoing hemorrhage (>2–3 mL/kg/h over 4 h)
- Expanding hematoma at the thoracic outlet
- Imaging with evidence of great vessel injury

Successful repair of these injuries is most dependent on adequate exposure. Patient stability as well as suspected injuries should dictate your operative approach.

Specific Injuries

Ascending Aorta and Aortic Arch

- Approached through a median sternotomy with cervical/supraclavicular extension as indicated.
  - The innominate vein crosses anterior to the arch vessels, and it should be ligated if necessary to provide adequate exposure.

- Will most likely require cardiopulmonary bypass or circulatory arrest and the assistance of a cardiothoracic surgeon.
- Deflation of the left lung using a bronchial blocker or dual-lumen endotracheal tube will facilitate visualization of the superior portion of the left thorax. The lung should be retracted inferiorly.
- The ascending aorta is intra-pericardial. The superior pericardial reflection should be dissected free, and the innominate vein should be identified, ligated, and divided in order to facilitate exposure.
- Mobilize the aortic arch. Do not grasp large amounts of adjacent tissue as the vagus and recurrent laryngeal nerves are easily injured during this portion of the dissection.
- Small anterior or lateral lacerations may be repaired primarily using interrupted polypropylene sutures without the need for bypass.Descending Aorta

- A hemodynamically stable child with an isolated descending thoracic aortic injury can be approached through a posterolateral thoracotomy.
  - Position the patient in the lateral decubitus position, with a roll under the right axilla. The left arm should be appropriately supported, and all pressure points should be padded. In infants and small children, both hips and knees should be slightly flexed. In adolescents, the lower leg should be flexed at the knee and hip, and the top leg should remain straight and supported by a pillow.
  - Identify the inferior angle of the scapula (which correlates with the tip of the 6th rib), as well as its spinal and axillary borders. The incision should be made parallel and a cm away from the spinal border of the scapula, and then extended around the angle of the scapula to the anterior axillary line. The incision should be deepened through the subcutaneous tissue with electrocautery until the fascia overlying the latissimus dorsi and trapezius are exposed.
  - Total transection of the latissimus dorsi is performed using electrocautery, exposing the anterior serratus and rhomboid muscles. The serratus is then elevated and retracted anteriorly.

    A muscle-sparing variant is often described for other indications in children, and if time allows, can be considered in order to preserve shoulder function

    - Generous subcutaneous dissection is required to facilitate retraction of the latissimus for full exposure.
    - The thoracolumbar fascia is transected, and the muscle is retracted.

  - The 4th intercostal space is identified by placing a hand below the scapula and pressing gently cephalad, identifying the first rib and counting down. The intercostal muscles should be divided with electrocautery just superior to the rib.
  - The rib spreader is placed and opened slowly and progressively to avoid fracture.

- Children with concomitant intra-abdominal or other intra-thoracic injuries should be placed supine and approached through a median sternotomy, left anterolateral thoracotomy, or clamshell thoracotomy as indicated. Those approaches have been described previously in this chapter.

- If the injury is contained by a hematoma, obtain proximal and distal control prior to entering the hematoma. If uncontained, use digital pressure or a sponge stick to control bleeding while obtaining control.
- We advocate for the "clamp and sew" technique, as cardiopulmonary bypass is rarely immediately available, and as long as cross clamp times are limited to less than 30 min. Postoperative paraplegia is rare [23].

  – To expeditiously obtain proximal control, follow the left subclavian proximally to the aortic arch, and place a Rumel tourniquet around the aortic arch between the takeoff of the left common carotid and the left subclavian, taking care to avoid injury to the left recurrent laryngeal nerve. The left subclavian should then also be controlled with a Rumel tourniquet or vessel loop depending on the size of the child.
  – Distal control can be obtained with soft aortic clamps or other appropriately sized vascular clamps, depending on the size of the child.
  – The hematoma is entered after control is established, and the extent of the injury is determined. Both sides of the aorta should be inspected to rule out a through and through injury. The internal portion of the aorta should also be evaluated for intimal flap or dissection, which can lead to thrombosis if not identified.
  – At this point, if the injury can be controlled with a side-biting partially occlusion clamp, this should be placed and proximal and distal flow re-established.
  – Attempt to repair injuries primarily with fine polypropylene sutures. This is especially important in small children in order to avoid future issues with pseudocoarctation due to aortic expansion during normal growth. This is possible even with significant injuries up to and including complete transection, as long as there is sufficient length to repair without undue tension. Keep in mind that there will be some associated blast injury with gunshot wounds, and the tissue should be debrided to healthy ends.

  Children have soft arteries without atherosclerotic disease, and as such meticulous attention to following the curve of the needle when sewing these vessels is mandatory, as slight derivation can lead to tearing of the artery.

  – Patch angioplasty and interposition graft can be performed if necessary, with attention paid to post-operative follow-up and the possible need for re-intervention if pseudocoarctation occurs.

  Remember to account for the presence of vasospasm when sizing prosthetic grafts, and the largest possible graft should be used to accommodate for growth.Innominate artery/Proximal Left Common Carotid artery

- Approached through a median sternotomy with cervical extension along the anterior border of the sternocleidomastoid (SCM).

- Ligate and divide the innominate vein to improve exposure.
- Small/partial tears can be repaired primarily with fine polypropylene sutures.
- Larger injuries can be repaired with bypass and exclusion, which can be done without systemic heparinization or the need for cardiopulmonary bypass.
  - The transected artery should be controlled proximally and distally with appropriately sized vascular clamps.

    If both the innominate and left common carotid are significantly injured, a left common carotid shunt should be placed while the innominate is repaired to ensure perfusion to the brain.

  - The distal end should be debrided to healthy appearing tissue.
  - Proximal ascending aorta to innominate artery/distal left common carotid artery interposition graft with vein or PTFE can be performed depending on the size of the vessel.
  - A side-biting vascular clamp can be placed on the proximal aorta in order to facilitate aortotomy and proximal graft anastomosis.
  - After completion of the graft, the injury at the origin of the aortic arch should be over sewn (Image 32.3). Proximal Subclavian artery

- Proximal Left Subclavian is approached through a left anterolateral thoracotomy.
- Proximal Right Subclavian is approached through a median sternotomy.
- Injuries should be repaired primarily, if possible, with fine polypropylene suture.
- Larger injuries or those with significant devitalized tissue will require interposition graft with vein or PTFE, as mobilization of the subclavian for end-to-end anastomosis is exceedingly difficult.
- Ligation of the subclavian artery is often well tolerated and can be performed in a damage control setting. Distal Subclavian artery

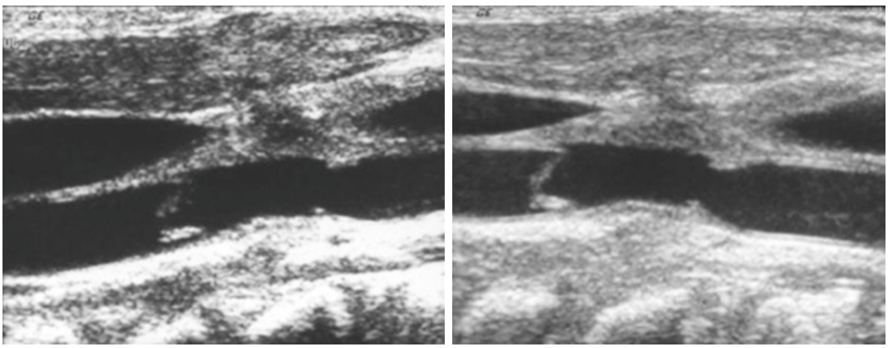

Image 32.3 Doppler study showing carotid injury in a child with blunt trauma

- Approached tailored based on the location of the injury.
  - Proximal control can be obtained as described above.
  - Supraclavicular incision can be used to obtain distal control.

    Incision is made parallel to and just above the medial half of the clavicle.
    Carried down through the platysma and clavicular attachment of the SCM, exposing the internal jugular vein and scalene fat pad.
    Identify the phrenic nerve as it courses over the anterior scalene muscle; this should be gently retracted and preserved.
    Divide the anterior scalene just superior to the clavicle to expose the subclavian artery.
    If exposure is still limited, the clavicle can be divided.

    - Clear the anterior surface of the clavicle and circumferentially dissect it free from surrounding tissues.
    - Use a perforating towel clamp to grasp the clavicular head, and divide the clavicle in the mid-portion using the Gigli saw.
    - The clavicle can be re-approximated after the vascular repair is complete, but this is not necessary.

- Injuries should be repaired in a similar fashion to proximal subclavian injuries.

  Thoracic Vena Cava

- Approached through a median sternotomy
- Simple anterior lacerations can be controlled with a partially occluding vascular clamp and repaired primarily with fine polypropylene sutures.
- Posterior injuries require the use of cardiopulmonary bypass, and repair through the right atrium.

  Subclavian Vein

- Managed similarly to subclavian arterial injuries, primary repair should be attempted, but in the unstable patient or those with large complex injuries, this vein can be ligated.
  Azygos Vein

- Usually found at the time of exploration for other suspected injuries
- Primary repair can be attempted, but in the unstable patient or those with large complex injuries, this vein should be ligated.

Blunt Great Vessel Injuries

Blunt injury to the thoracic aorta and great vessels can occur when these vessels are essentially crushed between the anterior and posterior chest wall, or from rapid deceleration due to shearing forces in areas where the aorta is stabilized, specifically the isthmus, but also at the take-off of the great vessels. The majority are caused by motor vehicle accidents, with a higher incidence of thoracic aortic injuries in unrestrained children [24].

Indicators of Possible Blunt Thoracic Vascular Injury

- Presence of other injuries that are known to be associated with significant force, including first rib fractures, scapular fractures, sternal fractures, bilateral clavicular fractures, pulmonary contusions, diaphragmatic injuries, tracheobronchial disruption, and esophageal injuries.
- Massive HTX
- Thoracic outlet hematoma
- Diminished and asymmetric peripheral pulses in the presence of blunt thoracic injury.
  - Again, blunt vascular injuries can be completely contained by the perivascular adventitia, which can allow for persistent flow past the injury, and thus the child may still have a normal pulse exam.
- Upper extremity hypertension with associated paraplegia and lower extremity pulse deficit .

Adjuncts to the primary survey should include

- Chest X-ray to evaluate for the above associated bony injuries, HTX/PTX, obliteration of the aortic knob, widened mediastinum (most common radiographic finding), depression of the left main bronchus, left apical pleural cap.
- eFAST cardiac window to evaluate for a pericardial effusion of evidence of tamponade.

Patients with blunt thoracic trauma and high clinical suspicion should undergo CTA to evaluate the thoracic vessels. If CT thorax without angiogram is performed initially, findings suspicious for aortic injury include localized increase in aortic diameter and linear lucencies within opacified aortic lumens.

Initial management should include permissive hypotension, with pharmacologic blood pressure control using beta blockage to keep systolic pressure of 120 mmHg in very small children (or 20 mmHg less than baseline in older children/adolescents) [25]. This has been shown to slow the expansion of the injury and reduce the risk of rupture to <2% [26]. This must be balanced with the risk of compromising cerebral perfusion pressure in the case of concomitant closed head injury. Esmolol is an excellent choice due to its short half-life, making it easy to adjust course should the patient develop hemodynamic instability due to ongoing hemorrhage or other causes of shock.

Given that blunt thoracic vascular injury is usually associated with polytrauma, a systematic approach to the management of all major injuries is necessary, and the most immediately life-threatening injury should be treated first. Aortic and arch vessel injury can be monitored with intra-operative transesophageal echocardiography, and it can repaired after other life-threatening injuries have been addressed [23].

Specific Injuries

Blunt aortic injury

- Given the multilayer aortic wall, blunt aortic injuries can often be complex. An improved grading system was introduced in 2009, and is used to describe various types of thoracic aortic injuries, and also assist in directing their management.
  - Grade I injury is an intimal tear, which can often be managed non-operatively with continued blood pressure control, as most will heal without intervention [26]. Again, this may not be possible in the case of severe closed head injury, and in those cases, operative intervention may be indicated.
  - A grade II injury is an intramural hematoma, grade III is a pseudoaneurysm, and grade IV is a complete rupture.
  - The current recommendation is for operative repair (either open or endovascular) of all grade II-IV injuries; although in adults, some grade II injuries are being treated with medical management with good results.
  - In select cases where the patient is a prohibitive operative risk and also not a good candidate for endovascular repair, medical management alone may be employed. Serial imaging is required in these cases to evaluate for progression of the injury despite medical management.
- Hemodynamically unstable patients with blunt thoracic aortic injuries as the cause of their instability should be taken immediately to the operating room for repair. Choice of incision and type of repair is similar to that for penetrating injuries and is discussed in the prior section.
- Ascending aorta/arch injuries will require cardiopulmonary bypass and the assistance of a cardiothoracic surgeon.
- Interposition graft is more commonly required in blunt injury, and again sizing of grafts should take into account vasospasm and future aortic growth.
- In recent years, endovascular repair has been used with greater frequency in the pediatric population. It is especially useful in older children with larger vessels, as a bridge to definitive operative intervention in an unstable patient, or if there is a contraindication to anticoagulation. This should be approached in a multidisciplinary fashion, with consultation with interventional radiology or vascular surgery [27].
  - The method of placement is determined by the caliber of the access vessels, the size of the introducer sheath required based on the aortic diameter, and the distance from the site of access to the injury.

Blunt injuries to the other great vessels are managed as described above for penetrating injuries.

Conclusions

While injury to the heart and great vessels in children is rare, it is associated with a disproportionately high morbidity and mortality, especially given that these injuries are often associated with polytrauma. A multidisciplinary approach including general, trauma, cardiothoracic, and vascular surgeons is often required, and transfer to a Level 1 Trauma Center should be initiated early if deemed necessary. Managing these injuries requires prompt identification, careful preoperative planning for optimal patient position and incision to ensure adequate visualization, and meticulous attention to vascular surgical principles.

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Chapter 33
Vascular Injuries of the Abdominal Vessels

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Abstract Abdominal vascular injury presents itself on a wide spectrum. Rarer occurrences, such as aortic or inferior vena caval (IVC) injuries, can have devastating outcomes, while injuries to the mesentery or renal vasculature can be primarily managed non-operatively. The diagnosis heavily relies on provider suspicion when a patient presents to the trauma bay. A thorough physical exam in conjunction with advanced imaging techniques such as a focused assessment with sonography in trauma (FAST) exam and/or computerized tomography (CT) angiography are important for diagnosis and potential operative planning. In some scenarios, hemodynamic instability drives decision making, in which imaging is bypassed for a quick transfer to the operating room. Operative interventions have evolved from traditional open surgery to more endovascular techniques and hybrid options. This chapter goes into depth on the presentation and management of several vascular systems within the abdominal cavity.

Keywords Vascular trauma · Aorta · Inferior vena cava · Renal · Mesenteric · Vessel injury

Key Concepts
- CT Angiography is the gold standard for abdominal vascular evaluation.
- High incidence of associated intraabdominal injuries when large vessel injury is present.
- Hemodynamic stability with a vascular injury can be managed non-operatively.
- Endovascular approaches, though rare, are increasing over the past decade.

Initial Radiographic/Ancillary Studies
- Chest X-ray, Pelvis X-ray
- FAST exam (more helpful in hemodynamically unstable patients)
- CT Abdomen Pelvis (preferably CT Angiography if a vascular injury is suspected early)

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Introduction: Initial Management of Trauma Patient: Vascular Injury Consideration

To aid in the discussion, two different trauma scenarios follow:

Patient 1 is a 15-year-old male with no significant past medical history was dropped off at the emergency department with what appears to be two gunshot wounds to the abdomen. The patient is alert and talking with staff as he is brought into the trauma bay as a Level 1 activated trauma. In contrast, Patient 2 is a 6-year-old female improperly restrained passenger involved in a motor vehicle collision. She is complaining of abdominal pain, bruising, and distention. She arrives as a Level 2 trauma with a seatbelt sign on the initial exam.

Regardless of either patient above or any other presenting scenario, the primary survey taught during Advance Trauma Life Support (ATLS) training remains of utmost importance. This encompasses the ABCDEs of trauma care—Airway, Breathing, Circulation, Disability, and Exposure [1]. Each of these above scenarios needs a successful primary survey; otherwise, potentially life-saving opportunities may be missed. At this point, hemodynamics will likely influence whether or not patients receive advanced imaging, are transitioned to the operating room, or are admitted for observation. With this transition in care, it is crucial to consider a broad differential diagnosis and the possible outcomes for each. Remember, a child's initial response to hypovolemia is tachycardia, not hypotension. Hypotension typically occurs late when a child has severely low blood volume [2]. Therefore, appropriate resuscitation with intravenous fluids and transition to blood products is essential, especially when an abdominal vascular injury is of concern. Ensuring type-specific blood products are available or activation of your massive transfusion protocol should considered if needed.

Additionally, alerting the anesthesia team and operating room staff early will allow for a quick transition if operative intervention is needed. Admission to the intensive care unit will allow for more frequent vitals and additional resources if non-operative management fails.

Abdominal Vascular Injury

Trauma is one of the leading causes of morbidity and mortality in children [3]. The two most common trauma mechanisms leading to pediatric injuries and/or death are motor vehicle collisions followed by firearm injuries [3, 4]. These mechanisms can affect any part of the body. This chapter focuses on abdominal trauma, more specifically, major vascular injury within the abdomen.

Two broad mechanisms should come to mind when initially evaluating a trauma patient with abdominal injury concerns—penetrating versus blunt. The specific mechanism will determine the best algorithm for patient management and potential operative intervention that may be needed. Once a patient is stabilized, a decision is made whether advanced imaging will assist in diagnostic purposes for the trauma patient. For abdominal vascular injury, the computed tomography angiography (CTA) of the abdomen and pelvis has become the gold standard for imaging [5]. It is a non-invasive method to obtain a detailed evaluation of the abdominal vasculature. This specific CT scan utilizes image acquisition in three different phases to help identify vessel injury versus benign calcifications [6]. This imaging technique has largely replaced the prior standard of digital subtraction angiography. Another imaging adjunct that may be considered, and will be discussed later in the chapter, is the abdominal FAST exam.

The following sections focus on specific abdominal vascular injury presentation, recognition, and potential management options.

Aorta

Traumatic vascular injuries involving the abdominal aorta are rare in children. Selective pathways are more well-established in the adult population, but the pediatric surgical literature consists of small case reports or series [7, 8]. As many studies have identified, an underestimation of aortic injuries likely exists as individuals with aortic transection or other high-degree injuries die at the scene [7, 9]. However, for patients that make it to the hospital, typical physical exam findings that should clue you into a possible aortic injury include a significant seat belt sign, hemodynamic instability with associated abdominal pain, neurologic deficits, and acute lower body arterial insufficiencies [7]. In addition, abdominal aortic injuries are associated with restrained patients versus thoracic aortic injuries in unrestrained ones [8].

Patients with a seatbelt sign or abdominal pain with a suspicious mechanism have traditionally been evaluated with a CT scan of the abdomen and pelvis. This imaging technique can identify aortic injuries, including aortic dissection and intimal flaps. In addition to providing an evaluation of the vasculature, the CT scan may identify associated injuries that are secondary to high-speed mechanisms, including spinal fractures and hollow viscus injuries. However, if a vascular injury is high on the differential, performing CTA of the abdomen and pelvis may provide additional valuable information that can be used for preoperative planning.

Clear indications for surgical interventions in this trauma population include hemodynamic instability, concern for continuing or new hemorrhage, and associated intraabdominal injuries. However, many abdominal aortic injuries are treated with non-operative management or minimally invasive techniques. In fact, endovascular approaches for angioembolization or stent graft placement have significantly increased over the last decade [10]. Monitoring these patients in the pediatric intensive care unit with hourly neurovascular checks is recommended. Following resuscitation, anticoagulation strategies should be considered, especially if an intimal flap or dissection is identified. Consultation with hematology and/or vascular surgeons for long-term follow-up should be considered.

Inferior Vena Cava

Inferior vena cava (IVC) injuries are also rare in pediatric patients. A previous study by Rowland et al. reviewed the National Trauma Data Bank (NTDB) and concluded that when a venous injury is identified, the most common vessel involved is the IVC [11]. The patient's overall presentation following the trauma is variable. Injuries may be due to both blunt and penetrating mechanisms. Similar to aortic injuries, many arrive hemodynamically stable allowing advanced imaging, while others may be hypotensive with the discovery of a major venous injury during operative exploration. One important association is that over 13% of patients had a concurrent arterial injury when a venous injury was diagnosed [11].

In a hemodynamically stable patient, a CT scan of the abdomen and pelvis may indicate an IVC injury that can be monitored. Figure 33.1 reveals a suprahepatic IVC injury just distal to the hepatic vein confluence that was managed non-operatively in the pediatric ICU. Depending on resources and pediatric vascular surgery experience, vascular surgery may be consulted in the event non-operative management fails.

The injury location of the IVC helps predict survival. Prior reports have identified retrohepatic IVC injury to have a nearly 100% mortality rate [12, 13]. When operative intervention is warranted, a surgeon must decide whether they can primarily repair the vessel, utilization of a vascular conduit is needed, and in rare cases, if IVC ligation is warranted. IVC ligation is drastic and should be avoided unless this is determined to be a potentially life-saving measure. If performed, frequent neurovascular monitoring for venous congestion may lead to compartment syndrome,

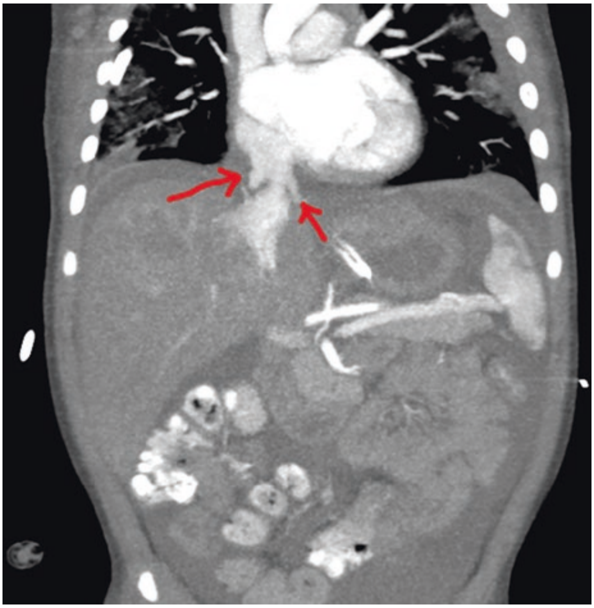

Fig. 33.1 Suprahepatic IVC injury with concerns of active extravasation in the 2-year-old patient that was involved in a motor vehicle collision. (*Source: Division of Pediatric Surgery, Children's of Alabama; Birmingham, AL*)

especially of the lower extremities is needed [13]. Significant lower extremity edema or neurologic changes may indicate a need for vascular reconstruction with a prosthetic conduit.

Renal

With a larger kidney to abdominal cavity ratio, children have a higher risk for renal trauma as the kidney partially lies below the rib cage [14, 15]. Prior studies have reported as high as 20% of children with blunt abdominal trauma suffer a kidney injury [16]. However, these injuries are more likely to involve renal parenchyma, not the vascular pedicle. When a vascular injury is involved, renal artery injuries occurred more frequently than other intraabdominal arterial injuries from a blunt trauma mechanism [17]. Mechanisms typically include a mix of high-riding lap belts, unrestrained patients, and firearm injury. The majority of these patients arrive hemodynamically stable, allowing for further imaging to aid in diagnosis.

One controversial imaging technique is the FAST exam. In adults, this exam assesses for free fluid associated with cardiac or intraabdominal injury and is primarily helpful in the setting of hemodynamic instability. It evaluates the right and left paracolic gutters, which would potentially identify bleeding involving the kidney. However, in hemodynamically stable children, the use of the FAST exam has been controversial in demonstrating improved clinical care, identifying injuries, or reducing the use of hospital resources [18, 19]. The FAST examination may be best utilized in these situations when clinicians are highly experienced with ultrasound and/or the child is clinically stable enough for repeat FAST examinations to denote any changes [20, 21]. Rather than relying on ultrasound, many undergo a CT scan of the abdomen and pelvis with IV contrast. This would identify renal vascular injury as well as combined renal vascular and parenchymal injury as suggested by a grade IV or V injury diagnosis. Figure 33.2 is a CT image showing a left renal artery transection with associated hematoma and nonperfusion of the left kidney.

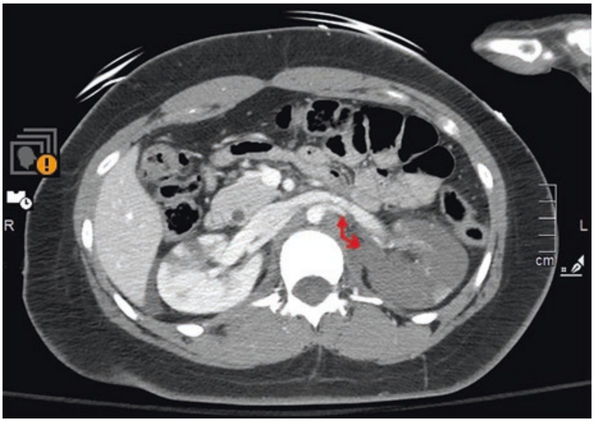

Fig. 33.2 Left renal artery transection with subsequent nonperfusion of the left kidney in a 15-year-old patient that was involved in a motor vehicle collision. (*Source: Division of Pediatric Surgery, Children's of Alabama; Birmingham, AL*)

Renal trauma in children has widely moved to nonoperative management strategies. This is primarily for non-vascular injury, but more recently has been evaluated for even grade V injuries [22, 23]. These patients will likely require blood transfusions and more frequent monitoring. However, certain scenarios require procedural intervention. Ongoing bleeding may signify the need for operative intervention with either nephrectomy or angioembolization.

Surgical management of a renal artery occlusion remains controversial. These injuries can be caused by traumatic transection, intimal flaps, or an occlusive thrombus, to name a few. In this scenario, identifying the contralateral kidney is of utmost importance. If both kidneys were healthy prior to the trauma and a single renal artery occlusion is identified with a visualization of a normal, contralateral kidney, arguments can be made to monitor conservatively with frequent lab checks, monitoring for hypertension, and no procedural intervention [24]. However, early intervention is warranted if a renal artery occlusion is identified with non-visualization of the contralateral kidney. Patients that can be anticoagulated may benefit from a minimally invasive endovascular stenting approach for revascularization [24, 25]. If postoperative anticoagulation is contraindicated, consideration for open surgical repair with revascularization is needed [25]. Other vascular injuries to identify include arterial pseudoaneurysms that can also be treated from an endovascular approach.

Finally, one may consider the involvement of pediatric urology if there is a suspicion for an associated injury to the renal pelvis, collecting system, or ureter. Often, additional imaging, such as a CT urogram, may be needed to better evaluate the urinary system. These patients may need long-term follow-up from a pediatric urologist as well.

Retroperitoneum

The prior sections discussed several of the retroperitoneal structures that may be injured during trauma. However, in many trauma cases, a retroperitoneal hematoma is the only sign on imaging for a potential injury. To aid in surgical trauma management, the retroperitoneum is divided into different "zones" as follows [26]:

Zone 1—central-medial, which is located between the two psoas muscles.

Zone 2—perirenal, which is lateral to the psoas muscles.

Zone 3—pelvic, which is inferior to the iliac wings in the pelvis.

Once diagnosed with advanced imaging, treatment pathways are individualized to the mechanism of injury, location of the injury, and hemodynamic stability of the patient. Penetrating injuries tend to have other associated injuries warranting exploration. However, in blunt trauma with a hemodynamically stable patient, only Zone 1 injuries have traditionally been surgically explored due to the major abdominal vessels within this area [27]. Advancements in endovascular approaches have further limited the exploration needed for Zone 2 and Zone 3 injuries, which are typically managed conservatively with observation. If concerns for an expanding hematoma or an ongoing transfusion requirement for Zone 2 or 3 injuries, definitive management with endovascular angioembolization may be warranted [27].

Mesenteric Vessels

The final abdominal vessel injury we will discuss involves the group of mesenteric vessels. This consists of the superior mesenteric artery/vein, the inferior mesenteric artery/vein, and the associated distal vessels that branch from these origins. These vessels supply a large portion of the gastrointestinal tract. Similar to the previous vessels discussed, these vessels are vulnerable to both penetrating and blunt traumatic mechanisms. Mesentery injuries are found in approximately 10% of blunt traumas [28]. Damage to one of these vessels is highly associated with other intraabdominal injuries such as a hollow viscus injury or solid organ parenchymal injury. Patient presentation largely varies when it comes to hemodynamic stability but typically consists of an abdominal pain picture with or without bruising and possible signs of peritonitis.

The cause of mesenteric vascular injury is partially due to the anatomy of the bowel. Due to the fixation points to the retroperitoneum and vascular attachments, shearing forces along those attachment sites are prone to injury [28]. Mesenteric arterial injury ranks second behind renal artery injury when an arterial vessel is injured [17]. These injuries are typically identified with a CT scan of the abdomen and pelvis. Delayed images may also help identify venous phase injuries, such as the superior mesenteric vein injury with active extravasation as seen in Fig. 33.3.

Vascular compromise to the bowel means operative ligation may not be an option. Inspecting collateral flow to the bowel and the bowel mesentery is critical before any vessel ligation is performed. Conservative management should be

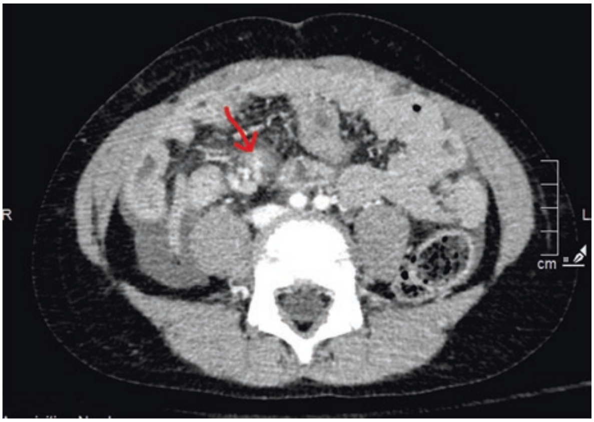

Fig. 33.3 Superior mesenteric vein injury in with active extravasation in the right lower abdomen of an 8-year-old patient involved in a motor vehicle collision. (*Source: Division of Pediatric Surgery, Children's of Alabama; Birmingham, AL*)

considered when a mesenteric hematoma is identified on advanced imaging or during a diagnostic laparoscopy. The surgical team must keep in mind bowel viability may be at risk due to a compromised vascular supply. Bowel compromise typically reveals itself over the next 24–48 h of close monitoring. Serial abdominal exams and hemodynamic monitoring is an appropriate strategy for these patients. These patients must be continually evaluated for any change in their abdominal exam, new onset of fevers, or signs of peritonitis that may warrant exploration.

Role of Endovascular Therapy

Minimally invasive techniques are continuing to replace traditional open approaches with similar success rates. The endovascular approach for vascular injury has been well-established in the adult population with both vascular surgeons and interventional radiology performing the procedures. However, pediatric endovascular literature, especially in the trauma population, remains scarce. Endovascular techniques can serve multiple purposes, including diagnostic imaging, helping to gain temporary hemorrhage control, and potentially provide definitive management for vascular injury. A prior NTDB review identified a significant increase in endovascular therapy in pediatric arterial trauma over the past decade [10]. Though many of these interventions involve extremity and chest injuries, angioembolization of the internal iliac artery for hemorrhage control was one of the most common procedures performed. However, no in-hospital survival advantage was identified despite the minimally invasive approach when comparing endovascular versus open approaches in these pediatric trauma patients [10].

As Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) is utilized more frequently in adult trauma for hemorrhage control, this method may be considered in adolescent patients for temporary hemorrhage control. The current literature estimates that pediatric patients with REBOA-amenable injuries represents 0.6% of all pediatric trauma [29] and the current pediatric experience in only in its infancy [30].

Outcomes

Abdominal vascular injuries in children are relatively rare. However, both patient scenarios previously mentioned are common trauma alerts. Patient 1 sustained a penetrating injury to the abdomen, meaning operative intervention is the next step. Active hemorrhage or hemodynamic instability in this patient should clue in a surgeon that a vascular injury is likely. In contrast to patient 1, patient 2's seatbelt sign and associated abdominal pain should raise awareness for a bowel injury, solid organ injury, and potential vascular injury. This patient warrants advanced imaging as they are hemodynamically stable. Likely they will be admitted to the intensive care unit with frequent abdominal exams and continuous vital sign monitoring.

Though vascular injuries are infrequent, reported morbidity and mortality rates are high. Prior studies have identified blunt trauma to be the more common mechanism; however, underestimation of penetrating injury is likely due to death on scene or during transport to the hospital [31, 32]. In addition, Allison et al. has shown overall survival from truncal vascular injury to be related to hemodynamic status upon arrival to the trauma bay [31]. Lastly, remembering that as many as 75% of abdominal vascular trauma has an associated intraabdominal injury will help ensure the patient gets the best care possible.

Conclusion

Abdominal vascular injury presents following both penetrating and blunt trauma. The severity of these injuries varies greatly. In hemodynamically stable patients, the trauma team should consider ordering advanced imaging if abdominal vascular trauma is suspected. The CTA abdomen and pelvis remain the gold standard, with the FAST exam acting in a supporting role. Remembering to have the operating room on standby for quick transfer is of utmost importance. Though many injuries are managed conservatively, the ones that do need an intervention need it emergently.

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Chapter 34
Vascular Injuries of the Extremity

James M. Prieto and Romeo C. Ignacio

Abstract Pediatric peripheral vascular injuries are uncommon but can cause significant morbidity and mortality. These injuries are often iatrogenic secondary to central venous catheter placement; however, traumatic fractures or direct penetrating trauma can cause vascular trauma as well. In traumatic extremity injuries, prompt examination and diagnosis are required in order to prevent limb loss and potential mortality. Soft and hard signs of vascular injuries must be evaluated to determine whether immediate surgical intervention is required. Additionally, the appropriate application of tourniquets can minimize blood loss while other life-threatening injuries are evaluated. The use of adjuncts such as ultrasound with duplex, computerized tomography (CT), and magnetic resonance angiography (MRA) can assist in the diagnosis and management of vascular injuries. Although endovascular techniques have made many advances over the last two decades, the mainstay of operative management in trauma is still open vascular exploration and repair. The availability of vascular expertise, operative resources, and hemodynamic status of the patient will determine the best operative approach. The key technical aspects of hemorrhage control, exposure, shunting, ligation, and vascular anastomosis (if possible) are imperative for optimal outcomes and decreased life-long morbidity. The variability in vessel sizes, physiologic response to shock, and propensity for vasospasm are some of the unique challenges in pediatric vascular trauma that must be considered in treating these injuries.

Keywords Vascular trauma · Pediatric vascular trauma · Pediatric extremity vascular injuries · Pediatric peripheral vascular trauma

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Key Concepts/Clinical Pearls

- Pediatric extremity vascular injuries are rare but carry a high potential for life-long morbidity and mortality.
- Prompt diagnosis is critical because limb salvage is dependent on timely revascularization when indicated.
- "Hard signs" of vascular injury on physical exam include absence of distal pulses, pulsatile bleeding, a rapidly expanding hematoma, an audible bruit or thrill, or multiple signs of distal ischemia (i.e., pain out of proportion, pallor, paresthesia, paralysis, and poikilothermia).
- CT angiogram is the best diagnostic test for extremity vascular injuries.
- Goals of management include hemorrhage control, shunting or ligation (if required), timely vascular reconstruction if indicated, and reduction of any associated fractures.

Initial Management of Trauma Patient

The initial management of a child presenting with a suspected vascular injury should focus on the principles of Advanced Trauma Life Support (ATLS®). Attention should quickly be directed to hemorrhage control if applicable. Vascular injuries to an extremity may require a tourniquet, but direct pressure should be initially applied. Topical hemostatic agents are also a potential adjunct to aid in slowing severe bleeding that is not responsive to direct pressure or not amenable to tourniquet placement. A complete physical exam must be performed as part of the secondary survey with specific attention to the pulse exam. Doppler signals or pulses should be assessed in all extremities as well.

If hard signs of vascular injury or distal ischemia are present, immediate exploration in the operating room is warranted. If advanced imaging techniques are expediently available, these may be helpful to localize the injury and assist with operative planning. Patients with fractures or dislocations in areas prone to vascular injuries should have a thorough exam performed before and after reduction and repair of the orthopedic injury to ensure appropriate vascular flow in the respective extremity. The availability of vascular expertise, operative resources, and the clinical status of the trauma patient will determine the optimal management to avoid loss of limb and potential death.

Initial Radiographic/Ancillary Studies

Initial studies indicated in a patient with a suspected extremity vascular injury include X-rays to diagnose any acute fractures or dislocations as well as a number of other advanced imaging methods. CT angiography has been established as the "gold standard" in the diagnosis of extremity vascular injuries. It is readily available at most trauma centers and provides high diagnostic accuracy, and may assist in operative planning before surgical intervention. Special attention must be considered to avoid unnecessary exposure to ionizing radiation and decrease the potential risk of secondary malignancies. Vascular ultrasound may also play a role in diagnosis and follow-up, as it may help avoid successive CT scans and increased radiation exposure. Angiography is another diagnostic adjunct with a similar sensitivity/

specificity to CT angiography. However, catheter angiography is an invasive procedure that has the potential for complications, including hemorrhage, dissection, hematoma, pseudoaneurysm, thrombus, embolism, vasospasm, and limb ischemia. In younger children, the smaller diameter of peripheral vessels can make catheterization difficult and increase the risk of iatrogenic injury. Several pediatric studies evaluating the safety of femoral arterial access for angiography describe complications such as vasospasm, transient pulse loss, hematoma, and long-term arterial occlusion, especially in children less than 2 years of age.

Introduction

Extremity vascular injuries are rare in children accounting for less than 1% of all annual trauma admissions [1, 2]. Iatrogenic injuries secondary to central venous or arterial catheterization are more common than blunt or penetrating trauma [3]. These traumatic injuries can be associated with mortality, limb loss, limb-length discrepancy, and poor quality of life [4]. Early diagnosis is critical, given that in many cases, the chance of limb salvage depends on timely operative intervention and revascularization. Injury mechanism, anatomic location, and additional associated trauma are important factors to consider as they can impact surgical management and outcomes.

Peripheral vascular trauma can be due to either blunt or penetrating mechanisms (51% blunt trauma in a recent study of the National Trauma Databank) [5]. Upper extremity injuries are generally more common and carry a more favorable prognosis compared with lower extremity trauma. Risk factors for increased morbidity and mortality in extremity trauma include lower extremity injuries, proximal vascular injuries, and limb-associated fractures [6].

Traditionally, management guidelines have been derived using data from adult trauma admissions. However, there are physiologic and anatomic factors that make pediatric vascular trauma particularly challenging. Children have smaller, thin-walled vessels and a higher incidence of vasospasm which can obscure the diagnosis and complicate management [7]. The rarity of these injuries and the unique ways in which they are present highlights the need for a clear algorithm for diagnosis and management.

Initial Evaluation and Management

Initial evaluation and management of a child with a suspected extremity vascular injury should focus on complete primary and secondary surveys. Additionally, priority should be given to rapid hemorrhage control. This is particularly important in children as their blood volumes are smaller than adults', and a seemingly small amount of blood loss may have greater physiologic consequences than anticipated. The highest blood volumes are in neonates at 85–90 cc/kg, and this gradually decreases to 70 cc/kg as the child ages. The average adult blood volume is approximately 65–70 cc/kg. From a physiologic perspective, children exsanguinating from an extremity injury will maintain their blood pressure until relatively late in the clinical course. Acute hemodynamic decompensation will occur later than in adults and represents a greater degree of hemorrhagic shock. A tourniquet or direct pressure should be applied immediately in the setting of active bleeding. Prompt tourniquet application in pediatric extremity trauma has been shown to reduce the amount of intravenous fluids and blood transfusions required [8]. Blood products should be made available, and an effort should be made to correct any coagulopathy, hypothermia, acidosis, and hypotension if present.

A complete physical exam is performed as part of the secondary survey with specific attention paid to any obvious extremity deformities as well as any "hard" or "soft" signs of vascular injury (See Table 34.1). The physical exam is extremely sensitive in both adults and children. "Hard signs" of vascular injury include absent distal pulses, pulsatile bleeding, a rapidly expanding hematoma, an audible bruit or thrill, or multiple signs of distal ischemia (i.e., pain, pallor, paresthesia, paralysis, and poikilothermia) (See Fig. 34.1). Hard signs of vascular injury are highly sensitive and specific in detecting vascular injuries, especially in the setting of penetrating trauma (See Fig. 34.2). Blunt trauma may obscure the diagnosis, and up to 10–15% of patients with a normal physical exam may still have an extremity vascular injury. "Soft signs" of vascular injury include a history of arterial bleeding, the proximity of a wound to an artery, a neurologic deficit, and a non-expanding hematoma. The presence of soft signs has been associated with a 3–25% chance of an extremity vascular injury [9]. It should prompt advanced imaging studies, which will be detailed later in this chapter.

The ankle brachial index (ABI), also known as Doppler Pressure Index or Arterial Brachial Index, is an adjunct to the physical exam that can aid in the diagnostic workup of a suspected vascular injury. The ABI has been utilized to determine the presence of an arterial injury with a sensitivity of 95% and specificity of 97% in adult studies [9]. This is calculated by dividing systolic blood pressure in the extremity distal to the possible injury by the systolic blood pressure in the brachial artery of an uninjured upper extremity. A normal ABI (>0.9) in conjunction with a normal

Table 34.1 Clinical signs of vascular injury

Hard signs	Soft signs
Absent distal pulse	History of pulsatile bleeding
Pulsatile bleeding	Proximity of wound to an artery
Rapidly expanding hematoma	Neurologic deficit
Palpable thrill/audible bruit	Non-expanding hematoma
Ischemic limb	

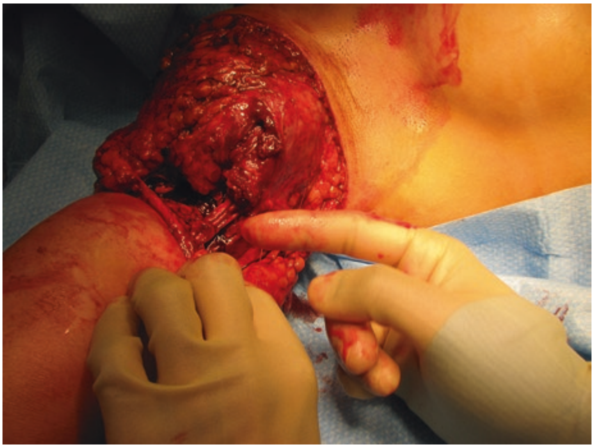

Fig. 34.1 Traumatic laceration to the upper extremity with a brachial artery injury

Fig. 34.2 Gunshot wound to the knee with popliteal artery injury

physical exam can definitively rule out an arterial injury and obviate the need for any further imaging. However, a normal ABI cannot independently exclude the presence of an arterial injury. Caution should be used when applying the ABI in children, as it may vary among different age groups and has not been as extensively studied in the pediatric population [10]. A further limitation of the ABI occurs when patients cannot tolerate a blood pressure cuff on an injured limb secondary to pain.

Plain films are often obtained of potentially injured extremities as part of the initial evaluation. Several specific long bone fractures have been associated with an increased risk of arterial injury (Table 34.2). Careful pulse examination, calculation of ABI's, and additional cross-sectional imaging may be indicated based on the diagnosis of these fractures. After reduction or repair of a fracture, a repeat exam is warranted to ensure adequate distal perfusion.

Table 34.2 Musculoskeletal injuries associated with vascular trauma

Skeletal injury	Associated vascular injuries
Upper extremity	
Humerus neck	Axillary artery
Supracondylar humerus	Brachial artery
Shoulder dislocation (anterior)	Axillary artery
Elbow dislocation	Brachial artery
Lower extremity	
Acetabulum	External iliac/femoral vessels
Femoral shaft	Superficial femoral artery
Supracondylar femur	Popliteal artery
Proximal tibia	Popliteal artery/Tibioperoneal trunk
Distal tibia	Tibial or peroneal artery
Hip dislocation	Femoral artery
Knee dislocation	Popliteal artery
Ankle dislocation	Posterior Tibial artery

Diagnosis

Prompt diagnosis of vascular injuries in pediatric extremity trauma is paramount, as timely revascularization can reduce the risk of limb loss. As previously reviewed, the physical exam is the first and most critical step in the diagnosis. It has excellent sensitivity in detecting vascular injuries and can guide the provider in ordering more advanced imaging studies when indicated. Lack of technologies to adequately assess such vascular injuries may require transfer to a facility with appropriate capabilities to diagnose and manage peripheral vascular injuries in children.

Historically, conventional angiography has been the "gold standard" for detecting extremity vascular injuries. However, more recent data have established the CT angiogram as the diagnostic modality of choice in extremity vascular trauma. CT angiography is readily available at most trauma centers and is non-invasive, eliminating the morbidity risk of conventional angiography as this requires arterial catheterization. Contemporary evidence demonstrates that CT angiography has a sensitivity and specificity approaching 100% in detecting vascular injuries [11, 12]. Potentially limiting factors include severe allergies to IV contrast, known renal disease, patient motion or positioning constraints, displaced fracture fragments, or the presence of shrapnel or missile fragments which can produce imaging artifacts in the area of injury and obscure the diagnosis.

Vascular ultrasound is also potentially valuable in the workup of pediatric extremity trauma. It is particularly appealing in children, given the lack of radiation exposure. Evidence regarding the diagnostic utility of duplex ultrasound is highly variable. It is highly operator-dependent and requires an experienced ultrasound technologist who may not be available at all hours, depending on the institution. Duplex ultrasound may be useful specifically in the follow-up of many vascular injuries. The characteristics of the doppler signal (triphasic, biphasic, monophasic, or absent) should be compared on both sides. Depending on the specific injury or operative repair performed, multiple follow-up images may be indicated. The cumulative radiation exposure of multiple CT angiograms should not be ignored. Therefore, establishing a baseline ultrasound image at or near the time of injury may be useful for subsequent follow-up.

Magnetic Resonance Angiography (MRA) and Magnetic Resonance Venography (MRV) are both cross-sectional imaging methods available for a detailed study of extremity vasculature. While attractive in the pediatric population due to the lack of ionizing radiation exposure, MRA is typically not practical given the significant amount of time required to complete the study. In infants and young children, sedation is routinely required. MRV may have a role in detecting deep venous thrombosis after musculoskeletal trauma in cases where duplex ultrasound is not available or non-diagnostic.

Management

Management of extremity vascular injuries is dependent on multiple factors, including the complexity of vessel trauma, associated injuries, and hemodynamic status of the patient. Goals of management include hemorrhage control, adequate exposure of the injury, ligation or shunting if required, and timely vascular reconstruction if feasible. In addition, reducing and repairing any associated fractures should be performed with a reassessment of the vascular exam postoperatively.

Most patients with hard signs of vascular injury should be taken to the operating room immediately for exploration and repair. If the patient is stable, a CT angiogram may be obtained to assist with operative planning, provided it will not significantly delay surgical management. CT angiography may be especially helpful after blunt traumatic injuries with multiple fractures or after shotgun wounds where the vascular injury may not be immediately apparent on physical exam. It is important to note that the physical exam may not be as reliable in patients who are in acute shock or hypothermic. Hard signs such as absent pulses or signs of distal ischemia may result from underlying physiologic derangements rather than an actual vascular injury. In these patients, it is appropriate to initiate fluid resuscitation and warming measures prior to re-performing the pulse exam and to determine the need for surgical exploration.

Surgical management of vascular injuries in children depends mainly on the type and severity of the insult. Vessels that are partially transected may be repaired using interrupted or continuous polypropylene sutures depending on the luminal diameter. Vessels that have undergone complete transection should be debrided to healthy edges before attempting an anastomosis [13]. If there is excessive tension when the edges are brought together, branches may be ligated to gain length, or a graft may be used. In patients with significant segmental loss of a vessel, reversed saphenous vein or Dacron/PTFE interposition grafts have both been successfully applied in pediatric trauma patients. The Eastern Association for the Surgery of Trauma

Fig. 34.3 Mangled distal left foot secondary to crush mechanism from railroad injury

(EAST) guidelines state that venous injuries found during exploration for an arterial injury should be repaired only if the patient is hemodynamically stable and if the repair will not significantly delay other necessary treatment [14]. Concerning isolated venous injuries, there is insufficient data to support primary repair at the time of exploration [15].

Peripheral vascular trauma in some cases may be associated with a mangled extremity (See Fig. 34.3). A mangled extremity is defined as an extremity with a significant injury to three out of the four major components of the limb (soft tissue, bone, nerve, vessels). These injuries are typically associated with significant morbidity and high rates of limb loss. The Mangled Extremity Severity Score is a prognostic scoring system that can be used to evaluate the probability of eventual limb salvage [3]. The score takes into account skeletal/soft tissue injury characteristics, vascular injuries, and systemic factors like hemodynamic instability and shock. While initially developed as a predictive tool for lower extremity injuries in adults, the score has shown a good correlation in pediatric extremity injuries as well [16].

Children who present with a mangled extremity or with other injuries causing significant hemodynamic compromise may benefit from the placement of a temporary vascular shunt to temporarily restore arterial inflow until they can undergo a definitive repair. Shunts are available in various sizes to accommodate different vessel calibers depending on the patient's age and the location of the injury. Intravenous tubing has been used in some cases as well [17]. In the case of a mangled extremity, a shunt allows for quick revascularization, after which any orthopedic procedures may be performed to stabilize the limb and increase the chance of salvage. If the patient is hemodynamically unstable, it allows for a damage-control type operation with an expedient return to the intensive care unit for ongoing resuscitation prior to formal revascularization.

Wounds in close proximity to a major vessel may result in vascular spasm, which can be difficult to distinguish from other types of vascular injury. This is especially important in pediatric patients who are more prone to vessel spasm than adults. While vessel caliber reduction or a "beaded" appearance on a CT angiogram may be suggestive of spasm, this can also be seen in cases of dissection, external compression, or thrombus [18]. If distal flow to the extremity is still intact, then re-examination after warming and further resuscitation is appropriate. If there is a concern for ischemia, further workup in the OR with an angiogram and possible surgical intervention is indicated. In extreme cases, vasospasm may induce limb ischemia, and the successful use of intra-arterially infused papaverine has been described [19].

Patients with extremity vascular injuries are at risk of developing acute compartment syndrome (ACS) pre-and post-revascularization. Compartment syndrome occurs due to increased tissue pressure in a closed space resulting in nerve damage and muscle necrosis. It can lead to significant morbidity and mortality. Patients with long-bone fractures and lower extremity arterial injuries causing distal ischemia are at especially high risk for ACS. Signs of compartment syndrome on physical exam include pain out of proportion to physical exam findings, pain with passive stretching of the extremity muscles, and tense compartments. When the diagnosis is in question, compartment pressures can be measured. A difference of less than 30 mmHg between the diastolic pressure and compartment pressure (ΔP) is diagnostic for acute compartment syndrome. While the diagnosis of compartment syndrome mandates immediate fasciotomy, the role of prophylactic fasciotomy after a vascular injury remains unclear. There is evidence to suggest that early fasciotomy (within 8 h of injury) compared to late fasciotomy (>8 h) reduces the risk of subsequent amputation in lower extremity vascular injuries [20]. However, the decision to perform a prophylactic fasciotomy should be individualized and consider ischemia time, associated injuries, and the risk for reperfusion injury.

Endovascular techniques play a critical role in managing peripheral vascular trauma in adults; however, they are used much less frequently in the pediatric population. While increasing use of endovascular techniques in children has been reported in recent years, many of these techniques are designed to treat proximal vascular trauma (i.e., aortic or iliac injuries) [21]. The long-term outcomes and durability of these techniques remain unknown; thus, open repair remains the mainstay of management for peripheral vascular trauma in children.

Conclusion

Pediatric extremity vascular trauma is rare but carries a significant risk of morbidity, including prolonged disability and even limb loss. Initial management should focus on hemorrhage control and a complete physical exam to aid in diagnosis. CT angiography is a beneficial diagnostic adjunct and can assist in operative planning. Prompt operative management and revascularization, when indicated, will lead to better outcomes.

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Chapter 35
Envenomation, Bites and Stings

Sanaz Devlin and John Devlin

Abstract This chapter discusses the management of mammal, reptile, and arachnid bites that pediatric surgeons may encounter. Infection risk should be considered in all pediatric bite victims. Most pediatric patients can be managed in the outpatient setting and most do not require surgical intervention. Dog bites to the face typically need surgical care in the operating room. Some envenomations from North American species can produce life-threatening systemic effects. Younger age puts patients at risk for greater severity of illness/injury and the need for more complex care.

Keywords Mammal bites · Rabies · Envenomation · Antivenom · Reptile bites

Key Concepts/Clinical Pearls

- Dogs represent the most common bite threat to pediatric patients.
- Most animal bites can be managed in the outpatient setting.
- The biggest threat from mammal bites is infection; whereas, infection from reptile bites is rare.
- The use of antivenom can be life-saving, but patients must be closely monitored for hypersensitivity reactions.
- The use of fasciotomy on crotalid envenomation is rare and should only be utilized after antivenom administration has been optimized.

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Initial Management of Trauma Patient with Envenomation, Bites and Stings

The initial management of pediatric bite and envenomation patients should follow established trauma patient management guidelines focusing on fluid resuscitation, airway management, and hemorrhage control. Once acute threats to life have been identified and treated, the consideration of envenomation-specific medical management is appropriate. Biopharmaceutical companies have developed several antivenoms that target venom components of North American species.

Antivenom for crotalids (rattlesnakes, copperheads, water moccasins), bark scorpions, and black widow spiders are commercially available in the United States. Antivenom administration can be life-saving for children but the risk of hypersensitivity reactions must be weighed against potential benefits in clinical decision-making.

Surgery can be avoided in most mammal bites. Facial dog bites in children are an exception with approximately half requiring operative care.

Operative intervention for pediatric rattlesnake envenomation should be reserved for those who have failed adequate antivenom administration, have developed evidence of compartment syndrome, have intra-articular envenomation, and/or have evidence of deep tissue necrosis.

Radiographic/Ancillary Studies

Imaging may help identify fractures associated with bites and crush injuries, as well as identifying retained foreign bodies such as tooth fragments. Timely identification of open fractures facilitates the early implementation of optimal antibiotic treatment and consultation with the appropriate surgical specialists. Although no guidelines exist for imaging for animal bites, clinical suspicion should indicate if radiographic studies are needed.

Bites and Stings

Bites and stings from North American mammals, reptiles, and some arachnids may result in significant tissue injury. Of these encounters, mammal bites represent the greatest incidence of injury to children. Bites and stings can produce puncture wounds (depth greater than width), crush injury, envenomation with and without systemic effects, and secondary infection, resulting in significant morbidity and mortality.

Mammal Bites

Human Bites

Human bites account for 3.6% to 23% of all bite wounds, making them the third leading cause of bite wounds seen in North American emergency departments. Human bites may occur from accidental biting injuries, intentional biting, or closed-fist injuries. Individuals aged 10 to 34 years old have the highest prevalence. Patients with human bite wounds often have more than one wound, so a complete examination of all of the skin is warranted. Approximately 50% of all human bite wounds occur in the upper extremities [1].

Human bites can be classified as either occlusive bites (similar to animal bites) or clenched fist bites, otherwise known as 'fight bites.' Human occlusive bites occur when the teeth sink into the skin and breach its integrity. Unlike animal bites which are frequently associated with tissue avulsions, human bites generally compress tissue; tissue avulsion is uncommon. A clenched fist bite occurs when a fist hits a tooth and often results in significant morbidity due to underlying tendon injury. Typically, the injury occurs over the dorsal aspect of the third, fourth or fifth metacarpophalangeal joints. All patients with clenched fist injuries should be examined for extensor tendon injuries. Up to 67% of clenched fist injuries will have disruption of the extensor mechanism or joint space violation [2]. Elson's test is a relatively rapid bedside examination technique that can be used to identify tendon injuries [3]. The patient should be positioned with proximal interphalangeal (PIP) joints in 90-degrees of flexion. The patient extends his or her fingers at the PIP joint while the provider prevents extension at the middle phalanx. An abnormal test results in no active extension of the PIP joint and a slightly extended, tight distal interphalangeal joint similar to a boutonnière deformity. An abnormal Elson's test should prompt surgical exploration under anesthesia. Approximately 52–62% of bites result in penetration of the MCP joint, 20% result in tendon injuries, cartilage injuries in 6%, and bony injuries in 17–5% [4]. Children with flexor tendon injuries, bony defects on radiography, extensive devitalization, and/or significant contamination will likely benefit from treatment in the operating room with an orthopedic surgeon or hand specialist [5].

Due to the avascular nature of the extensor tendons and MCP joints, these bites are prone to infection. Additionally, finger extension after injury allows entry of bacteria along the extensor tendons, which may invade the joint space and the tendon sheath resulting in septic arthritis of the MCP joints. Approximately 10% of human bites become infected [6]. Amoxicillin-clavulanate is the treatment of choice for human bites. Parenteral antibiotics should be considered in severe infections, patients with systemic manifestations, failure of oral antibiotics, bone or joint involvement, hand wounds, and immunosuppressed patients. In these instances ampicillin-sulbactam is the appropriate antibiotic.

Dog Bites

Dog bites represent 80–90% of all animal bites requiring medical care in children [7]. It is estimated that 4.7 million dog bites occur annually in the United States in adults and children. Of these, 17% require medical care and 1.8% of patients are hospitalized. The highest rate of injury is amongst children aged 5–9 years old with a higher prevalence in males [8]. In a general population, the most common location for dog bites is the arm/hand (45.3%) followed by the leg/foot (25.8%) and head/neck (22.8%) [9]. However, among children <4 years old, the majority of injuries (64.9%) are to the head/neck region.

Dog bites can result in a range of injuries, including scratches, lacerations, puncture wounds, and crush injuries. Approximately 15% of dog bite injuries result in complex lacerations, fractures, joint injuries, amputation, or neurovascular damage [10]. One in five dog bite wounds become infected, and while they may be severe, death is rare [11].

Initial management should begin with a thorough history that includes the timing of the bite, provoked versus unprovoked attack, anatomic location of the bite, prehospital treatment, rabies status of the animal, and medical history of the patient including asplenia, immunocompromised state, tetanus status, and diabetes. Inspect the wound to identify deep injuries ensuring that there is adequate visualization of the base of the wound. Inspection should include the location and depth of the wound as well as the type of wound (puncture, abrasion, avulsion, or laceration). A thorough neurovascular examination should also be completed. Special consideration should be given to periocular bites and evaluation for eyelid lacerations, medial and lateral canthus tendon lacerations, and canalicular lacerations. Consider appropriate imaging in facial and skull bites due to the high probability of underlying fracture and penetrating injuries overlying bones and joints.

The incidence of dog bite wound infections in non-puncture wounds that are not closed primarily is only 2.6% [12]. Patients who have sustained a dog bite wound can show signs of infection within hours to days after the injury. Other than cellulitis, other complications include osteomyelitis, tenosynovitis, orbital cellulitis, and intracranial abscesses. Wound infections from dog bites are typically polymicrobial, with a mix of aerobic and anaerobic bacteria originating from the oral cavity of the dog and the skin flora of the victim [13].

One of the most important methods of preventing bacterial infection is proper irrigation. Low-pressure irrigation can be used for clean wounds. Most bite wounds can be cleaned with an 18-gauge blunt needle and a 30 or 60 mL syringe. Generally, 100–200 mL of irrigation solution per inch of wound is required [14]. High-pressure irrigation, defined as 7 psi (pounds per square inch), should be utilized for dirty or heavily contaminated wounds [15]. Avoid blind high-pressure irrigation of puncture wounds. Isotonic sodium chloride is an effective irrigating solution. Antimicrobial and anti-infective solutions offer no advantage and may cause tissue irritation. Heavily contaminated wounds may require debridement and removal of foreign material in order to prevent infection. Wound edges and nonviable tissue require surgical debridement [1]. Obtain aerobic and anaerobic wound cultures if there are signs of infection. Fresh wounds without signs of infection do not require culturing.

Preemptive early antimicrobial therapy for 3–5 days is recommended for patients who (a) are immunocompromised; (b) are asplenic; (c) have advanced liver disease; (d) have preexisting or resultant edema of the affected area; (e) have moderate to severe injuries, especially to the hand or face; or (f) have injuries that may have penetrated the periosteum or joint capsule. Primary wound closure is not recommended for most wounds except those to the face [16]. The goal of initial empiric antibiotic therapy is to cover both anaerobic and aerobic organisms. Amoxicillin-clavulanic acid is the treatment of choice for most bite wounds. For patients with severe penicillin allergy, alternative therapies include extended-spectrum cephalosporins or trimethoprim-sulfamethoxazole in conjunction with clindamycin or metronidazole. Macrolides should be avoided due to variable activity against Pasteurella species. For patients who are hospitalized or require the parenteral route, ampicillin-sulbactam is an appropriate initial antibiotic. The addition of Vancomycin in severe infections or clindamycin should be considered. A 5 to 10-day course of antibiotics is typically sufficient for most soft tissue infections. However, longer courses of therapy (4–6 weeks) are required for bone and joint infections. Bite wounds are puncture wounds and require assessment of tetanus immune status [16].

Consider hospitalization for patients with systemic manifestations of infection (fever, hypotension, elevated white blood cell count), immunocompromised state, severe local infection, failed outpatient antibiotic management, severe edema, bone, tendon, or joint involvement, wounds with cranial involvement, and unreliable social circumstances. All patients with bite wounds should be re-evaluated within 48 h after discharge from the inpatient setting to re-evaluate for evidence of infection.

Facial wounds, particularly in children, are an exception. Approximately half of pediatric dog bites to the face require surgical repair in the operating room, with younger age being the strongest predictor of operative necessity [17]. Because of the rich blood supply to the face and scalp, particularly in children, facial wounds have a low incidence of infection. Deferring closure and leaving facial lacerations open to heal by secondary intention reduces absolute infection risk by only 3.7% [18]. Due to this negligible benefit, the esthetic benefit from closure often outweighs the risks of infection. Primary closure is recommended for facial dog bite wounds presenting for care within 24 h of injury [19]. Primary closure of wounds greater than 24 h old is controversial. Delaying closure for 2–7 days has been traditionally recommended [15, 20]. However, wounds with significant avulsed tissue present challenging reconstructive approaches if not directly closed. Local skin flaps, composite grafts, or staged repairs should be considered in these situations [21–23].

Cat Bites

Cat bites account for 5–15% of all animal bite wounds, making them the second most common type of animal bite in the United States. The rate of infection after a cat bite can be as high as 50%. Approximately 60% to 67% of cat bite wounds occur in the upper extremities, 15% to 20% on the head and neck, 10% to 13% on the lower extremities, and less than 5% on the trunk. Wounds can occur through the teeth or the claws of the animal and tend to penetrate deeply, oftentimes affecting bones and joints. Due to the high predilection for puncture wounds, deep abscesses and osteomyelitis are more common in cat bite injuries [1].

Similar to dog bites, cat bite wound infections are typically polymicrobial. Amoxicillin-clavulanate is the drug of choice for cat bite wound infections, given its proven coverage against Pasteurella multocida [16]. If the patient requires a parenteral route for antibiotics, then ampicillin-sulbactam would be the appropriate antibiotic. If the patient is penicillin allergic, then an extended-spectrum cephalosporin or trimethroprim-sulfamethoxazole plus clindamycin would be an appropriate choice. Other systemic infections transmitted by cat bites include Cat-scratch disease (Bartonella spp.), Tularemia (F tularensis), Sporotrichosis (Sporothrix spp.), and Rabies (rabies virus) [16].

Rabies

All mammals are susceptible to rabies infection. With the advent of mass companion animal rabies vaccinations in North America, the greatest rabies transmission risk to children now comes from wildlife. Patients aged <15 years represent 40% of patients bitten by rabid animals [24]. Timely wound care after a bite from a rabid animal can significantly reduce the risk of rabies transmission [25]. With rabies post-exposure prophylaxis (PEP), clinical rabies virus infection is 100% preventable. The decision to administer PEP to a child following a mammal bite is based on a rabies risk assessment. Often the rabies risk is indeterminate, and rabies PEP is administered empirically. Because domestic pet vaccination status and wildlife rabies vectors vary by region, the use of state public health risk assessment tools can help clinicians determine which patients need rabies PEP. The incubation period for clinical rabies is 1–3 months, so the absence of symptoms is not considered in the risk assessment for rabies PEP [26]. Bites from non-mammal species do not transmit rabies and do not require rabies PEP.

The Centers for Disease Control and Prevention currently recommends both human rabies immune globulin (HRIG) and rabies vaccine as soon after exposure as possible and preferably on the day of exposure, followed by additional vaccine doses administered on days 3, 7, and 14 after the initial dose [27]. Patients previously vaccinated for rabies do not require HRIG.

Snake Envenomation

The majority of clinically significant reptile bites in North America come from snakes. On average, 5000 snakebites are reported to United States poison control centers annually, with 28.2% involving patients less than age 12 [28]. Many snakebites in North America are nonvenomous, but bites from members of the genera

Crotalus, Sistrurus, and *Agkistrodon* within the family Crotalinae may result in life-threatening envenomation with or without significant tissue injury. Bites from snakes of the Elapidae family may also result in neurotoxic envenomation, but these patients are typically managed medically with early airway management and supportive care. Crotalinae, also known as new world vipers or "pit vipers," derive their nickname from heat-sensing depressions located caudal to the nostril. Pit vipers may also be identified by large triangular heads, elliptical pupils, and keeled mid-dorsal scales [29]. Members of the genera *Crotalus* and *Sistrurus* possess modified terminal tail scales which rattle when the snake vibrates its tail, leading to their common name rattlesnakes. However, members of the genus *Agkistrodon* also vibrate their tails when threatened but do not possess rattles. This genus includes copperheads (*Agkistrodon contortrix*) and water moccasins (*Agkistrodon piscivorus*), whose envenomations are associated with less morbidity and mortality than rattlesnakes. Rattlesnake bites occur most commonly in the southwestern and southeastern United States; whereas, copperhead and water mocassin bites primarily occur in the southeastern states. Crotalids typically leave paired puncture wounds from large retractable fangs after striking (Image 35.1); whereas, elapids and colubrids tend to grasp and chew, leaving a semi-circular teeth imprint pattern [30, 31].

Snakebite does not imply envenomation has occurred. Many species in North America are nonvenomous, and venomous snakes have the ability to modulate the amount of venom they deliver when striking. Approximately 20% of snakebites from venomous species are "dry bites" in which no symptoms attributable to envenomation occur. Clinical manifestations of envenomation may be delayed for up to 10 hours and vary by species, amount of venom introduced, location of the bite, and size of the patient.

Clinical manifestations of envenomation range from mild local edema to life-threatening systemic effects. In most envenomations, pain and swelling around the bite site occurs within minutes. Edema may progress over the course of hours and often extends proximally over time in extremity bites. Ecchymosis and hemorrhagic oozing from the fang marks are common. Myokymia, localized involuntary wave-like contractions propagating through affected striated muscle, around the bite site

Image 35.1 Rattlesnake. Pit Vipers (crotalids) have retractable fangs capable of delivering venom deep into subcutaneous tissue. Crotalid venom is composed of metalloproteinases, serine esterases, hyaluronidase, disintegrins, phospholipases, and C-type lectin-like proteins with variable effects

has also been described. Copperhead and water moccasin envenomation is usually limited to local tissue effects; however, rattlesnake envenomation may produce severe systemic effects. In severe envenomation, hemorrhagic blebs may develop at or proximal to the bite site. Systemic effects include confusion, hemodynamic instability with significant hypotension, a metallic taste, and xanthopsia, a yellowing of the vision similar to digitalis toxicity.

Laboratory evaluation should include a complete blood count, basic metabolic panel with renal function tests, hepatic function tests, prothrombin time / international normalized ratio, fibrinogen, D-dimer, and urinalysis. An electrocardiogram should be obtained for patients with chest pain. Evidence of coagulation dysfunction, termed venom-induced consumptive coagulopathy (VICC), resembles disseminated intravascular coagulopathy (DIC) and is common in rattlesnake envenomation. A drop in fibrinogen may be the earliest indicator that VICC is occurring [32]. Elevations of prothrombin time, international normalized ratio (INR), and D-dimer may also occur. Thrombocytopenia may manifest in VICC, particularly after envenomation by the canebrake rattlesnake (*Crotalus horridus*, formerly called the timber rattlesnake) of the southeastern United States due to the presence of crotalocytin in the venom of this species. Myonecrosis with rhabdomyolysis can occur at the micro and macroscopic level. Myoglobinuria with or without renal injury is common. Significant myonecrosis requiring operative intervention may be more common in pediatric patients. Rotational thromboelastographic indices of coagulopathy developed for trauma have been used successfully to identify VICC in military settings. This may offer advantages over traditional coagulation studies in the future management of crotalid envenomations but have been incompletely studied at this time [33–35].

Medical Management

A unified treatment algorithm for managing of crotalid envenomation in the United States was published in 2011 [36]. This consensus document incorporates evidence from clinical pharmacology, emergency medicine, medical toxicology, and pediatric critical care. It represents the most commonly referenced medical management plan for North American crotalid envenomations. The Wilderness Medical Society also published practice guidelines in 2015 [37]. Venom characteristics exhibit regional variation even within the same species. Physicians without experience managing crotalid envenomation within their region should contact their regional certified poison control center through the national toll-free number 1-800-222-1222 to receive guidance from specialists in poison information and/or medical toxicologists experienced in the management of snakebites within their region.

Children who are rapidly transported to the emergency department for evaluation may not exhibit immediate signs and symptoms of envenomation upon initial presentation. Children with fang marks but no evidence of envenomation ("dry bite") should be observed for at least 8 hours in a monitored setting. All jewelry and constrictive clothing should be removed. The bitten extremity should be marked in two to three locations, and the circumference recorded to monitor for changes in edema [38]. Oral suction, mechanical suction extraction devices, cryotherapy, and electrotherapy have no benefit and may cause harm [36, 37]. The affected area should be washed with soap and water. In properly cleaned wounds, the incidence of wound infection after snakebite is 3% [39]. Prophylactic antibiotics are unnecessary and not recommended [40].

Crotalid envenomation produces local tissue effects that require local wound care and pain control. The leading edge of ecchymosis and edema should be included in marked locations for serial circumference measurements [37]. The interval for serial circumference measurements ranges from 15 to 30 min [36, 37]. Splinting and immobilizing extremities reduces pain, but tourniquets may cause harm [36, 37]. Compression dressings to limit lymphatic venom spread should not be used with North American crotalid envenomation as this intervention is associated with significant elevation of extremity compartment pressures in animal models [41, 42]. Pain control often requires weight-based opioid administration. Opioid pain regimens are preferred over non-steroidal anti-inflammatories (NSAID) due to NSAID-associated platelet effects and the potential to exacerbate coagulopathy. Tetanus status should be addressed, and tetanus prophylaxis administered if needed. For patients with isolated local venom effects that are not progressing and no evidence of coagulopathy, antivenom may be withheld. However, patients with systemic symptoms, progressing tissue edema and pain, and/or laboratory evidence of VICC require more aggressive treatment.

Systemic toxicity may cause profound hypotension. Volume expansion with intravenous crystalloid is indicated. Patients experiencing significant hemorrhage from rattlesnake envenomation may rarely require transfusion of blood products. The use of blood products to reverse VICC is controversial, with most experts favoring more aggressive antivenom use over plasma and whole blood [36, 37]. However, if clinical circumstances increase the risk-to-benefit ratio of continued antivenom administration, hemostatic resuscitation may have a role with blood derivatives. Consultation with a medical toxicologist through a certified poison control center prior to transfusion is highly recommended.

Administration of antivenom can be life-saving but should be used cautiously. In North America, two crotalid antivenoms are currently approved for use in the United States by the Food & Drug Administration (FDA). (Table 35.1) Ovine-derived Crotalidae Polyvalent Immune Fab (CroFab®, BTG International Inc., West Conshohocken, PA) has been FDA-approved for the treatment of crotalid envenomation since 2000. CroFab® should be administered to pediatric crotalid envenomations with any evidence of progression beyond local tissue venom effects. In pediatric patients, these include progressive edema, laboratory evidence of VICC (fibrinogen <150 mg/dL, elevated INR), thrombocytopenia (platelets <150,000/mm^3), airway compromise, clinical evidence of systemic bleeding, or clinical

Table 35.1 Antivenom commercially available in the United States

Antivenom	Host animal	Species targeted in production	Protein	Initial dosing	Immediate hypersensitivity reaction	Serum sickness	Ref
CroFab®	Sheep	*C. adamanteus, C. atrox. C. scutulatus, A. piscivorus*	F(ab)	4–6 vials diluted to 250 mL and infused at 25–50 mL/h	8%	13%	Schaffer (2012)
Wyeth Anti-Crotalid	Horse	*C. adamanteus, C. atrox, C. durissus,* Fer-de-lance *(B. atrox)*	IgG	Not available. Data presented for comparison.	26–56%	23%	Dart (2001)
Anascorp®	Horse	*Centruroides sculpturatus*	$F(ab')_2$	3 vials diluted to a 50 mL and infused over 10 min	2.7%	0.5%	LoVecchio (1999), pack insert
Merck Anti-Latrodectus	Horse	*Latrodectus mactans*	IgG	1 vial diluted to 50 mL and infused over 15 min	Case reports	1.7%	Hoyte (2012) and Isbister (2003)

evidence of hemodynamic compromise [36, 37, 43, 44]. Progressive edema has been loosely defined by various authors as either edema that progresses past a major joint, such as the wrist, elbow, ankle, or knee, or an increase in the leading edge of tissue edema, erythema and/or ecchymosis ≥2 cm [36, 37].

Antivenom is dosed to achieve control of venom effects. The recommended initial dose of CroFab® is 4–6 vials [45]. Each vial of lyophilized protein should be reconstituted by mixing with 18–25 mL 0.9% normal saline and "rolling" the vial between the hands [37, 45]. Shaking should be avoided as this causes the antivenom protein to foam. Each dose should be diluted to a volume of 250 mL in 0.9% normal saline and infused over an hour. Infants weighing less than 10 kg may not tolerate the volume load required for the initial antivenom load [43]. For these patients, it is acceptable to dilute the antivenom to a volume of 20 mL/kg [37]. Starting the infusion slowly at a rate of 25–50 mL/h during the first 10 minutes has been recommended by some authors to minimize severe hypersensitivity reactions [37, 43]. Patients presenting with cardiovascular collapse may need higher initial doses in the 8–12 vial range [36]. Clinical experience has shown that copperhead envenomation may respond to the lower 4-vial dose of CroFab® while rattlesnake envenomation generally requires higher doses to achieve initial control [46]. Initial control is defined as cessation of tissue edema progression, resolution of systemic effects, and improvement (but not necessarily normalization) of laboratory indices of VICC [36]. For patients in whom initial control is not achieved after the recommended initial dose of 4–6 vials, another 4–6 vial dose should be administered. In a representative snakebite registry, the median antivenom dose required to achieve initial control was 10 vials for both patients aged ≤18 years and those aged 19 and older [28]. For those patients in whom initial control is achieved, maintenance infusions of 2 vials every 6 h for three doses should be administered. If after these three 2-vial infusions are complete, the patient's laboratory indices have normalized, local tissue edema is resolving, and the patient is experiencing no systemic effects, they may be discharged with 2–3 day follow-up.

Operative Management

Predicting which patients with envenomation will require surgical intervention is challenging. Other than tachycardia and tachypnea, presentation vital signs and laboratory indicators are often normal in envenomated children [47]. In the largest study of adult envenomation associated with dermatonecrosis, 40% of envenomated patients developed necrosis with the presence of ecchymosis (relative risk 4.04) and cyanosis (relative risk 2.98) at presentation being the strongest predictors [48]. Most of these patients underwent bedside unroofing of hemorrhagic bullae for pain control and better visualization of the underlying tissue bed. Only 11 of 77 patients underwent dermotomy and/or operative debridement. None required amputation or fasciotomy. However, adults tend to be bitten on upper extremities, which are associated with more necrosis; whereas, children display a more even distribution of upper extremity and lower extremity bites [47, 48]. Patients whose fingers exhibit decreased capillary refill, tense soft tissue edema, and/or pallor should be considered for digital dermotomy [49]. After rattlesnake envenomation, the need for digital dermotomy is 2.5 times more prevalent than fasciotomy for compartment syndrome [50].

The development of compartment syndrome requiring fasciotomy is exceedingly rare when adequate antivenom therapy is administered. Snake strikes rarely penetrate the muscle compartment with most bites resulting in subcutaneous deposition of venom. Investigations conducted by both surgeons and medical toxicologists demonstrate that fasciotomy with or without antivenom administration is independently associated with increased myonecrosis and poorer functional outcomes [51, 52]. Most surgical and toxicology authorities recommend increasing antivenom dosing in lieu of fasciotomy in the context of elevated compartment pressures [36–38, 47].

Clinical scenarios may develop where fasciotomy may be necessary. In patients with rising compartment pressures despite maximal antivenom administration, small infants who cannot tolerate the volume load required for adequate antivenom administration, and/or children exhibiting severe hypersensitivity reactions to antivenom precluding further use, a fasciotomy may be a beneficial clinical intervention. Recommended compartment pressure thresholds for consideration of fasciotomy vary from 30 to 40 mmHg [36–38].

Arachnid Bites

There are few arachnid envenomations of clinical importance and fewer that require surgical care. In North America, the bark scorpion, black widow spider, and brown recluse spider represent arachnid species that are most likely to cause clinically significant injury and illness in pediatric patients. Most can be managed medically, but severe systemic reactions, particularly in infants, are possible.

Scorpions

Scorpions are arthropods which inject their venom via a telson, a stinging organ located at the end of their segmented tails. In North America, the only scorpion of clinical concern is the bark scorpion (*Centruroides sculpturatus*) whose range is limited to Arizona, New Mexico, Texas, California, and Nevada. In children, autonomic effects (hypertension and tachycardia), muscarinic stimulation (drooling/hypersalivation), nicotinic effects/neuromuscular hyperactivity (restlessness, muscle fasciculations, ataxia, and opisthotonus), and craniofacial abnormalities (vision difficulty, facial twitching, and opsoclonus-like roving eye movements) are more common [53, 54]. Management involves supportive care with appropriate analgesia and anxiolysis. In patients exhibiting autonomic excitation, α_1-blockade with intravenous prazosin is recommended [55]. Although this has not been prospectively evaluated in children envenomated by *C. sculpturatus*, efficacy and safety have been demonstrated in a pediatric population envenomated by other species [56]. Severe neuromuscular excitation should be treated with intravenous benzodiazepines, such as midazolam 0.05–0.1 mg/kg bolus followed by infusion at 0.1 mg/kg/h [55]. An equine-derived immune $F(ab)_2$ antivenom (Anascorp®, Rare Disease Therapeutics, Inc., Franklin, TN) was approved by the FDA for *Centruroides* sp. envenomation in 2011. Patients with severe neurotoxic symptoms should be considered for antivenom therapy. The recommended initial dose is 3 vials each reconstituted in 5 mL of 0.9% normal saline and further diluted to a total volume of 50 mL in 0.9% normal saline before infusing intravenously over 10 minutes [57]. Anascorp® is safe and effective in pediatric patients [53, 54].

Spiders

In the United States, *Latrodectus sp*., or widow spiders, can be found in every state except Alaska. The best known is *Latrodectus mactans*, the black widow, which is easily recognized by the red hourglass marking on the ventral surface of the female spiders (Image 35.2). They are reclusive and prefer small, dark spaces such as woodpiles and garages. Their venom contains a neurotoxin that disrupts voltage-gated calcium channels, resulting in massive neurotransmitter release [58]. The

Image 35.2 Black Widow. Female black widows, the North America species of *Latrodectus* spiders, are identifiable by the hourglass-shaped marking on their ventral abdomen. This marking is typically red but fades to orange or yellow in preserved specimens like this one

initial bite may be unnoticed by the patient or perceived as a pinprick [53]. This is followed by local irritation and a "halo sign," blanching around the dual fang marks surrounded by hyperemia with or without localized diaphoresis [59]. In severe envenomation, local symptoms can progress to systemic dysfunction within 60 min, termed latrodectism, characterized by severe muscle cramping, facial grimacing, hypertension, tachycardia, agitation, seizures, and abnormal sweat patterns [53, 58, 59]. Atypical diaphoresis may be unilateral or isolated to a small patch of skin, such as the one side of the upper lip or the tip of the nose [53]. Abdominal pain is more prevalent in children envenomated by widow spiders than in adults. Of interest to pediatric surgeons, the abdominal pain from widow spider envenomation can be significant and mimic an acute abdomen. However, children suffering from widow spider envenomation do not exhibit peritoneal signs on physical exam. They tend to move to seek a comfortable position as opposed to lying motionless like patients with peritoneal irritation [60]. Most patients can be management supportively with analgesia and benzodiazepines for muscle cramping. Calcium gluconate, dantrolene, and methocarbamol are ineffective and no longer recommended. Latrodectism may be life threatening, particularly in small children. An equine-derived IgG antivenom (Black Widow Spider Antivenin, Merck & Co., Inc., Whitehouse Station, NJ) has been available in the United States since 1936. The current use of widow spider antivenom is controversial as deaths from black widow spiders bites have not been reported in North America in decades. As no controlled trials in children after spider envenomation have been performed, consultation with a regional poison control center may aid clinical decision-making regarding administering antivenom [61]. Antivenom should be used cautiously in children with asthma. The dose for children is 1 vial reconstituted in 2.5 mL of sterile water, then dilute to a total volume of 50 mL with 0.9% normal saline and infused intravenously over 15 minutes [61]. All children receiving widow spider antivenom should be monitored for hypersensitivity reactions.

Spiders from the genus *Loxosceles* are responsible for dermatonecrotic arachnidism. The brown recluse spider, *loxosceles reclusa*, is the best known example in North America and identified by a dark violin-shaped mark on the dorsum of its cephalothorax (Image 35.3). The bite from a brown recluse is typically painless, but its venom contains sphingomyelinase D and hyalurondase [62]. Within hours, the bite site may progress to a necrotic lesion characterized by a vesicle, bluish-gray macule, or pale area [53]. Central ulceration with eschar formation typically occurs 3–4 days later. The progression pattern of an initial hemorrhagic area degrading into blue necrosis, which eventually forms an eschar is referred to as a "red, white, and blue sign" [63]. However, many necrotic lesions and infections are misattributed to bites from *Loxosceles* sp. [64]. The most beneficial management of dermatonecrotic arachnidism is controversial. Supportive care with analgesia, local wound care, and

Image 35.3 Brown Recluse. Brown recluse spiders can be identified by their dark violin-shaped coloring on the dorsal surface of their cephalothorax

tetanus prophylaxis is clearly warranted. Antivenom directed against *Loxosceles* venom is not available in the United States. Evidence to support the use of oral dapsone is weak with conflicting results in the literature. In a prospective clinical study of suspected dermatonecrotic arachnidism, patients treated with dapsone prior to surgery experienced fewer complications than patients receiving immediate debridement [65]. The off-label dosing for dapsone based on this study is 100 mg PO twice daily for 2 weeks; however, the dapsone arm included only a single pediatric patient, a 16 year-old male. No dapsone dosing in children for this indication has been studied. The FDA-approved dose for dapsone in pediatric patients with leprosy is 1 mg/kg up to 100 mg PO daily. There is some controversy regarding the timing of surgery. Most authorities recommend delaying surgery for patients without evidence of systemic symptoms or wound infection until the wound inflammation has stabilized at 2–8 weeks [63, 66]. For patients with tissue breakdown or infection, early surgical debridement can prevent the morbidity of secondary infection, sepsis, and limb amputation [64, 67]. When the need for surgery has been determined, surgical principles for debridement of other acute cutaneous necrosis are applicable [68]. Like widow spiders, *Loxosceles* sp. can produce a systemic symptom complex termed systemic loxoscelism unrelated to the severity of the cutaneous manifestations. Systemic loxoscelism, which is more prevalent in a pediatric population, is characterized by fever and arthralgia can progress to gastrointestinal effects (vomiting and diarrhea), hemolysis, coagulopathy, and rhabdomyolysis in 24 to 72 hours after envenomation [63]. Death can result from cardiovascular collapse [62]. Treatment for systemic loxoscelism is supportive; however, its occurrence in North America is rare.

Conclusions

Millions of bites are inflicted on pediatric patients each year. Although the majority of these injuries can be safely managed in the outpatient setting, pediatric surgeons must be comfortable managing these conditions. Dog bites are the most common in the pediatric population. However, most of these injuries can be managed nonoperatively. Human and cat bites have a high likelihood of infection if wound care is delayed; whereas, infection from reptile bites is uncommon. Snakebites can result in life threatening coagulopathy and systemic effects. In these children, antivenom can be life-saving. Antivenom is also commercially available for bark scorpion and black widow spider envenomation. Antivenom administration involves exposing the patient to foreign antigens, and hypersensitivity reactions can occur. Consultation with specialists at regional poison control centers, available at 1-800-222-1222, can assist in clinical decision-making for clinicians unfamiliar with envenomated patient care. Operative intervention is uncommon in envenomated patients and should be attempted only after antivenom therapy has been optimized.

Disclaimers

Military disclaimer

The views expressed in this chapter are those of the authors and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, or the United States Government.

At least one author is a military service member. This work was prepared as part of their official duties. Title 17 U.S.C. 105 provides that "Copyright protection under this title is not available for any work of the United States Government." Title 17 U.S.C. 101 defines a United States Government work as a work prepared by a military service member or employee of the United States Government as part of that person's official duties.

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Chapter 36
Child Abuse

Elizabeth Woods, Torbjorg Holtestaul, and Mauricio A. Escobar Jr

Abstract The Centers for Disease Control and Prevention (CDC) categorize child maltreatment into physical abuse, sexual abuse, emotional abuse, and neglect. In the 2019 Department of Health and Human Services (DHHS) report on Child Maltreatment, approximately 656,000 children were identified as victims, and 1840 children died from child abuse and neglect. Children who are victims of abuse can present along a continuum of disease, from a bruised child undergoing a routine exam in the outpatient clinic to a fatally injured child brought to the emergency department in extremis. When the patient's condition permits, a thorough and objective history and physical exam should be obtained with an emphasis on accurate documentation. The child should be completely undressed (although may remain in a gown) for a full skin survey, and all body regions should be examined. Diagrams and photographs should be obtained, ideally with the assistance of a child abuse pediatrician. The most common injuries identified in victims of child abuse are bruises, fractures, head trauma, burns, and abdominal trauma. Once a concern for child physical abuse (CPA) is raised, the trauma team should be activated, and a social worker consulted. In the United States, professionals are obligated by law to notify Child Protective Services (CPS) of suspected child abuse, although specifics of reporting requirements vary by state. If the child's initial presentation is to a non-trauma center without optimal pediatric-specific resources, the treating team should consider a tele-consult or transfer to a tertiary referral center with pediatric resources. If the child's injuries or physiologic condition require

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inpatient treatment or if there is no safe home or alternative identified, then the child should be admitted to the trauma service. If a safe discharge is agreed upon by all members of the treating team (including CPS and law enforcement if available), then optimal follow-up should be coordinated, including a two-week follow-up skeletal survey if indicated.

Keywords Child maltreatment · Child physical abuse · Neglect · Non-accidental trauma · Abusive head trauma · Abusive abdominal trauma

Key Concepts/Clinical Pearls (Learning Objectives)

- Child maltreatment can be categorized as either child abuse (physical, sexual, or emotional) or neglect; however, a maltreated child can suffer from any combination of the above.
- In 2019, the United States Department of Health and Human Services identified 656,000 children as victims of maltreatment, and 1840 children died from abuse and neglect.
- Institutions should implement standardized screening guidelines for identifying and evaluating children who are victims of abuse.
- Several validated clinical prediction rules, including the TEN-4-FACES P Bruising Clinical Decision Rule (BCDR), Burns Risk Assessment for Neglect or Abuse Tool and head injury rules such as PEDIBIRN, PIBIS, PredAHT, and validated screening tools such as the Escape instrument and STUPOVAMO checklist are available to guide the evaluation of CPA.
- Efforts such as the American College of Surgeons Trauma Quality Improvement Best Practice Guideline [1] and the Western Trauma Association and Pediatric Trauma Society Critical Decisions Algorithm for Child Abuse Trauma Evaluation and Management [2] Fig. 36.1, while not validated, attempt to provide a comprehensive instrument incorporating screening tools and clinical decision rules to aid emergency departments and trauma centers in the identification and management of this vulnerable patient population.

Initial Management of Trauma Patient

Children who are victims of abuse can present along a spectrum of disease, from a bruised child undergoing a routine exam in the outpatient clinic to a fatally injured child brought to the emergency department in extremis. In the context of trauma, priority should be given to stabilizing and managing the child according to the Advanced Trauma Life Support and Pediatric Advanced Life Support guidelines. Please refer to the included “Child Physical Abuse Trauma Evaluation and Management: A Western Trauma Association and Pediatric Trauma Society Critical Decisions Algorithm” [2] for a rapid reference to screen an injured child for abuse (including a brief resolved unexplained event [BRUE]). When the patient’s condition permits, a thorough and objective history and physical exam should be obtained with an emphasis on accurate documentation. The child should be completely undressed (although may remain in a gown) for a full skin survey, and all body

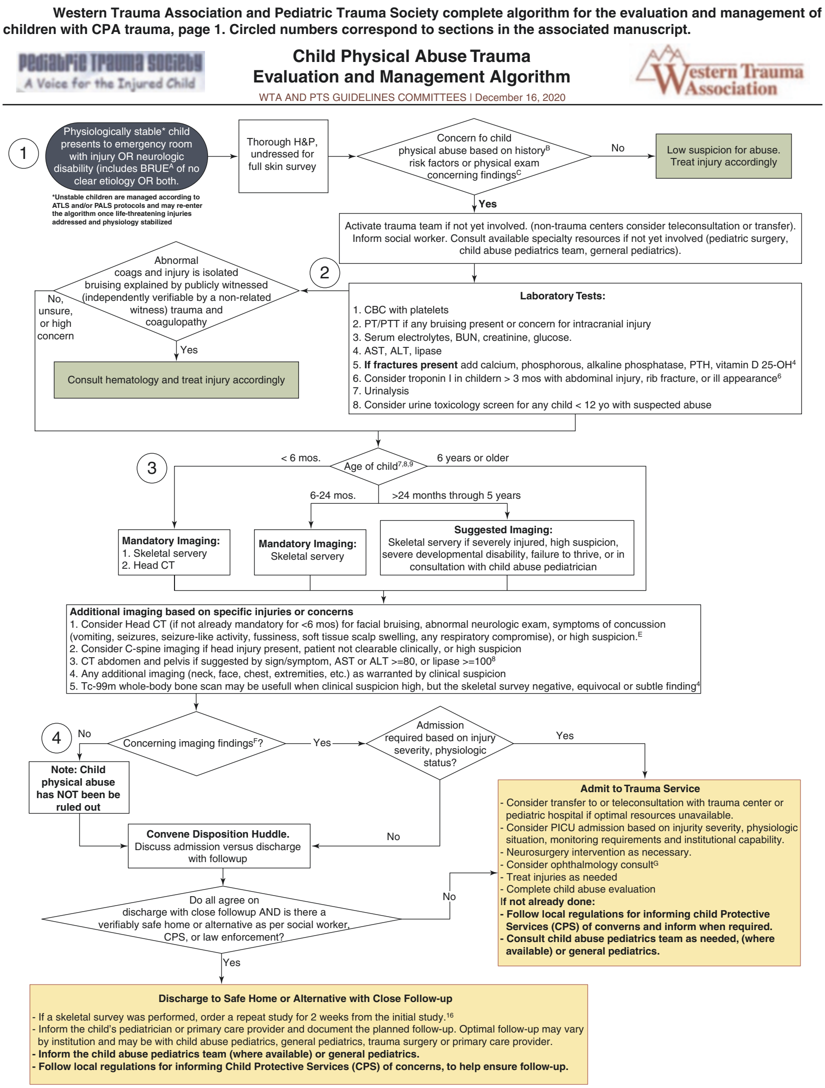

Fig. 36.1 Western Trauma Association and PTS algorithm for the evaluation and management of children with CPA trauma

regions should be examined, including the oft missed oral frena, perineum, genitals, and anus. Diagrams and photographs should be obtained, ideally with the assistance of a child abuse pediatrician or other forensics-trained practitioner if available. The trauma team, social workers, and other appropriate specialty resources (pediatric surgery, child abuse pediatrics, general pediatrics) should be activated. If the child's initial presentation is to a non-trauma center without optimal pediatric-specific resources, the treating team should consider a consult with or transfer to a tertiary referral center with pediatric resources.

Initial Radiographic/Ancillary Studies

If concern for child physical abuse is present based on history and physical exam, the following labs should be obtained [1, 2].

- Screening labs to be obtained in all patients:
  - AST, ALT, lipase, hematocrit, and urinalysis to evaluate for blunt abdominal injury
  - Serum electrolytes, BUN, creatinine, glucose
  - Urine toxicology screen
- Biochemical evaluation of possible non-traumatic causes of injuries (*consider expert consultation with Child Abuse Pediatrics, Pediatric Hematology and/or Pediatric Orthopedic Surgery)*
  - If fractures are present:

    Calcium, phosphorus, alkaline phosphatase, PTH, vitamin D 25-OH
  - If bruising or spontaneous bleeding is present:

    Prothrombin time (PT), activated partial thromboplastin time (PTT), von Willebrand factor (VWF) antigen, VWF activity (ristocetin cofactor), Factor VIII level, Factor IX level, and CBC with platelet count.
  - If unexplained intracranial hemorrhage is present:

    PT, PTT, Factor VIII level, Factor IX level, CBC, fibrinogen level, and d-dimer level

Mandatory and suggested imaging depend on the patient's age as below [1, 2]:

- For patients <6 months old
  - Mandatory imaging

    Skeletal Survey
Head CT
- For patients 6–24 months old
  - Mandatory imaging

    Skeletal Survey
- For patients >24 months through 5 years old
  - Suggested imaging

    Skeletal survey if:

      Severely injured
High suspicion for abuse

Severe developmental disability
Failure to thrive
In consultation with a Child Abuse Pediatrician

- For patients of all ages
  - Head CT if

    Facial bruising
    Abnormal neurologic exam
    Symptoms of concussion (vomiting, seizures, seizure-like activity, fussiness, soft tissue scalp swelling, respiratory compromise)
    Macrocephaly
    High suspicion for neurologic injury
    *Obtain MRI brain and c-spine if neurologic impairment present, but do not delay emergent intervention
    *Consider MRI of the cervical, thoracic and lumbar spine if intracranial injury present

  - MRI C-spine if

    Head injury present
    Patient not clearable clinically
    High suspicion for injury
    *If C1 to C3 fracture present, consider Computed Tomography Angiogram (CTA) or Magnetic Resonance Angiogram (MRA) to evaluate for cervical vascular injury.

  - CT abdomen and pelvis with contrast if

    Abdominal trauma suggested by signs/symptoms
    AST or ALT ≥80
    Lipase ≥100
    *If CT equivocal for duodenal injury, perform upper GI series

  - Any additional imaging as warranted by clinical suspicion
  - Tc-99 m whole-body bone scan may be useful when clinical suspicion is high, but the skeletal survey is negative.
  - Obtain 2-week follow-up skeletal survey.

Introduction

The World Health Organization (WHO) defines child maltreatment as "the abuse and neglect that occurs to children under 18 years of age. It includes all types of physical and/or emotional ill-treatment, sexual abuse, neglect, negligence, and commercial or other exploitation, which results in actual or potential harm to the child's health, survival, development, or dignity in the context of a relationship of responsibility, trust or power." [3]

The Centers for Disease Control and Prevention (CDC) further categorizes child maltreatment into acts of commission or omission. Acts of commission are deliberate and intentional resulting in inflicted injury, including physical abuse, sexual abuse, or emotional abuse. However, harm to the child may or may not be the intended consequence. Intentionality only applies to the caregivers' acts, but not the consequences of those acts. Acts of omission, or neglect, are defined as "failure to meet a child's basic physical and emotional needs. These needs include housing, food, clothing, education, and access to medical care." [4] 74.9% of victims are neglected, and 17.5% are physically abused. A smaller but significant proportion of children (15.5%) suffer from multiple types of maltreatment [5].

The Child Abuse Prevention and Treatment Act (CAPTA) (P.L. 100–294) (amended by the CAPTA Reauthorization Act of 2010 [P.L. 111–320]) establishes the standard federal legal definition of child abuse and neglect as "any recent act or failure to act on the part of a parent or caretaker which results in death, serious physical or emotional harm, sexual abuse or exploitation; or an act or failure to act, which presents an imminent risk of serious harm." [5] All states, the District of Columbia, and the U.S. Territories have laws that mandate the reporting of suspected child abuse to Child Protective Services (CPS).

Epidemiology

In the 2019 Department of Health and Human Services (DHHS) report on Child Maltreatment, approximately 656,000 children were identified as victims of child abuse and neglect (8.9 per 1000 children). Young children were the most susceptible, and rates of abuse decline with increasing age. Children under 3 years old were at the highest risk for maltreatment and made up more than one-quarter (28.1%) of victims in the United States. Infants and toilet-training toddlers were particularly high-risk groups. In 2019, approximately 1840 children died from abuse and neglect. 70.6% of all child fatalities were younger than 3 years old, and 46.6% were younger than 1 year old.

While child physical abuse affects all ethnicities and socioeconomic groups, there were differences in the reported rates across social groups. Rates of abuse and neglect were five times higher for children in families with low socioeconomic status [4]. 43.5% of victims in 2019 were White, 23.5% were Hispanic, and 20.9% were African American. American Indian or Alaska Native children and African American children had the highest victimization rates (14.8 per 1000 children and 13.8 per 1000 children, respectively) [5]. African American children were at significantly higher risk of mortality; the rate of African American child fatality was 2.8 times greater than that of White children (5.48 and 1.94 per 100,000 children, respectively) [5]. Screening for child abuse is biased by race and socioeconomic status, but the implementation of a standardized child abuse screening algorithm has demonstrated removal of this bias for screening [6, 7]. The concept of utilizing a standardized approach to screen for red flags may avoid the effect of implicit racial bias on recognition of child abuse [8], so it is important that the clinician remain aware of one's own implicit biases and strive to treat every family with an objective and clinical eye.

Presentation

Sentinel and Escalation Injuries

Children who are victims of abuse can present with subtle findings, and the clinician must maintain a high index of suspicion to avoid missed injuries. Discharging a child who is a victim of abuse to the same environment without intervention can have tragic, even fatal, consequences. The American College of Surgeons Trauma Quality Programs Best Practices Guidelines for Trauma Center Recognition of Child Abuse, Elder Abuse, and Intimate Partner Violence (ACS TQIP BPG) defined sentinel injuries as "injuries suspicious for physical abuse. These are poorly explained visible or detectable minor injuries such as bruising, musculoskeletal, head or minor oral injury including torn labial frenum (or frenulum) in a pre-cruising infant." An expanded definition includes any injury with rates of abuse high enough to warrant routine evaluation for abuse [9]. Children who suffer sentinel injuries without intervention are at higher risk for escalation injury, defined as "repeat events, potentially resulting in a more severe or even fatal injury." [1] In one review of victims from the Ohio State Trauma Registry between 2000–2010, children who experienced recurrent abuse had 24.5% mortality compared to 9.9% mortality in patients with a single episode [10].

Screening and Algorithms

There are different approaches to identifying children at risk for abuse: the traditional "case-finding" approach, in which a provider has a high index of suspicion based on clinical evaluation and findings, and a screening approach. For mass screening, a tool is applied across the entire population of patients coming to the ED. For selective screening, a tool is applied to selected high-risk groups. Multiphase screening involves two or more screenings applied at different times across the continuum of care. Each has its distinct advantages and disadvantages.

General screening tools have been developed and evaluated for identifying risk factors and clinical indicators of child maltreatment. The Escape tool is a six-item questionnaire with the purpose of screening for and identifying children at risk of child abuse [11]. When validated using 18,275 ED visits across three Dutch hospitals, it was demonstrated to have a sensitivity of 0.8 and a specificity of 0.98 [12]. The SPUTOVAMO-R instrument is a similar six-item checklist evaluated in the

CHAIN-ER [13] study, which demonstrated a positive predictive value of 0.03 and a negative predictive value of 1.0. However, in one systematic review, the use of screening tools was associated with high numbers of child abuse cases being falsely suspected or missed [14], and the authors of CHAIN-ER cautioned about the high false-positive rate of general screening tools, noting specifically cost-effectiveness and clinical and societal implications.

There are also injury-specific clinical decision rules for abuse-concerning findings including bruising, such as TEN-4 FACES P Bruising Clinical Decision Rule (BCDR) [15], and head injury (PediBIRN [6], PIBIS [16], PredAHT [17]). These are discussed in more depth in the following sections. It is important to keep in mind that first, the presenting injury must be detected and recognized as a sentinel injury. The ACS TQIP Guidelines recommended that "trauma centers need standardized targeted screening tools for physical abuse to implement across the continuum of care," or multiphase screening, such as the Mary Bridge Screening Tool [1, 18].

The Western Trauma Association (WTA) Algorithms Committee and the Pediatric Trauma Society (PTS) published a Critical Decisions Algorithm for Child Physical Abuse Trauma Evaluation and Management in 2021. This algorithm synthesized and complemented the ACS TQIP BPG. The authors recommended the use of this algorithm as a framework for institutions to develop individualized protocols for the evaluation of any child presenting with an injury or a brief resolved unexplained event (BRUE) [2]. Of note, BRUEs were not mentioned or addressed in the ACS TQIP BPG.

History

A thorough and well-documented history is crucial when there is a suspicion of child abuse. It can, however, be difficult to obtain due to either reticence on the part of the involved adults (e.g., if they are concerned about their safety or negative consequences) or the child (e.g., due developmental stage or fear) [1]. With older children and adolescents, the clinician should attempt to interview the patient alone. The clinician should ensure that documentation is thorough but also objective and without bias.

When eliciting the history, it is important to allow the caregiver or patient to speak without interruptions to avoid influencing the story. After they have finished, the clinician should ask clarifying questions. Important information to obtain about the event includes the mechanism of injury, the onset and progression of symptoms, events leading up to the injury, the child's behavior before, during and after the event, when the child was last normally active and well-appearing, the last time the child fed normally, the child's level of responsiveness, and the child's usual developmental capabilities. Additionally, the history-taker should elicit who was with the child at the time symptoms began and who else was in the home. If the caregiver does not volunteer a history of trauma in the setting of an injury, the clinician should specifically ask if a trauma occurred and record any denial in the medical record. Other useful information that should be obtained includes a family history of bleeding, bone disorders, and metabolic or genetic disorders, pregnancy history, familial patterns of discipline, the child's temperament, parents' expectations of child behaviors and development, history of abuse to the child, siblings, or parents, previous and/or present CPS involvement, other social concerns (e.g., substance abuse in the household, mental health problems, interactions with law enforcement), and financial stressors [19].

Historical findings independently associated with abuse include no reported history or inconsistent history (e.g., a vague or minor explanation for a significant injury) and referral for suspected child abuse. Red flags that are concerning for abuse include a history that changes over time by the same source, discordant stories between caregivers, delay in seeking care (>24 h after injury), lack or denial of reported trauma when an obvious injury is present, an inappropriate response or child behavior reported by the caregiver after the injury, an injury attributed to harm inflicted by the patient, a sibling, a pet, or during the course of treatment, an injury mechanism inconsistent with the child's developmental stage, and any prior history of an unexplained death of a child in the household [1, 19]. The ACS TQIP Guidelines also report "clues of concern" based on expert opinion and health professional experience that include concerning social factors (substance use or abuse, mental health disorders, arrests or incarcerations, or intimate partner violence in the household), inappropriate affect on the part of the child and/or caretakers, inappropriate comments by the parents about or to the child, inappropriate parent reaction to the child's behaviors or pain, inappropriate interactions between family members, and the family's approach to discipline [1].

Physical Exam

The clinician may encounter a child who is a victim of physical abuse either after presentation of the injury or during a routine physical exam. In both cases, it is important to maintain a high index of suspicion and, when abuse is suspected, perform a thorough physical exam with the child undressed in a gown. Areas that require evaluation but are often overlooked include the neurologic exam, mouth exam, genitals, perineum and anus.

When evaluating a child with concern for abuse, physical exam findings to look for include traumatic scalp wounds or alopecia, oral mucosal tears, dental trauma, acute or healing injury of the frena in infants, and skin findings including bruises, lacerations, burns or bites, particularly in unusual locations such as the pinna, back of the ear, buttocks, thighs, or perineum. Careful palpation of the extremities, hands and feet should be performed to evaluate for fractures. A complete neurologic exam with special attention to alertness and developmental status is critical to evaluate abusive head trauma. Neglect and physical abuse can occur concurrently, and it is imperative to note any evidence of neglect, such as failure to thrive, malnutrition, extensive dental caries, untreated diaper dermatitis or neglected wound care.

General findings that indicate abuse include:

- Any injury to a preambulatory infant
- Injuries to multiple organ systems
- Multiple injuries in different stages of healing
- Patterned injuries
- Injuries to non-bony or other unusual locations (torso, ears, neck, face, upper arms)
- Significant injuries without explanation
- Additional evidence of neglect

Any findings concerning for abuse should be carefully documented in the medical record with written descriptions, diagrams and photos. If available, a child abuse pediatrician or another provider with forensic training should be involved for appropriate documentation.

Radiographic Findings

If there is a concern for abuse after obtaining a thorough history and physical exam, appropriate laboratory and radiographic studies should be obtained as described above. Concerning findings on a skeletal survey include: metaphyseal fractures (corner, chip, bucket handle), any fracture in a non-ambulating child, an undiagnosed healing fracture, an isolated humerus or femur fracture in a child <18 months old without public trauma to account for it, and rib fractures (especially posterior) in a child <3 years old. On neuroimaging, a subdural or subarachnoid hemorrhage in a child <1 year old, particularly in the absence of a skull fracture, is concerning for abuse. Concerning findings on a CT of the abdomen and pelvis include a hollow viscus injury, particularly a duodenal or small bowel injury, in children <4 years old or a combined hollow viscus and solid organ injury [2]. Specific discussions of these injury patterns are discussed in the below sections.

Management

Children presenting with injuries suspicious for abuse require a quick and coordinated response to ensure adequate evaluation and treatment with a goal of minimizing increasing morbidity or risk of mortality. Upon presentation, the following should occur:

1. Activate trauma team (non-trauma centers can elect to teleconsult or transfer)
2. Consult child abuse team or local/regional child abuse expert
3. Consult specialty resources as needed (e.g., neurosurgery, radiology, ophthalmology)
4. Notify social work

(a) Support child, caregiver
(b) Notify Law Enforcement
(c) Assist in the navigation of limiting visitors

5. Notify CPS (May Be Notified by Social Work)

In the United States, healthcare professionals are obligated by law to notify CPS of suspected child abuse, although specifics of reporting requirements vary by state. When child abuse is suspected, a trauma provider should assemble a team capable of completing a child abuse screening assessment. At a minimum, this team includes a trauma surgeon, a pediatrician (or child abuse pediatrician), and a social worker. If these resources are not available, the child should be transferred to a capable center (teleconsult is also acceptable). Additional resources include surgical subspecialists, nurses, child life, psychology and neuropsychology.

One of the most challenging aspects of evaluating a child for abuse can be communicating concerns to the child's parents. During this difficult conversation, it is important to be objective, neutral, and culturally sensitive. Prior to concluding the discussion, the provider should notify the parents of the need for additional resources such as CPS.

If required based on injury severity or physiologic status, the child should be admitted to the hospital or transferred to a trauma center with pediatric capabilities. A more difficult scenario arises when the child's physical status does not necessitate admission. In this scenario, a huddle with all members of the treatment team should be convened to discuss disposition. If there is no verifiably safe home or alternative per the social worker, CPS, or law enforcement, then the child should be admitted to the hospital. If there is a safe home or alternative with close follow-up, then the child may be discharged. In this scenario, the child's pediatrician or primary care provider should be informed and optimal follow-up coordinated. If a skeletal survey was performed, a repeat study is required 2 weeks after initial evaluation.

Evaluation and Management by Injury Pattern

Bruises

Bruises are the most common and often first injury resulting from child physical abuse [20–22] yet can be difficult to distinguish from innocuous bruises which are so common in childhood [23]. Despite this difficulty, it is crucial to recognize intentional bruises and take appropriate action, as these are the most commonly missed sentinel injuries [24–27]. In one review, 80% of sentinel injuries in infants were bruises [26].

Bruises resulting from unintentional injury more commonly occur over bony prominences (rather than soft areas). The "one and done" rule refers to the fact that a single bruise typically results from a single non-abusive injury. Bruises to non-bony prominent areas of the body, patterned bruising and petechiae are all concerning for abuse, and any bruising in an immobile child should prompt further investigation [28]. It is not possible to date bruises based on color, and the color of bruises should not be used to determine multiple stages of healing [29].

Pierce et al. derived and validated a bruising clinical decision rule (BCDR) to identify children at risk of being physically abused. The TEN-4 FACES P components included any bruising of the torso, ear, neck, frenulum, angle of the jaw, cheeks [fleshy], eyelids, and subconjunctivae, bruising anywhere on an infant 4.99 months and younger, or patterned bruising. These criteria were validated in children younger than 4 years old with bruising across five emergency departments with a sensitivity of 95.6% and specificity of 87.1% for distinguishing abuse from non-abusive trauma. If a bruised child <4 years old meets any of these criteria, further evaluation for abuse is warranted [15, 20].

Abusive Head Trauma

The CDC defines pediatric abusive head trauma (AHT) as "an injury to the skull or intracranial contents of an infant or young child (<5 years of age) due to inflicted blunt impact and/or violent shaking." [30] In one review of children <5 years old treated for abuse at two Level 1 Pediatric Trauma Centers, head injuries were the most common injury sustained and had the greatest increased risk of death [31]. The presentation of children suffering from AHT can range from subtle, non-specific symptoms to comatose. Victims may demonstrate reduced activity, lethargy, irritability, poor feeding, vomiting or apnea, and depending on the severity of the injury, may develop seizures or coma [19]. BRUE, macrocephaly or full/bulging fontanelles should also raise suspicion for abusive head trauma. The most common history given by caregivers is an unknown trauma or a low-risk mechanism (e.g., a short distance fall) that is unable to explain the injury pattern.

When there is a concern for abusive head trauma, the initial imaging obtained should be computerized tomography (CT) of the head. Patterns of subdural hemorrhage (SDH) more highly associated with abusive (versus non-abusive) head trauma include interhemispheric hemorrhage, hemorrhage without an associated skull fracture and multiple subdural hemorrhages [32]. SDH related to birth trauma should remain a consideration in the young infant but generally resolves within 1–3 months of life [33]. Unintentional skull fractures are more commonly unilateral, linear fractures without a significant associated intracranial injury [34]. Magnetic resonance imaging (MRI) of the brain can be useful for evaluating brain tissue changes such as micro-hemorrhages, cerebral edema, and stroke, as well as for distinguishing extra-axial fluid collections. The American Academy of Pediatrics (AAP) also recommends considering MRI of the cervical spine to assess for ligamentous injuries or spinal subdural hemorrhage in the setting of AHT [35]. The most commonly encountered injuries on MRI of the spine in cases of AHT include injuries to the posterior ligamentous complex and to the atlanto-occipital/atlantoaxial joint capsule [36]. Fractures of the cervical spine are uncommon in abusive head trauma. Radiographic findings that suggest greater injury severity include cerebral edema, midline shift and evidence of hypoxic-ischemic changes. Children with these findings are at greater risk for seizure, and the provider should consider a prompt neurology consultation with possible continuous electroencephalography (EEG).

Three AHT-specific clinical prediction rules (CPR), PediBIRN, PredAHT and PIBIS, have been developed and validated with the aim of reducing missed cases of pediatric abusive head trauma (Fig. 36.2).

All children in whom abusive head trauma is suspected should undergo a retinal exam to evaluate for retinal hemorrhage. Ophthalmology should be consulted for a dilated exam within 24–48 h of injury, as intraretinal hemorrhages can resolve within 72 h. However, a dilated exam should be delayed in a child with severe neurologic injury until serial pupil reactivity examinations are no longer necessary. Additionally, it is worth mentioning that a dilated exam can be emotionally traumatic, and in children with low risk of abusive head trauma (no evidence of intracranial hemorrhage, normal mental status, no bruising of the head or face), the need for a dilated exam should be thoughtfully considered rather than considered a matter of routine [1].

Children under 2 years old are most susceptible to serious injury with shaking alone. Intra-retinal hemorrhages are caused by elevated intraocular pressure resulting in papilledema or by acceleration-deceleration shear injury to the vitreo-retinal surface. Findings suggestive of AHT include extensive bilateral posterior segment hemorrhages, particularly if they are bilateral, present in large numbers in each eye, in all layers of the retina, or with extension to the periphery. Other suspicious findings include retinoschisis, perimacular retinal folds, and retinal and vitreous detachment. While intraretinal hemorrhages can resolve within 72 h, subretinal, preretinal, and inravitreal hemorrhages indicate more severe AHT and can take weeks to months to resolve [1].

Outcomes in children who are victims of AHT are related to injury severity. Worse outcomes are seen in patients with secondary injury from hypoxia, ischemia, or metabolic/inflammatory cascades. 70% of AHT victims have some degree of last neurologic impairment, such as static encephalopathy, intellectual disability, cerebral palsy, cortical blindness, seizure disorders, behavior problems or learning disabilities [37].

Skeletal Injuries

Fractures are the second most common sign of child abuse after bruising [22]. They are often occult injuries necessitating a high index of suspicion to avoid a missed diagnosis [38, 39]. Skeletal injury presents a diagnostic dilemma—while any fracture can be associated with abuse, they are also a non-specific and common finding in the unintentionally injured child. Skeletal fractures in children less than 3 years old are the most suspicious for abuse [22], but any fracture pattern inconsistent with

Overall Group	Prediction Tool	Aim	Patient Population	Test Characteristics	Level of Evidence
Hymel et al. (2014),[41]	4-variable AHT clinical prediction rule (PEDIBIRN) Variables: Acute respiratory compromise before admission; bruising of the torso, ears, or neck; bilateral or interhemispheric subdural hemorrhages or collections; and any skull fractures other than an isolated, unilateral, nondiastatic, linear, parietal fracture	To validate the screening performance for AHT of a previously derived 4-variable prediction rule	No. of subjects: 124 AHT cases, 167 non-AHT cases Age range: children <3 years of age Subject characteristics: Hospitalized patients in the pediatric intensive care unit with intracranial injury on CT or MRI, confirmed as AHT or HART (HART) Confirmation of Abuse: A priori definitional criteria for AHT*	When $\geq$ 1 feature were present: sensitivity: 0.96 (95% CI, 0.90–0.99); specificity, 0.43 (95% CI, 0.35–0.50); AUC, 0.78	Level II
Cowley et al. (20l5),[40]	Predicting Abusive Head Trauma Tool (PredAHT) Variables: Retinal hemorrhage, rib and long-bone fractures, apnea, seizures, and head or neck bruising	To validate the previously developed PredAHT tool to provide a prediction of the probability of AHT in children aged <36 months presenting with an intracranial injury.	No. of subjects: 133 non-ART cases and 65 AHT cases Age range, children <36 months Subject characteristics: Hospitalized patients with intracranial injury, confirmed as AHT or nAHT Confirmation of abuse: abuse ranking 1-2**	When $\geq$ 3 features were present in children <3 years with intracranial injury: Sensitivity, 72.3% (95% CI, 60.4–81.7); Specificity, 85.7% (95% CI, 78.8–90.7); AUC, 0.88	Level II
Berger et al. (2016),[38]	Pittsburgh Infant Brain Injury Score (PIBIS) Variables: Abnormal dermatologic examination results (2 points), age $\geq$ 3 months (1 point), head circumference >85th percentile (1 point), and serum hemoglobin <11.2 (1 point)	To validate the previously developed PIBIS, a clinical prediction rule to assist physicians decide which high-risk infants should undergo CT of the head	No. of subjects: 214 cases (abnormal neuroimaging at enrollment or during follow-up—traumatic and nontraumatic) and 826 controls (normal neuroimaging, or no imaging at enrollment and follow-up); age range, infants <365 days. Subject Characteristics: well-appearing infants with temp <38.3°C, no history of trauma, and a symptom associated with having a brain abnormality (vomiting, apnea)	Test characteristics of identification of abnormal neuroimaging at a score of 2: sensitivity, 93% (89–96); specificity, 53% (49–57); NPV of a score <2 for detection of abnormal neuroimaging was 96% (93.6–97.9)	Level III

*One or more of these criteria: 1. Primary caregiver admission of abusive acts. 2. Witnessed abusive acts. 3. Specific primary caregiver denial of any head trauma, although the perambulatory child in his or her care became acutely, clearly, and persistently ill with clinical signs linked to traumatic cranial injuries visible on CT or MRI. 4. Primary caregiver account of the child's head injury event was clearly historically inconsistent with repetition over time. 5. Primary caregiver account of the child's head injury event was developmentally inconsistent with child's known or expected gross motor skills. 6. Two or more categories of extracranial injuries considered moderately or highly suspicious for abuse.

**Nonaccidental trauma was defined in each report by meeting one of the following criteria as proposed by Maguire, et al.:[14] 1. Abuse confirmed at case conference, family, civil or criminal court proceedings or admitted by perpetrator or witnessed. 2. Abuse confirmed by stated criteria where diagnosis was based upon additional features and did not rely on the variable of interest, and included multidisciplinary assessment. 3. Abuse defined by stated criteria. 4. Abuse stated as occurring, but no supporting detail given as to how it was determined. 5. Abuse stated simply as "suspected".

Fig. 36.2 Test characteristics and prediction tools for nonaccidental trauma the developmental status and degree of mobility with the child's age should prompt a child abuse evaluation.

Fracture types, location and the developmental stage of the injured child all must be considered when evaluating for potential abuse. Fracture locations most associated with abuse are the ribs, femur, tibia and humerus [40, 41]. Linear parietal skull fractures are the most common fracture-type in both abused and unintentionally injured children [40]. The fractures most associated with abuse in children are rib fractures, particularly in children under 3-years-old [40]. This is often due to ribs being held between hands in a compressive shaking maneuver and are often posterior, multiple, bilateral, and in various stages of healing. Chest compressions during CPR have not been associated with posterior rib fractures [42, 43]. All children younger than 3 years of age not in an independently verified incident presenting to a healthcare facility with a rib fracture should have a routine child abuse evaluation [41].

Other fracture patterns associated with abuse include metaphyseal lesions, which are fractures through the primary spongiosa of the distal metaphysis of a long bone. These are commonly seen as corner or bucket-handle fractures. Long-bone fractures are particularly concerning in pre-ambulatory infants; however, in ambulatory toddlers, femur and tibia fractures are not very specific as they can occur due to low energy mechanisms such as falls. In the humerus, proximal and mid-shaft fractures are particularly concerning [22]. Other concerning locations are those that are unusual in other mechanisms but are associated with blunt force trauma (e.g., holding, shaking, stomping, slamming, among others) such as the sternum, scapulae and vertebrae. All children younger than 18 months of age not in an independently verified incident presenting to a healthcare facility with humeral or femoral fractures should have a routine child abuse evaluation [41].

A careful and thorough history is particularly important to distinguish between abusive versus unintentional fractures [1, 22, 44, 45]. Fractures in non-ambulatory children are particularly suspicious. Highly associated historical findings are a mechanism that does not explain the fracture type in addition to the findings discussed above, such as delayed presentation and unwitnessed injury [1, 22, 44, 45]. When evaluating a child with fractures, one must also consider uncommon illnesses that predispose to bone fragility such as collagen disorders, malnutrition, vitamin deficiencies, chronic renal disease and prolonged immobility. Children with fractures often present with irritability, pain, guarding and limited use of the fractured extremity. On exam, they may have swelling, deformity, or point tenderness, but it is also important to note that there may be no external evidence of injury in abuse-related fractures due to delayed presentation. A crucial aspect of the exam is assessing the child's capacity for independent movement (such as rolling, crawling, or walking) to inform the possible mechanism of injury.

The American Academy of Pediatrics (AAP) [46] and the American College of Surgeons (ACS) [1] support criteria for any injured child under 24 months of age should be evaluated with a skeletal survey. The American College of Radiology (ACR) provides the recommended technical equipment and parameters [47]. Skeletal surveys include frontal and lateral views of the skull, lateral views of the cervical and thoracolumbosacral spine, single frontal views of long bones, hands, feet, chest and abdomen, and oblique views of the ribs [48]. In one meta-analysis, skeletal surveys detected occult fractures in 13–26% of infants (<12 months old) and 7–19% of toddlers (12–23 months old) with suspected abuse [39]. In particular, oblique views of the chest are needed to detect occult rib fractures [22]. Any suspected fracture needs a dedicated two-view radiograph. Additionally, the American College of Radiology recommends a Tc-99 m bone scan when the skeletal survey is negative but clinical suspicion remains high and a search for further evidence of fracture is warranted [48]. However, these scans require intravenous injection and often sedation, and use should be thoughtfully considered and limited to necessary situations.

Interval follow-up skeletal surveys 2 weeks following the initial evaluation can improve detection of occult abusive fractures. The follow-up survey may have a more limited number of views while maintaining diagnostic accuracy [1, 49]. This should be performed when abnormal or equivocal findings are seen on the initial study or when there is a high suspicion for abuse [48]. Involvement of child abuse pediatricians, social workers and CPS can help ensure this is completed.

Abdominal Injuries

Abusive abdominal trauma includes both solid organ and hollow viscus injuries, and the most commonly injured organs are the liver, kidney, and stomach/small bowel [50]. Combined injuries (both solid organ and hollow viscus) should raise concern for abuse. Duodenal injuries from blunt abdominal trauma are considered sentinel injuries, particularly in children <4 years old (see below) [22, 44, 51–53]. As with other types of child abuse, abdominal trauma is most common in younger children [44]. Over 25% of abdominal trauma in children <1 year old is abusive, and abdominal injuries account for up to 50% of abusive fatalities [22]. Victims of abusive abdominal trauma are generally younger than children with noninflicted abdominal trauma and also have a higher mortality (9.2% versus 2.7%) [54].

Low mechanism falls are the most common history given by caregivers of victims of abusive abdominal trauma [55]. While abdominal tenderness and bruising should prompt further evaluation for abdominal trauma, external signs such as bruising may be absent up to 80% of the time [44, 51]. As with other visible signs of abuse, photographs should be taken of any bruising or patterned injury to the abdomen. Abusive abdominal trauma carries a high likelihood of associated injuries, such as fractures, head injuries, thoracic injuries, and skin lesions [1, 22]. In comparison to children with blunt abdominal trauma due to a fall, victims of abuse have more hollow viscus injuries, more pancreatic injuries, a higher injury severity score, and more severe head injuries [55]. Screening for occult abdominal injury should be performed with laboratory testing to include AST/ALT and lipase levels. If the child has abdominal tenderness, bruising, an unreliable abdominal exam, or elevated laboratory values (AST/ALT >80 or lipase >100), a CT scan should be performed. A surgeon should be involved early in the course of treatment, and operative exploration is indicated for cases of obvious peritonitis or bleeding even before imaging is obtained [54].

Duodenal injuries deserve special consideration, and non-motor vehicle-related duodenal trauma in a child less than 5 years old is concerning for child abuse [44]. One study demonstrated 100% of children ≤2 years of age and 53% of children >2 years of age who presented with duodenal injuries were related to abuse, and none were related to unintentional mechanisms such as falls. 12.5% of duodenal injuries were fatal [53]. Duodenal injury can present as hematoma or perforation, and children with perforations have a higher injury severity score and longer length of stay [52]. These injuries can present in a delayed fashion, and perforations into the retroperitoneum can be subtle on imaging. An upper gastrointestinal (UGI) series can be helpful in clarifying a diagnosis not immediately obvious on a CT scan [1]. Special note is also made of pancreatic injuries. In one study, abuse was present in 1% of all pancreatic fatalities, and each was associated with multiple additional injuries [56]. Pancreatic injuries in child physical abuse are often associated with hollow viscus injuries and may present late as a pancreatic pseudocyst [44]. Pancreatic injuries were more common among abused children when compared to fall casualties [55].

Burns

Pediatric burns account for 5.8–8.8% of all abuse cases annually. In one review of all pediatric burn admissions to Parkland hospital from 1974–2010, 5.3% were due to abuse [57]. Importantly, burns can be a result of either intentional abuse or neglect, both of which warrant the involvement of CPS. While victims of intentional burns are often still young children, they are slightly older than other types of physical abuse (mean age 2–4 years old) [22]. Significant predictors of abuse are younger age, gender, presence of a scald, contact or chemical burn, and injury to the hands, bilateral feet, buttocks, back and perineum [57]. Other findings concerning for abuse include deep partial-thickness or full-thickness burns, burns to the posterior trunk, burns caused by hot tap water, and burns with associated injuries [38]. In a recent review, 33% of children with abusive burns had associated fractures on skeletal survey [58].

Scald and contact burns, respectively, are the most common mechanisms of abuse in children, with less common mechanisms including flame and chemical burns. Burn patterns are perhaps the most crucial method of distinguishing intentional from accidental burns. In scald burns, concerning findings include immersion-patterned burns, stocking burns, demarcated borders, uniform depth, flexion sparing and sparing of the sole of the foot. Accidental scalds are more commonly due to a child spilling or pulling down a hot liquid, resulting in an unilateral anterior chest and shoulder patterning with irregular borders and decreasing burn depth. Abusive contact burns are usually secondary to a caregiver holding a hot item against the skin. These burns are generally located on the limbs or trunk, are sharply demarcated, and can present, for example, as punched-out lesions representing cigarette burns. Accidental contact burns are often from a child grabbing a hot object, resulting in a single burn on the palm with no demarcated edge. Chemical burns (e.g., bleach) can progress over days to very severe burns; thus, referral to a burn center is relevant even in a child who appears well.

Kemp et al. developed the BuRN (Burns Risk assessment for Neglect or abuse) Tool to assist with recognizing burns secondary to child maltreatment. The tool assigns a point value to the following variables: age less than 5 years old (scald: 2 points, burn: 2 points), age older than 5 years old (scald: 0 points, burn: 1 point), full-thickness burn (2 points), bilateral scald burns (1 point), atypical location of uppermost scald burn (back, buttocks, groin or hairline: 1 point), concern about supervision (1 point), concern about inappropriate explanation (2 points), and previous involvement with social services (3 points). A score of 3 or greater should prompt investigation for maltreatment [59]. As in other forms of abusive injury, photographs are crucial for documentation. The American Burn Association recommends referral to a burn center for all burned children in hospitals without qualified personnel or equipment for the care of children [60].

Conclusions and Take Home Points

- Elicit and document an extensive history of events leading up to and surrounding the injury.
- A history that is changing, inconsistent among caregivers, or which does not match the mechanism of injury should be cause for consideration of abusive injury.
- Ensure a full head-to-toe exam is completed with particular attention to the skin and often missed areas, including the oral frena, perineum, genitals and anus.
- Take photographs of any injuries and include diagrams in the medical record.
- Be aware that sentinel injuries can be vague or seem like mild injuries but can be the precursor for life-altering or deadly future incidents of abuse (i.e., bruising in an immobile infant or a fracture mechanism which does not match the history provided).
- Physically abused children may have significant intraabdominal injuries even in the absence of abdominal bruising mandating laboratory screening.
- Consider implementation or application of a protocol for all cases concerning for physical abuse to ensure a thorough evaluation and an unbiased approach to the patient and family.
- Engage experts in child abuse: consult the child abuse pediatrician at your facility or identify a regional contact for consultation.
- Engage social work to provide support for the family as well as to identify necessary community resources (Child Protective Services, law enforcement).

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Chapter 37
Hypothermia and Near-Drowning

Natalie M. Lopyan and Samir K. Gadepalli

Abstract The hypothermic or near-drowning patient should be approached as one would approach any trauma patient, starting with a primary and secondary survey. Young children and infants are at risk for hypothermia due to a large ratio of surface area to body mass, the inability to increase heat production through shivering, and an inability to recognize or escape hypothermic exposure. The stages of hypothermia correspond to the physiologic responses to cold, and care decisions in the hypothermic patient should be guided by core temperature measurement. Near-drowning has multi-organ effects, including pulmonary edema with resultant acute respiratory distress syndrome, hypoxic/ischemic cerebral injury, arrhythmias secondary to hypothermia and hypoxemia, and acid-base disturbances. This chapter provides a reference for the pediatric provider caring for the hypothermic and near-drowning patient on arrival to the trauma bay. It will describe the pathophysiologic response and optimum management of these unique trauma scenarios. Lastly, it will address recognition of specific injury patterns which may be non-accidental in nature.

Keywords Hypothermia · Drowning · Near-drowning · Unintentional injury · Non-accidental trauma · Pediatric trauma

Key Concepts/Clinical Pearls

- The hypothermic or near-drowning patient should be approached as one would approach any trauma patient, starting with a primary and secondary survey.
- Young children and infants are at risk for hypothermia due to a large ratio of surface area to body mass, the inability to increase heat production through shivering, and an inability to recognize or escape hypothermic exposure.

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- Near-drowning has multi-organ effects, including pulmonary edema with resultant acute respiratory distress syndrome (ARDS), hypoxic/ischemic cerebral injury, arrhythmias secondary to hypothermia and hypoxemia, and acid-base disturbances.

Initial Management of the Trauma Patient
The initial management of the trauma patient needs to be methodical and organized, with the primary and secondary survey being at the core of this assessment. The primary survey—evaluation of the patient's airway, breathing, circulation, and disability, with subsequent exposure—serves to identify immediately life-threatening injuries and to address them upon doing so. When a positive finding on this survey is identified and addressed, the provider must begin the survey from the beginning, starting with an evaluation of the airway once again. Once the primary survey has been completed, the provider should move on to a secondary survey of the trauma patient, which includes a full head-to-toe inspection of the victim for additional injuries. This secondary survey is not complete without a log roll of the patient to assess for bony tenderness and step-offs of the spine, as well as a rectal exam evaluating for tone and blood. Simultaneous to the primary and secondary survey is the establishment of IV access and placement on a monitor with blood pressure recording. A chest X-ray and focused assessment with sonography in trauma (FAST) exam should be performed as an adjunct to the primary survey.

Radiographic and Ancillary Studies
Near-drowning and hypothermic victims may sustain severe neurologic morbidity. Neurologic outcome after a cardiopulmonary arrest is determined by several factors, including the cause of arrest, the no-flow duration, the adequacy of blood flow during CPR, and time lapse to restoration of adequate blood flow [1]. Moreover, injury secondary to ischemia-reperfusion injury, hypothermia, and hypoglycemia have the potential to influence neurologic outcomes [1]. Neurocognitive outcomes of this trauma population cannot be accurately predicted in the early course of treatment, resulting in an inaccurate estimation of the degree of neurologic compromise. Victims who ultimately have a positive outcome generally awaken within 3 days after injury; most patients who remain neurologically unresponsive as a result of hypoxic-ischemic encephalopathy for more than 7 days fail to survive or have a very poor neurologic recovery [1]. Though there is no defined algorithm allowing for definitive prognostication, serial neurologic examinations should be performed with brain imaging, in the form of MRI, utilized as an adjunct. Repeated or continuous electroencephalography (EEG) within 72 h of injury and afterward may be considered, with reactivity to auditory and painful stimulations serving as a sign of good prognosis, and the presence of burst-suppression, generalized suppression, status epilepticus, and nonreactivity signifying a poor outcome [1, 2].

Pediatric near-drowning and accidental hypothermic patients will rarely have concomitant injuries. In 2003, Hwang et al. looked at the prevalence of traumatic injuries in children involved in drowning and near-drowning accidents [3]. A review of 143 cases found traumatic injuries in 4.9% of patients, with the predominant mechanism of injury being diving, and all injuries were to the cervical spine. By contrast, Chotai et al. published in 2017 on the management and outcomes of 363 pediatric drowning and near-drowning victims, with an associated injury rate of 1.92% which were primarily (1%) soft tissue in nature [4]. The history of the event and the victim's age should guide suspicion of C-spine injury. If there exist clinical signs of serious traumatic injury or a concerning mechanism of injury, spinal precautions should be maintained with immobilization in a cervical collar, and cross-sectional imaging of the cervical spine should be obtained [5]. While imperative that concomitant injuries be addressed in a timely manner, the timeline and extent of doing so are determined by the patient's stability from a cardiopulmonary standpoint and after rewarming. Anesthesia may affect neurologic examination and should be delayed when possible.

Introduction

Hypothermia is defined as a core body temperature less than 35 °C. The three stages of hypothermia are defined as follows: (1) mild—core temperature 32 to 35 °C, (2) moderate—core temperature 28 to 32 °C, and (3) severe—core temperature below 28 °C, with some experts defining profound hypothermia as a core temperature less than 25 °C [6]. Young children and infants are at greater risk for hypothermia as a result of the larger ratio of surface area to body mass [7]. Further, infants lack the ability to increase heat production through shivering and are inherently unable to recognize or escape hypothermic exposure [7]. Etiologies of accidental hypothermia include environmental exposure, drowning, intoxicating substances or other drugs, trauma, and severe illness. Early recognition of hypothermia is paramount, as its presence increases mortality in patients after trauma and in hospitalized children overall [7]. Estimated death rates among infants and children less than 14 years of age range from 0.2–1 death per million, although the diagnosis may be missed in a significant number of deaths [7]. Nevertheless, providers must be wary of a premature declaration of death in pulseless severely hypothermic patients.

Drowning is the leading cause of unintentional injury deaths in toddlers and the second leading cause of accidental deaths in children 1 to 16 years of age [4]. For each fatal drowning victim, five patients receive emergency department care for near-drowning events [4]. Near-drowning, defined as survival at least 24 h after a submersion incident, is the leading cause of injury in toddlers. At risk, populations include male toddlers, African American children, children with seizure disorders and cardiac dysrhythmias, and children of low socioeconomic status [8–11]. The near-drowning victim who presents to the emergency department must be concomitantly evaluated for the sequelae of submersion and the potential for resultant hypothermia.

Physiology of the Hypothermic and Near-Drowning Victim

The stages of hypothermia correspond to the physiologic responses to cold [6, 12]. In cases of mild hypothermia, the body increases the production of heat by shivering and increasing metabolism and reduces heat loss by peripheral vasoconstriction. In moderate hypothermia, these mechanisms of compensation begin to fail, and in severe hypothermia, the basal metabolic rate decreases by approximately one-half the normal, with resultant cardiorespiratory depression and markedly depressed mentation [12]. As the core temperature continues to fall, fixed and dilated pupils are observed on examination, with the concomitant development of apnea, pulselessness, and rigor mortis [12]. The use of echocardiography benefits in the management of cardiopulmonary resuscitation, as profound bradycardia may prompt unnecessary chest compressions. Moreover, myocardial irritability and ischemia are often observed, with ventricular fibrillation being a common arrhythmia in this patient population. Importantly, slowed metabolism may necessitate a dose adjustment of medications utilized in the resuscitation process so as to mitigate toxicities. A marked decrease in blood volume is witnessed secondary to extravasation, with a “cold diuresis” to follow as a result of renal concentrating failures [13]. The latter necessitates large volumes of crystalloid in the resuscitation process of the hypothermic patient.

Care decisions in the hypothermic patient should be guided by core temperature measurement, utilizing a low-reading thermometer. It should be noted that core methods may vary in accuracy, and thus rectal temperatures must be taken 15 cm deep in the rectum and measured for several minutes, and esophageal temperature probes need to be placed in the lower third of the esophagus [14]. An indwelling bladder temperature probe may be beneficial in that it enables ongoing monitoring. Providers must be aware of the paradoxical core temperature after drop, or further cooling of the body after removal from the cold exposure [15]. This phenomenon occurs as a result of vasodilation and convective heat loss in the extremities, and it may be more profound in the pediatric population as a result of decreased body mass and increased peripheral vasoconstriction [15]. By warming the patient’s chest/core prior to the extremities, the provider can aim to minimize the afterdrop and its potentially fatal outcomes. Laboratory analysis must be frequent, with close monitoring for electrolyte and acid-base disturbances. Notably, the lactate level is an unreliable indicator of recovery in this patient population as a result of poor liver metabolism.

Management of the Hypothermic and Near-Drowning Victim

Methods of rewarming the hypothermic patient vary and are largely dependent on the degree of hypothermia and the capabilities of the facility to which the patient presents (Table 37.1). Patients with a core body temperature between 32 and 35 °C can be managed with less invasive passive rewarming methods, including radiant

Table 37.1 Methods of rewarming the hypothermic patient based on core body temperature

Mild hypothermia (32–35 °C) – Removal of wet clothes – Radiant heat – Administration of warmed intravenous crystalloid – Bair hugger placement
Moderate hypothermia (28–32 °C) without cardiopulmonary collapse – As above – Gastrointestinal tract irrigation – Bladder irrigation – Peritoneal irrigation – Hemodialysis – Mediastinal lavage – Continuous thoracic lavage with two chest tubes
Severe hypothermia (<28 °C), moderate hypothermia (28–32 °C) without a palpable pulse, or patients with respiratory insufficiency on conventional ventilator – As above – Veno-arterial extracorporeal membrane oxygenation

heat, the administration of warmed IV fluids, and the application of a Bair Hugger. In cases of moderate hypothermia (core body temperature of 28–32 °C without cardiopulmonary collapse), more invasive active rewarming methods include gastrointestinal tract and bladder irrigation, peritoneal dialysis, hemodialysis, mediastinal lavage, and continuous thoracotomy lavage with two chest tubes [16–18]. Patients with a core body temperature less than 28 °C or ranging from 28–32 °C in the absence of a palpable pulse and those with respiratory insufficiency on a conventional ventilator as a result of pulmonary edema and ARDS should be evaluated for extracorporeal membrane oxygenation (ECMO) [19–21]. Though data on the role and long-term outcomes of ECMO in the resuscitation of near-drowned and hypothermic children is largely limited to case reports and series, several institutions have reported on improved outcomes of this patient population after the establishment of protocols incorporating its usage [19–23]. Preemptive protocols bringing a perfusionist and primed ECMO circuit to the trauma bay serve to facilitate the rapid and efficient delivery of care.

Management of near-drowning victims can be divided into three phases: prehospital, emergency department, and inpatient care, as described in Table 37.2. Outcomes in drowning victims are improved by the immediate initiation of cardiopulmonary resuscitation by bystanders, when indicated and once the victim has been removed from the water [24]. Rescue breathing should begin as soon as possible, with ventilation prioritized over chest compressions as the most important initial treatment [25]. Pulses may be difficult to palpate, especially in the face of hypothermia. Thus, a careful pulse check (with or without the adjunct of echocardiography) should be performed prior to managing life-threatening arrhythmias per Advanced Cardiovascular Life Support (ACLS) protocol. Supplemental oxygen should be provided to spontaneously breathing patients, with intubation being performed for apneic patients, those in respiratory distress, and those unable to protect their airway secondary to altered mental status. Routine cervical spine

Table 37.2 Management of near-drowning

Pre-hospital
– Removal from the water
– Immediate initiation of CPR with ventilation prioritized over chest compressions
– Management of life-threatening arrhythmias per ACLS protocol
– Supplemental oxygen or intubation
– Possible cervical spine immobilization
Emergency Department
– Warming of the trauma bay prior to patient's arrival
– Assessment of airway, breathing, circulation, and disability
– Removal of wet clothes and initiation of passive rewarming
– Secondary survey
– IV access, EKG, CXR, FAST exam
– Additional X-rays and cross-sectional imaging at the provider's discretion
Inpatient
– Specialized service intervention (cardiac, neurologic, respiratory, trauma-related surgery)
– Neuro-prognostication

immobilization in the field is not recommended due to its potential interference with airway management, and thus it is only recommended for patients with a mechanism of injury suggestive of spinal trauma or obvious signs of injury [25].

Prior to the patient's arrival, the trauma bay must be adequately warmed to mitigate the sequelae of concomitant hypothermia. Upon arrival to the emergency department, the hypothermic or near-drowning patient should be approached as one would approach any trauma patient, starting with an assessment of the airway, breathing, circulation, and disabilities. Exposure of the patient should then commence, with the removal of wet clothes and the application of warm blankets, to facilitate in the secondary survey—a head-to-toe assessment of the patient for visible signs of injury. Intravenous (IV) access should be established simultaneously, and routine blood work should be obtained. An electrocardiography (EKG) should be obtained on all patients with an arrhythmia on continuous cardiac monitoring in light of the high prevalence of life-threatening arrhythmias in the hypothermic patient. Rewarming of patients with a temperature less than 35 °C is imperative, as is the maintenance of euglycemia. A chest X-ray and focused assessment with a FAST exam should be performed as an adjunct to the primary survey. Additional X-rays and cross-sectional imaging are ordered at the discretion of the provider.

Triage in the emergency department is based upon the presence or absence of symptoms, laboratory or EKG abnormalities, and/or hemodynamic changes. A systems-based pictorial representation of the physiologic ramifications of near-drowning can be seen in Fig. 37.1. Most patients will develop symptoms within 7 h of submersion, and thus the majority of near-drowning and hypothermic victims require hospitalization for close monitoring of clinical deterioration [26]. Loux et al. reported on demographic factors independently associated with admission for drowning, including child age less than or equal to 6 years, Medicaid payment, self-pay, and Non-Hispanic ethnicity [27]. Indicators of clinical severity independently associated with admission for drowning included helicopter transport, admission service to a pediatric intensivist, and ventilator use for more than 1 day [27]. In

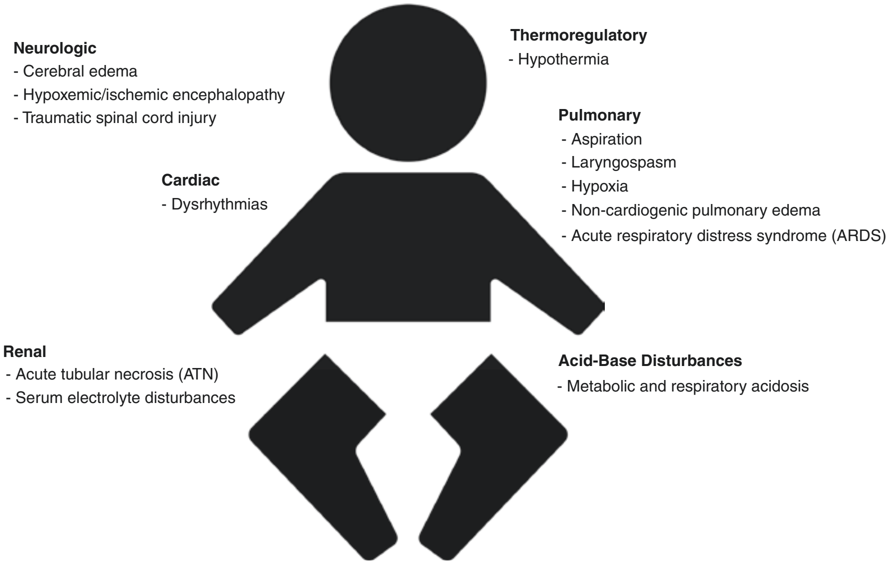

Fig. 37.1 Hypothermia

2019, a task force of nationally and internationally recognized clinical experts in pediatric critical care medicine addressed Pediatric Intensive Care Unit (PICU) characteristics and interventions by the PICU level of care, including quaternary or specialized, tertiary, and community [28]. Their recommendations summary highlighted that pediatric patients requiring specialized service interventions such as cardiac, neurologic, or trauma-related surgery, as is often seen in the near-drowning and hypothermic patient, have improved outcomes when cared for in a quaternary or tertiary ICU. Early interfacility transfer to the appropriate regional facility should be the standard of care [28].

Prevention and Suspicious Injury Patterns

The American Academy of Pediatrics' report on drowning prevention emphasizes the importance of continuous adult supervision in the prevention of drowning incidents, as the majority of fatal drownings are among unattended children [27, 29]. Thus, clinicians should be aggressive advocates for safety measures around pools and when participating in water sports. Further, social work intervention may be beneficial to review safety issues at home with caregivers. Moreover, the medical provider must always consider underlying conditions (i.e., epilepsy, cardiac arrhythmias) when assessing the hypothermic or near-drowning victim. Equally as important is the consideration of a nonaccidental nature or neglect as the etiology of these traumatic presentations. An estimated 25% of children who are ultimately diagnosed with nonaccidental trauma (NAT) have a sentinel injury before their abuse diagnosis [30]. There exist several red flags that the provider must be attuned to and not disregard when evaluating a pediatric patient in this setting. An investigation for NAT should ensue in patients with missing or incongruent history, an obvious lapse in supervision, or a delay in seeking care. Additionally, concomitant fractures in children less than 2 years of age or non-ambulatory children, rib fractures in infants, or undiagnosed fractures in various stages of healing should alert the provider of abuse. Similarly, failure to thrive, oral injury, patterned bruising, bruising in a non-ambulatory child, or bruising over soft tissue areas (cheeks, neck, genitals, buttocks, torso, and back) should be cautiously regarded and prompt further investigation.

Conclusion

The hypothermic or near-drowning victim poses a unique trauma situation that the pediatric provider must be well-versed in managing. These patients should initially be approached as one would approach any trauma patient, starting with a primary and secondary survey. Particular attention should be paid to the well-defined pathophysiologic sequelae that can be seen in this patient population, as doing so can improve outcomes. The hypothermic or near-drowning victim should be assessed for signs of non-accidental trauma, as early identification of abuse/neglect is imperative. Ultimately, education and prevention are paramount in reducing the incidence of these traumatic presentations.

Take Home Points

- The hypothermic or near-drowning victim poses a unique trauma situation which the pediatric provider must be well-versed in managing.
- Early recognition of the pathophysiologic sequelae seen in this patient population is imperative in improving outcomes.
- Parent education on prevention and immediate intervention may reduce the incidence and severity of this traumatic event.
- The medical provider's heightened awareness of suspicious injury patterns with early identification of abuse/neglect is essential.

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Chapter 38
Pediatric Burn Injury

Brielle Ochoa and Aaron Lesher

Abstract Burn injury is one of the most common causes of unintentional injury in the United States and has an even higher burden of disease in less developed countries. Heat from thermal sources accounts for the cause of burns in most cases. Electrical and chemical burns cause unique damage to tissue that must be recognized in affected patients. Early and appropriate management of burn wounds can substantially reduce the morbidity of burn injury, including over-resuscitation, wound complications, and scar development. Initial management of burns is based upon accurate physician assessment of the patient with calculation of the total body surface area burned and depth of burns shortly after patient presentation. Close attention must be paid to the pediatric burn patient to identify other traumatic injuries, airway damage, and deeper skin and organ injury if chemical or electrical burns have occurred.

Burn wound care must be managed appropriately, beginning with early debridement to prevent infection and continuing with accurate assessment of burn severity. Topical antimicrobial agents or advanced silver-containing dressings should be applied to the wound after initial debridement. In the days following initial injury, repeat examination of wounds must be performed to ensure that burn wound conversion does not occur, leading to the need for surgical excision and skin grafting. In the case of a deep burn wound, early excision and grafting improves long term burn wound complications and shortens hospital stay. New technology continues to be developed, particularly antimicrobial silver-based dressings and regenerative surgical therapies such as RECELL (AVITA Medical, Valencia, CA).

Long-term disability and rehabilitation from inadequate initial treatment of burn wounds can have serious consequences for the burned patient, their families, and the health care system. We will review initial management of the pediatric burn patient; pathophysiology of burn wounds that correlates with the need for fluid resuscitation, pain management, and early nutrition; indications for patient transfer to a burn

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center; and outpatient burn wound management. This chapter will act as a guide for the healthcare practitioner who does not frequently encounter burns.

Keywords Burn injury · Skin grafting · Scar management · Inhalational injury · Burn assessment · Burn management

Key Concepts/Clinical Pearls (Learning Objectives)

- Burn patients are trauma patients—always begin with evaluation of ABCs.
- Fluid resuscitation with Lactated Ringer's solution, proper estimation of burned skin area, and early nutrition are essential components of early burn care.
- Thorough patient assessment is needed to appropriately triage and stabilize the patient and to assess the need for transfer to a burn center.
- The goal of appropriate fluid administration is to sustain euvolemia. Fluid overload carries a high risk of morbidity.
- Tetanus prophylaxis should be administered to all burn patients if vaccination status is unknown or if the patient is unvaccinated. Antibiotic prophylaxis is not indicated for burn-injured patients at initial presentation.
- Nonaccidental trauma should always be considered in pediatric burn patients.

Initial Management of the Burn Patient

The following steps in Emergency Department management are key for assessing and stabilizing the pediatric burn patient. Some components of management may overlap, such as obtaining the history, beginning the physical examination, starting fluid resuscitation, and arranging transfer to a burn center. However, we recommend that the following steps be done in order so that no components of the evaluation are missed.

1. Begin assessment with ABCs.

   Burn wounds may be distracting and should not be fully assessed until the airway, breathing, and circulation (ABCs) are addressed.

   Airway: Assessment of the airway should include a visual examination of the face, nose, and mouth for facial and perioral burns, singed nasal hairs, soot, and pharyngeal edema and additional examination for hoarse voice, stridor, wheezing, tachypnea, and increased work of breathing. Any concern for airway edema should prompt consideration for immediate intubation, as worsening edema leading to airway compromise results in a difficult, if not impossible, intubation. Do not forget chin lift and jaw thrust.

   Breathing: Assessment of breathing begins with a thorough assessment of air exchange in both lungs. Special attention must be given to any patient burned in an enclosed space or who produces carbonaceous (sooty) sputum. In patients with a suspected inhalational injury, 100% oxygen via nonrebreather mask should be placed to improve hypoxemia and empirically treat carboxyhemoglobinemia. If the patient has a history of burn injury in a closed environment and altered mental status, consider Cyanokit (Meridian Medical

Technologies, Columbia, MD) for cyanide toxicity. Lastly, assess the patient's torso and extremities for circumferential burns that may inhibit adequate circulation and require escharotomy. Further detail on inhalational injury and treatment is provided later in this chapter.

Circulation: Pulse exam can reveal the adequacy of circulation, but also use other cues, such as blood pressure, heart rate, and capillary refill. In prehospital or early hospital settings, if burns appear to involve ≥20% total body surface area (TBSA), start infusion of Lactated Ringer's (LR) immediately at the following age-based rates:

0 to 5 years old: 125 mL/h
6 to 13 years old: 250 mL/h
14 years and older: 500 mL/h (considered as adults)

A more definitive calculation of post-burn fluid requirements occurs during the secondary survey.

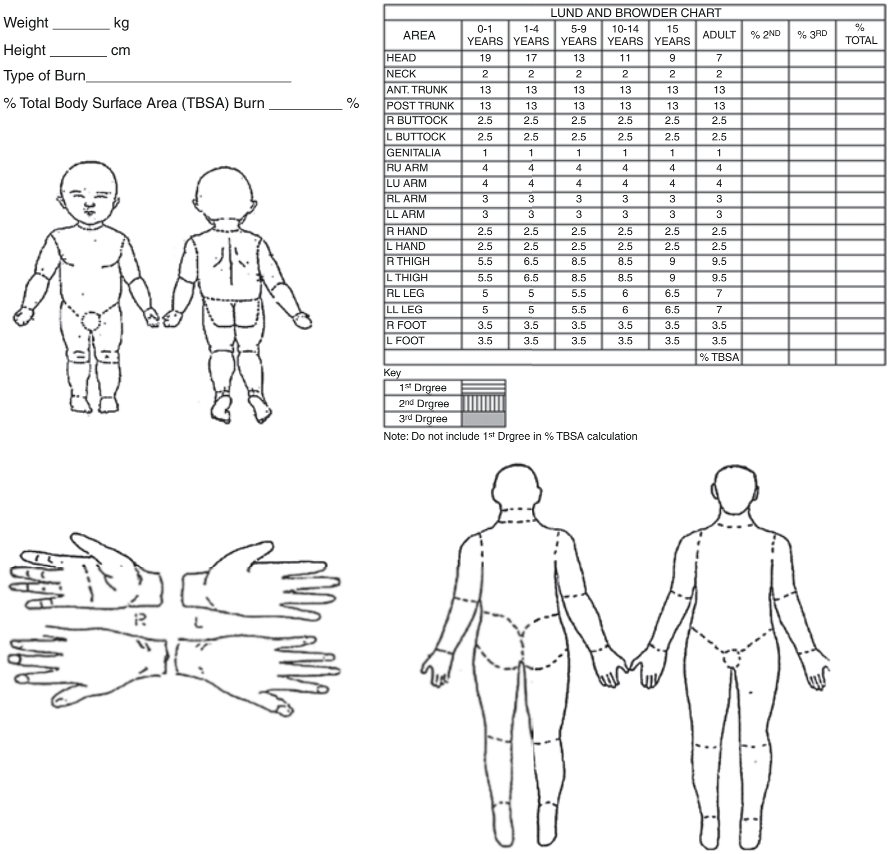
Disability: In infants and children, hypoglycemia and hypoxia are common causes of altered mental status, which include confusion, somnolence, and lethargy. Return to airway and breathing evaluation if a patient is hypoxic and consider airway injury and carbon monoxide poisoning based on injury mechanism. If the burn patient is not alert and oriented, do not forget to consider head injury, cyanide toxicity, hypoxia, or a pre-existing medical condition.

Exposure: For a thorough examination of the burn wound and other traumatic injuries, remove all items covering the patient, including clothing, diapers, jewelry, shoes, and all previously applied dressing and coverings. All body surface areas must be visually inspected, including the genital and perineal areas. Existing blisters should not be drained. Brush off dry chemicals and flush with large volumes of water. Remove contact lenses if applicable. Apply warmed blankets to prevent excessive heat loss during the initial resuscitative phase.

2. Determine the extent of the burn injury and calculate the burned TBSA using the Lund-Browder chart.

   The Lund-Browder burn chart and diagram should be used to assess the location, degree, and TBSA of burns (Fig. 38.1). If possible, all burns should be photographed and uploaded into the patient's electronic medical record. If the Lund-Browder chart is not available, the burn size may be estimated by using the patient's hand size (palm and fingers), where the patient's hand represents 1% TBSA.

   Once the skin assessment is complete, the patient should be covered with warm, clean, and dry blankets. The surface area of an infant's or young child's head is significantly larger than that of an adult (19% for infants and 17% for toddlers compared to 7% for adults), and the head should also be covered to prevent heat and fluid loss. Extremities with burns should be elevated above the phlebostatic axis to prevent edema.


Weight _______ kg

Height _______ cm

Type of Burn________________________

% Total Body Surface Area (TBSA) Burn _________ %

LUND AND BROWDER CHART									
AREA	0-1 YEARS	1-4 YEARS	5-9 YEARS	10-14 YEARS	15 YEARS	ADULT	% 2ND	% 3RD	% TOTAL
HEAD	19	17	13	11	9	7			
NECK	2	2	2	2	2	2			
ANT. TRUNK	13	13	13	13	13	13			
POST TRUNK	13	13	13	13	13	13			
R BUTTOCK	2.5	2.5	2.5	2.5	2.5	2.5			
L BUTTOCK	2.5	2.5	2.5	2.5	2.5	2.5			
GENITALIA	1	1	1	1	1	1			
RU ARM	4	4	4	4	4	4			
LU ARM	4	4	4	4	4	4			
RL ARM	3	3	3	3	3	3			
LL ARM	3	3	3	3	3	3			
R HAND	2.5	2.5	2.5	2.5	2.5	2.5			
L HAND	2.5	2.5	2.5	2.5	2.5	2.5			
R THIGH	5.5	6.5	8.5	8.5	9	9.5			
L THIGH	5.5	6.5	8.5	8.5	9	9.5			
RL LEG	5	5	5.5	6	6.5	7			
LL LEG	5	5	5.5	6	6.5	7			
R FOOT	3.5	3.5	3.5	3.5	3.5	3.5			
L FOOT	3.5	3.5	3.5	3.5	3.5	3.5			
						% TBSA			

Key

1st Drgree

2nd Drgree

3rd Drgree

Note: Do not include 1st Drgree in % TBSA calculation

Fig. 38.1 Lund-Browder chart and diagram used to calculate % TBSA by including second- and third-degree areas of burned skin

Table 38.1 Rate of fluid administration with Lactated Ringer's solution based on burn type and patient age and weight and calculated based on patient's weight in kilograms and % TBSA of burned skin

Burn type	Age and weight	Fluid rate
Thermal (flame or scald)	Infants and toddlers (≤30 kg)	3 mL × kg × % TBSA
	Children (<14 years old)	3 mL × kg × % TBSA
	Older children (≥14 years old)	2 mL × kg × % TBSA
Electrical	Any age	4 mL × kg × % TBSA

3. Establish IV access and begin administration of LR.

When the TBSA is calculated, fluid management should be titrated. If burns are ≥20% TBSA, a urinary catheter should be placed for close monitoring of urine output. To calculate 24-h fluid estimates, use 3 mL LR × kg × % TBSA for children (<14 years old) and 2 mL LR × kg × % TBSA for adults and older children (≥14 years old) (Table 38.1). Half of the calculated volume is to be given in the first 8 h and the other half given over the next 16 h. The initial hourly rate is known as the adjusted fluid rate. In infants and young children (≤30 kg), dextrose-containing LR should also be started in addition to the adjusted fluid rate and continued while the patient is nil per os. Of particular importance, hourly titration of fluid is more important than the 8 vs. 16 h concept. Careful hourly titration of fluid based on the patient's urine output and physiology is critical.

IV cannulas can be inserted through burned skin. Intraosseous or femoral venous access is preferred if unable to establish IV access. Intraosseous cannulation should not be attempted at a site distal to an extremity fracture or vascular injury and should be avoided at a burn site. If the patient's age is unknown, err on the side of giving more fluid until further information is obtained. Do not delay fluid administration to find out the patient's age, weigh the patient, or calculate the TBSA.

4. Secondary survey: Obtain history and remainder of the physical exam.

   Complete circumstances of the injury and patient's medical history, drug allergies, medications, vaccination status, and last oral intake (food or beverage) should be obtained and documented. Pre-burn weight should be obtained from medical records or a family member. Any remaining components of the physical exam should be performed, and the patient should be kept warm and dry.

5. Assess the need for patient transfer to a burn center.

   All pediatric patients with partial-thickness burns ≥10% TBSA, with any full-thickness component, or who are at a hospital without qualified personnel or equipment for pediatric patients should be referred to a burn center. A complete list of criteria for transfer can be found towards the end of this chapter.

   Patients who will transfer to a burn center do not need burns cleaned and dressed. These patients should be stabilized and transferred as soon as possible. Burn wounds can be covered with a nonadherent clean dressing, such as Vaseline gauze, and the patient should be kept warm with dry blankets. See *Outpatient Burn Management* for details on cleaning and debriding burn wounds if the transfer will not occur for more than 24 h. A Lund-Browder chart should be included in transfer documents as this will assist the accepting facility in evaluating evolution of burns. Patients awaiting transfer should be continuously monitored with hourly monitoring of vital signs, urine output, and airway status. If clinical status changes, begin assessment again with ABCs.

   For patients for whom there is any suspicion of child abuse or neglect, the initial care center and healthcare professional should initiate reporting to local police and child protective services as per local reporting procedures. Photographic and written documentation is essential to relay accurate information and to keep potential victims of abuse safe.

Initial Radiographic & Ancillary Studies

As previously mentioned, burn patients are trauma patients. Radiographic studies are not indicated for patients for whom burns are the only type of injury. However, if another mechanism of trauma, such as a fall or motor vehicle collision, is suspected or reported, appropriate imaging studies should be obtained if the patient is stable. If nonaccidental trauma is suspected, a skeletal survey should also be performed in the stable patient, along with consideration of consulting a child abuse specialist.

Concern for intracerebral, intrathoracic, intraabdominal, and long bone injuries requiring emergent or urgent management should be assessed appropriately.

All burn patients requiring hospitalization should have basic laboratory studies drawn, including a complete blood count and renal function panel. Blood glucose should be checked in any patient who is not at baseline neurologic status. Patients with inhalational injuries or mechanism of injuries, such as a house or car fire, should have a carboxyhemoglobin level checked to assess carbon monoxide poisoning. An arterial blood gas and chest X-ray should be obtained for the intubated patient.

Patients with electrical burns should have an electrocardiogram performed. Any patient with underlying health conditions should have appropriate studies obtained as needed (i.e., electrocardiogram for cardiac disorders, urinalysis for type 1 diabetes).

Demographics and Burn Mechanism by Age

Unintentional injury is the leading cause of death in children aged 1 to 19 and the third leading cause of death in infants. In 2010, Centers for Disease Control (CDC) data for patients ages 1 to 19 showed 430 deaths from burns, over 8000 hospitalizations, and over 122,000 patients treated for burns and released from the emergency department. Nonfatal emergency department visits for burned infants totaled over 6000 visits, for children aged 1 to 4 over 30,000 visits, and for children aged 5 to 9 over 13,000 visits. The CDC estimates that approximately 300 children aged 0 to 19 are treated in emergency departments for burn-related injuries every day, and of those children, two died because of being burned [1]. The most common burn mechanism in children under 5 years old is a scald injury, usually from hot water, other beverages, or food. Scald burns may also be caused by nonaccidental trauma. Flame burns are more common in older children.

Pathophysiology

Burns are caused by direct or indirect exposure to heat, friction, chemicals, electricity, or a combination of these. Sources of these burns in the pediatric patient include:

- Heat—steam, hot liquids (commonly water, tea, or coffee), boiling water, hot food (commonly soup or noodles), grease, direct flame, hot pavement
- Friction—bicycle crash, home treadmill, vacuum cleaners
- Chemical—household cleaning agents, smoke, fumes, ingestion, toxic plants
- Electricity—power cords, electrical sockets, lightning

Children have thinner skin due to a thinner dermal layer and are therefore more likely to develop burns at lower temperatures and from a shorter duration of contact compared to adults. Skin exposed to a temperature of 111 °F is tolerated by infants for an extended period of time, while a temperature of 160 °F will cause burns instantaneously at any age [2]. The extent of burns between these temperatures depends on the exposure temperature and duration.

Chemical burns can cause skin, mucosal, and ophthalmic injuries. Alkaline chemicals cause liquefactive necrosis and protein denaturation that lead to “melted” skin, while acidic chemicals cause coagulation necrosis and protein precipitation and lead to “leathered” skin. Chemical burns progress over varying periods of time depending on the causative agent and can be deceivingly superficial.

Electrical burns are a result of electrical current coursing through tissue that generates heat. Dry skin has high electrical resistance, while muscle and blood vessels have the least resistance. Therefore, electrical current flowing through any structures beneath the skin may cause deep and unpredictable injuries, including damage at the cellular levels that may affect cardiac function. The external electrical burn that is apparent on exam may not reflect the true extent of the injury.

Regardless of the burn source, burn injury begins with epidermal tissue damage and ultimately results in systemic circulatory and metabolic changes. Direct skin injury leads to areas of irreversibly damaged epidermis and dermis surrounded by areas of edema and inflammation. More severe burns may cause damage to underlying fat, muscle, and bone. Damaged tissue has increased vascular permeability that leads to leakage of fluid in the interstitial space. These fluid shifts and loss of skin barrier, especially in larger burns, cause intravascular hypovolemia that can result in hypovolemic shock. The burn wound and surrounding edema at presentation do not reflect the true extent of the injury, as the wound itself may continue to evolve, and inflammatory mechanisms progress 24 to 48 h post-injury.

The body enters a hypermetabolic state shortly after burn injury to accommodate for fluid losses, where the degree of hypermetabolism is directly related to the size of the burn as well as other concomitant injuries. Increased catecholamines trigger a sympathetic response leading to tachycardia, increased oxygen consumption, and protein catabolism. These processes result in increased energy expenditure that underlie the need for ongoing fluid resuscitation and early nutrition.

Nonaccidental trauma should be suspected with specific patterns of burns. Burns caused intentionally are more likely to be sharply demarcated, of uniform depth, or circumferential around the distal extremities (known as the glove and stocking pattern). Burns to the buttocks and perineal areas, small circular burns consistent with cigarette tips, and burns consistent with the shape of an object should raise concern for abuse. Additionally, the burn patient with burns of varying ages or a history of other forms of injury should be suspected as a victim of nonaccidental trauma.

Classification

Burns should be classified by type, depth, and TBSA. All three classifications together provide a full picture of the extent of a patient’s burn (Table 38.2 including Figs. 38.2, 38.3, 38.4 and 38.5). Burn types include thermal, chemical, and

Table 38.2 Burn classification by skin depth burned and associated burned skin characteristics

Degree	Thickness	Characteristics	Healing	Visual example
First	Superficial	• Involves epidermis only • Pink or red, may desquamate, but should not blister • Not included in TBSA	<1 week	
Second	Superficial partial thickness	• Involves papillary (superficial) dermis • Blistered or swollen • Moderate to severe pain	7–21 days	

Second	Deep partial thickness	• Involves some reticular (deep) dermis • Less moist • Dark red, pink, or white • May have mottled appearance • More likely to become infected	>21 days with severe scar formation, needs skin graft	
Third	Full thickness	• White or black • Dry or leathery • No moistness or blisters • Insensate	Needs skin graft	

Fig. 38.2 A first-degree burn. (Photograph courtesy of Dr. Aaron Lesher)

Fig. 38.3 A second-degree superficial partial thickness burn. (Photograph courtesy of Dr. Aaron Lesher)

Fig. 38.4 A second-degree deep partial thickness burn. (Photograph courtesy of Dr. Aaron Lesher)

Fig. 38.5 A third-degree burn. (Photograph courtesy of Dr. Aaron Lesher)

electrical. Burn depth can be categorized by degree as first-, second-, or third-degree based on the depth of skin involvement. Determining the degree of burns is based on appearance, including color and presence of blistering, texture, and sensation to pain.

A first-degree burn involves only the epidermis and is typically painful and erythematous. The pain usually subsides in the first 72 h, and dermal peeling may occur in 5–7 days with no residual scarring. An example of a first-degree burn is sunburn.

A second-degree burn, or partial-thickness burn, can be either superficial or deep. Superficial partial thickness burns involve the epidermis and superficial dermis and are pink, moist, and painful. These burns usually heal on their own within several weeks without major scarring. Deep partial-thickness burns involve the epidermis and deeper layers of the dermis. They may be white or darker pink or have a pink and white mottled appearance. These burns are associated with less pain. If left to heal on their own, deep partial-thickness burns lead to scarring and contractures.

A third-degree burn, or full-thickness burn, is one that extends through the epidermis and dermis into the subcutaneous tissue. These burns usually appear white, dry, and leathery with no sensation due to the destruction of sensory structures.

TBSA is additionally important in determining the need for fluid resuscitation and, in conjunction with burn degree and type, in determining the need for transfer to a burn center. TBSA includes only second- and third-degree burns and should be calculated using the Lund-Browder chart and diagram or the palmar method, as previously described in this chapter. Body surface area (BSA) of infants and children significantly varies from that of adults, and, in turn, incorrect use of adult BSA for pediatric patients may result in an undercalculation of the burn extent.

The pediatric patient who is quickly brought to medical attention may initially appear to have less severe burns. Burn wounds continue to evolve and blister over 24 to 48 h post-injury and require continual assessment.

Inhalational Injury

Most burn deaths are now due to smoke inhalation rather than the burn itself. Bedside providers should maintain a high suspicion for inhalational injury because of a high risk of morbidity and mortality. In fact, a significant burn wound combined with an inhalational injury doubles the mortality rate for patients of any age. Thermal airway burns should be differentiated from smoke inhalation. Heat transmitted into the upper and lower airway may cause direct tissue damage and must be assessed by bronchoscopy if suspected.

An inhalational injury should be suspected in any patient who has been burned in a house fire or otherwise exposed to toxic fumes. Three criteria are helpful for assessing a patient for inhalational injury:

1. History of a closed space fire
2. Carbonaceous (sooty) sputum (elicited by cough, not spit in mouth)
3. Carboxyhemoglobin level >10%

Pediatric patients may quickly develop upper airway obstruction compared to adults, and deciding to intubate a burn patient is an essential first step in management when following ABCs for initial evaluation. All patients with possible inhalational injury should be given 100% oxygen by facemask and require transfer to a burn center. Intubation should always be considered before transfer to a burn center, and a cuffed endotracheal tube should be used due to impending laryngeal and tracheal edema. The nearest burn center can be contacted to provide management and pre-transfer recommendations.

Products of combustion during a fire include carbon monoxide and hydrogen cyanide; when inhaled, these may result in carbon monoxide poisoning and cyanide poisoning, respectively. Carboxyhemoglobin is the product of a reaction between carbon monoxide and hemoglobin that normally comprises less than 1 to 2% of total hemoglobin. Carbon monoxide (CO) combines with hemoglobin at an affinity 200 times that of oxygen and impairs the ability of hemoglobin to carry oxygen and therefore decreases oxygenation of tissue, resulting in tissue damage. The half-life of CO on room air is approximately 4 h. Placing a patient on 100% oxygen via non-rebreather mask at a flow of 15 L/min decreases the half-life of CO to 40 to 80 min. Hyperbaric oxygen can shorten this further, though it is not widely available to critically ill patients [2].

Cyanide toxicity is a result of the inhalation of cyanide gas produced during the burning of synthetic materials. It should be considered if the patient was injured in a house or trailer fire, has altered mental status, or has a metabolic acidosis. The hydroxycobalamin cyanide antidote kit, available as Cyanokit in the United States, should be administered by intravenous injection if there is high suspicion for this injury. The Cyanokit contains hydroxycobalamin (Vitamin B12), which binds to cyanide to form a non-toxic compound that is excreted in the urine. Of note, Cyanokit use may turn the urine red or purple for several days after administration.

Electrical Injury

Modern electrical injury is most commonly a result of exposure to generated electricity in the workplace or at home. Electrical current preferentially flows through lower resistance structures such as muscle and blood vessels, resulting in unpredictable injuries deep to the skin. The external electrical burn on an exam may be small or even nonexistent. A high index of suspicion must be maintained for deep injuries when electricity is involved. Management of electrical injury begins with a higher rate of fluid resuscitation. LR should be started at 4 mL/kg/% TBSA and will likely need to be increased for a goal urine output of 1 mL/kg/h in a pediatric patient because the TBSA may grossly underestimate deep injury. A patient with urine that is red or red-tinged suggests myoglobinuria, which is an ominous injury. Myoglobinuria is the result of injured muscle breakdown, and the affected patient should continue to receive a high rate of fluids until the urine clears in color.

Special attention should be paid to cardiac function and deep muscle injury. Electrical current can damage the myocardium, and a baseline EKG should be obtained. The patient should be kept on a cardiac monitor if any dysrhythmias are present, and life-threatening dysrhythmias should be treated by following ACLS algorithms. Meanwhile, muscle injury results in swelling within the fascia that may lead to compartment syndrome and requires escharotomy.

Chemical Injury

The appearance of chemical burns depends upon the causative agent. As previously mentioned, chemical burns can be deceivingly superficial and will likely progress after initial evaluation. Reducing the duration of tissue contact by the agent is key in managing chemical injuries.

Whether the causative agent is known or unknown, all healthcare providers in the patient's vicinity should wear appropriate personal protective equipment (PPE), including gowns, gloves, eye protection, and mask. The patient's clothing should quickly be removed, and the affected part of the body should be continuously irrigated with copious amounts of lukewarm water. The irrigation can be stopped when the patient's pain or burning sensation at the wound decreases or the patient is evaluated in a burn center. The chemically injured eye should be treated in the same way except that the irrigation should not be stopped until the patient is evaluated by an ophthalmologist.

In the pediatric patient, ingestion should always be suspected when an external chemical injury is present. All chemical injuries require transfer to a burn center for further management.

Outpatient and Non-Surgical Burn Management

Patients who do not require transfer to a burn center (see *Burn Center Transfer Criteria*) may be managed in the outpatient setting by trained healthcare professionals. These patients include those with partial-thickness burns <10% TBSA and without full-thickness, electrical, or chemical burn, without inhalational injuries, and without concomitant trauma.

Wound Cleaning and Debridement

The burn wounds should be cleaned and debrided once the patient is assessed. Debridement should be performed with a gown, gloves, and mask worn by the healthcare professional in order to prevent infection. Bedside sedation is usually needed for pain and anxiety control. The minimum amount of sedative and pain medications needed for symptom control should be administered. Most patients undergoing debridement of second-degree burns benefit from conscious or moderate sedation delivered in the acute care settings. This allows thorough cleansing and debridement while alleviating pain and anxiety for the patient. Place the affected body area over absorbent pads. Cleanse the burned skin with lukewarm tap water or saline and mild soap, such as baby shampoo. Dirt, debris, and soap should be thoroughly rinsed away. Do not apply ice or cold fluids to the burn.

Immediately following this, the burn should be debrided with gauze and scissors. Saline-dampened gauze can be gently scrubbed on the skin to remove blistered and peeling skin. Blistered skin should be trimmed and removed with scissors as needed.

Application of Dressings

The burn should be assessed for size and depth, and the Lund-Browder should be completed. If daily wound care is prescribed, the burn wound should be covered in a layer of topical antimicrobial ointment, such as Polysporin or Bacitracin. A nonadherent dressing should be applied, such as Xeroform or Adaptic, followed by loose gauze wrap. An ACE bandage can also be loosely applied for additional protection. Daily wound care is used when close observation of the wound is needed to detect burn wound conversion or infection.

For wounds that are more superficial and cleaner, longer-term dressings can help alleviate the pain from dressing changes. Silver-containing dressings have antimicrobial and absorptive properties, making them ideal for burn wounds. They can be applied directly to a wound and left in place for several days and will absorb wound exudate and deliver antimicrobial silver. Commonly used dressings include Mepilex Ag™, Mepitel Ag™, Aquacel Ag™, and Acticoat™. If available, a silver-containing dressing can be placed on the burn wound and may be ideal for patients who will not tolerate daily dressing changes or have difficulty accessing follow-up care at a burn center within 3–5 days.

Collagenase ointment, currently available under the brand name Santyl, is an enzymatic debridement agent that breaks down collagen in necrotic tissue. Use of this dressing should be limited to burn wound professionals that can surgically intervene if necessary. This ointment can be used for daily cleaning of the burn wound bed, gently wiped away and reapplied with each dressing change, and stopped when the wound no longer has necrotic tissue and granulation tissue covered the wound base.

Dressings should be performed daily at home with a topical antimicrobial ointment, nonadherent dressing, and loose gauze wrap. Previously placed ointment and fluid should be gently removed by running the wound under cool water or wiping gently with dampened gauze.

Follow-Up

Patients should be referred to a burn center for follow-up care. If this is not possible due to accessibility, the patient should be seen within 2–3 days in the emergency department or primary care setting to assess the burn wound. The patient should be re-evaluated, and the burn wound should be reassessed on a weekly basis until healing, or epithelization, occurs.

Adjunctive Therapies

Referral to physical and occupational therapy should be strongly considered so that normal development is not hindered by the burn injury from digit or limb disuse and to improve function in more extensive burns. Therapists who specialize in burn patients are ideal but may not be widely available or accessible to patients.

Surgical Burn Management

Third-degree and deep-second-degree burns generally require surgical management, which includes debridement of necrotic tissue and grafting. Fundamentally, wounds that penetrate to the deep dermis (i.e., deep partial-thickness burns) do not heal spontaneously without significant scarring. Ideally, these deeper wounds are debrided within 24 to 48 h of injury, followed by grafting as soon as the wound bed is adequately cleaned and free of necrotic tissue, also called eschar. Early excision of eschar and wound closure within 5 days are essential steps in burn management and wound healing. Patients should be hemodynamically stable and nutritionally optimized prior to grafting, or the grafts are more likely to fail.

Grafts are commonly used for wound coverage. Autografts are harvested from the patient's healthy skin, usually from the back or thigh. In contrast, cadaver skin allografts and porcine xenografts are currently in use for temporary skin coverage until the patient's skin re-epithelializes. Patients with larger and deeper wounds likely will require multiple trips to the operating room for continual assessment and management of wounds.

New technologies in burn management are under active investigation, underscoring the need to optimize healing and minimize morbidity from burn wounds. These technologies focus on minimizing autograft surface area, creating skin substitutes, and decreasing scarring.

American Burn Association Designated Burn Center Transfer Criteria

Patients with burns and other injuries meeting the following criteria should be transferred to a burn center for further care [3]:

1. Partial-thickness burns greater than 10% TBSA. (Remember that the TBSA includes second- and third-degree burns only.)
2. Burns that involve the face, hands, feet, genitalia, perineum, or major joints.
3. Third-degree burns in any age group.
4. Electrical burns, including lightning injury.
5. Chemical burns.
6. Inhalation injury.
7. Burn injury in patients with preexisting medical disorders that could complicate management, prolong recovery, or affect mortality. In pediatric patients, this may include patients with neurodevelopmental delay, cardiac or pulmonary disorders, and mobility limitations from any cause.
8. Any patient with burns and concomitant trauma, such as fractures, in which the burn injury poses the greatest risk of morbidity or mortality. In such cases, if the trauma poses the greater immediate risk, the patient may be initially stabilized in a trauma center before being transferred to a burn unit. Physician judgment will be necessary for such situations and should be in concert with the regional medical control plan and triage protocols.
9. Burned children in hospitals without qualified healthcare professionals or equipment for the care of children.
10. Burn injury in patients who will require special social, emotional, or rehabilitative intervention. In pediatric patients, this may include patients with neurodevelopmental delay and concern for nonaccidental trauma.

Burn Wound Complications

More than 95% of all burn patients treated at burn centers survive; however, this does not reflect the lifelong morbidity that some patients will endure. Patients with higher TBSA burns, inhalational injury, and concomitant traumatic injuries are at greater risk for complications during the initial hospitalization and beyond. The purpose of proper burn patient assessment and management is not to cause further morbidity and to prevent various complications.

Further morbidity while managing a burn can be caused by over-resuscitation, which can lead to compartment syndrome and heart failure from fluid overload. In regard to the burn wound, over-resuscitation can also lead to tissue edema that results in additional ischemia around and deep in the wound. Fluids must be titrated to a goal urine output, which is 1 mL/kg/h in pediatric patients.

Complications include major organ dysfunction, poor cosmesis, inadequate function, and persistent symptoms. Major organ dysfunction primarily includes the skin as it loses its protective, temperature regulation, and sensory functions after undergoing burn injury. Burns that undergo delayed or no wound debridement are more likely to develop an infection, which can be noninvasive or invasive. History from the patient that includes a rapid change in burn appearance and an exam with purulent exudate or increased tenderness and erythema may represent a burn wound or peri-wound infection. Treatment of infection includes wound care, debridement, and antibiotics depending upon the burn wound category. These infections may lead to additional procedures for necrotic skin and failed grafts.

Acute kidney injury and renal failure can result from inadequate resuscitation, rhabdomyolysis and myoglobinuria, medication toxicity, and electrical injury. As previously discussed, cardiac dysfunction may arise after electrical injury. Inhalational injury may additionally result in airway stenosis as scar tissue forms.

Cosmetic complications occur even in burn patients who have been managed appropriately. These issues include scarring, uneven skin texture, permanent disfigurement, and wound hypertrophy. Functional complications often involve joints or the eye. Contractures may result from scarring of burns around small or large joints. The eye may be injured from direct exposure to chemicals or heat, or by damage to the eyelids that lead to a loss of protective function. This in turn can result in impaired vision.

Persistent symptoms related to pain and itching are a result of skin healing and peripheral nerve regeneration. Furthermore, the experience of initial injury, prolonged hospitalization, and rehabilitation for extensive burns involve significant physical and psychological pain for the patient who has undergone a traumatic event and must undergo multiple procedures.

Conclusions and Take Home Points

Basic assessment and care of the pediatric burn patient are essential to reduce morbidity and mortality. Complete assessment of the burn patient begins with ABCs. Particular attention must be paid to the airway if exposure to smoke or other hazardous fumes occurs and to circulatory status with more extensive burns, as these patients have insensible fluid losses through the loss of skin barrier. Failure in patient management resulting from the underestimation of burn TBSA, under or over-resuscitation, and missed injuries can lead to lifelong morbidity. The healthcare practitioner should become familiar with basic dressings for burns and ultimately must recognize patients that warrant transfer to a burn facility. For further information, the American Burn Association provides prevention, education, and research materials at www.ameriburn.org.

- A Lund-Browder burn chart should be used to accurately estimate the total body surface area (TBSA) of the debrided burn.
- Documenting burn wounds with photographs is an efficient way to communicate the extent of burns and to formulate future care plans.
- It is generally safe to assume that a burn and associated injuries are more extensive or serious than they initially appear.

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Chapter 39
New Technologies in Pediatric Trauma

Howard I. Pryor II and Nicolle Burgwardt

Abstract Trauma remains the leading cause of death for children and adolescents, most often due to blunt trauma from falls or motor vehicle collisions (Stewart et al., National trauma data bank pediatric annual report, p. 32, 2016). Traumatic brain injury is the most common cause of death overall. Of potentially preventable deaths, hemorrhage accounts for almost half (Drake et al., Pediatr Surg Int 36(2):179–189, 2020). Interestingly, pediatric trauma patients are less likely to undergo invasive procedures. Two level-1 trauma centers in Denver, Colorado, had an overall rate of emergent intervention of 0.6% over almost two decades (Boatright et al., J Am Coll Surg 216(6):1094–102, 2013). Efforts are underway to tailor advances made in adult trauma to pediatric trauma management. The purpose of this chapter is to outline several new technological advances aimed at providing less invasive care for pediatric trauma patients; retrograde endovascular balloon occlusion of the aorta (REBOA) for systemic hemorrhage control, direct site endovascular hemorrhage control and repair, point-of-care ultrasound (POCUS) of optic nerve sheath diameter (ONSD) for intracranial pressure (ICP) monitoring, POCUS of lungs for pediatric acute respiratory distress syndrome (PARDS) management, and pulse co-oximetry monitoring for solid organ injury management.

Keywords REBOA · Endovascular surgery · Point-of-care ultrasonography · PARDS · Non-invasive ICP · Pulse co-oximetry · Non-invasive hemoglobin

Key Concepts/Clinical Pearls

- Endovascular techniques have proven to be successful alternatives to systemic and direct site open hemorrhage control.
- Point-of-care ultrasound examination of optic nerve sheath diameter can be an effective surrogate monitor of increasing intracranial pressure.

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- Point-of-care ultrasound examination of the lungs can aid in ventilator management to optimize lung aeration in pediatric acute respiratory distress syndrome.
- Pulse co-oximetry is a non-invasive hemoglobin monitoring technique useful in the management of solid organ injury.

Introduction

Trauma remains the leading cause of death for children and adolescents, most often due to blunt trauma from falls or motor vehicle collisions [1]. Traumatic brain injury is the most common cause of death overall. Of potentially preventable deaths, hemorrhage accounts for almost half [2]. Interestingly, pediatric trauma patients are less likely to undergo invasive procedures. Two level-1 trauma centers in Denver, Colorado, had an overall rate of emergent intervention of 0.6% over almost two decades [3]. Efforts are underway to tailor advances made in adult trauma to pediatric trauma management. The purpose of this chapter is to outline several new technological advances aimed at providing less invasive care for pediatric trauma patients; retrograde endovascular balloon occlusion of the aorta (REBOA) for systemic hemorrhage control, direct site endovascular hemorrhage control and repair, point-of-care ultrasound (POCUS) of optic nerve sheath diameter (ONSD) for intracranial pressure (ICP) monitoring, POCUS of lungs for pediatric acute respiratory distress syndrome (PARDS) management, and pulse co-oximetry monitoring for solid organ injury management.

REBOA for Pediatric Systemic Hemorrhage Control

Retrograde endovascular balloon occlusion of the aorta (REBOA) is a technique used to control non-compressible torso hemorrhage until definitive control can be obtained. It accomplishes the same goals as a resuscitative thoracotomy: prioritizing the circulatory volume of the heart and brain during uncontrolled hemorrhage. This method involves placing an occlusive balloon into the aorta. The balloon is inserted through an introducer sheath after obtaining retrograde common femoral artery access. The balloon can be placed in zone 1 of the aorta to obtain supraceliac control for intra-abdominal hemorrhage, or zone 3 of the aorta to obtain infrarenal control for pelvic hemorrhage (Fig. 39.1). Once in place, the balloon is inflated to achieve aortic occlusion. This provides an adequately perfusing blood pressure to the coronary and cerebral circulatory systems while definitive hemostasis is obtained.

REBOA has shown a survival benefit when compared to resuscitative thoracotomy particularly in patients not requiring cardiopulmonary resuscitation (CPR) before its use [4]. A gap analysis performed by Theodorou et al. suggests that 20% of pediatric trauma patients may benefit from the use of the REBOA technique [5].

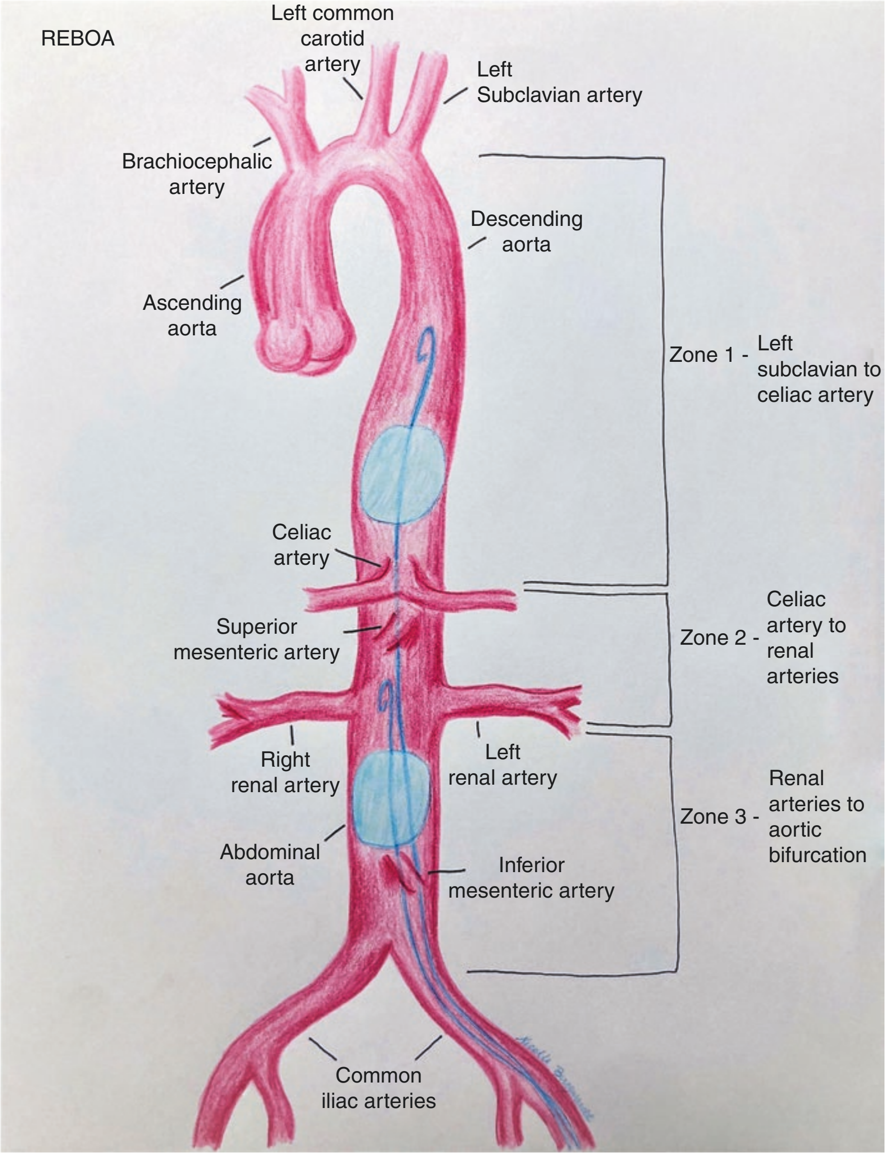

Fig. 39.1 Illustration of the Aorta with zones for balloon placement during REBOA

A recent retrospective review of the Aortic Occlusion for Resuscitation in Trauma and Acute Care Surgery (AORTA) Registry revealed 11 pediatric patients (ages 16–18) who underwent REBOA for hemorrhagic control over the last 7 years. Albeit a small sample size and the cohort being 16–17 years of age, 100% of patients had a drastic improvement in hemodynamics, and 30% survived to discharge neurologically intact [6].

Although a favorable initial evaluation, several factors limit the rapid adaptation of REBOA to pediatric cases. First, the REBOA device is a well-engineered balloon system adapted from adult endovascular techniques and explicitly designed for the average adult aorta. Equipment used to access the common femoral artery is likewise intended for adult-sized vessels. Currently, the standard femoral access sheath for REBOA balloon insertion is 7 French. Recent literature however demonstrates successful use of a novel 4 French REBOA device in organ donors prior to organ procurement [7]. This novel equipment could greatly expedite the adaptation of the REBOA device to the Broselow pediatric distribution of device sizes for trauma. Secondly, pediatric trauma care providers need to undergo formal training in this technique as inappropriate use of this equipment can result in significant morbidities. Complications from REBOA placement are not insignificant and include access site complications such as hematoma, pseudoaneurysm, thrombosis, ipsilateral lower extremity ischemia, limb loss, and reperfusion injury resulting in multi-organ failure as well as broader complications including paralysis, aortic dissection, rupture, perforation, and hemodynamic shock [8].

Despite these limitations, the adaptation of the REBOA technique for the pediatric trauma patient population should be aggressively pursued because children can withstand hemorrhagic shock better than adults. REBOA has proven to be a viable option in patients with severe hemodynamic instability as a bridge to more definitive management. With defined clinical indications, patient selection, and adequately trained providers, an even more significant survival benefit may be conferred by REBOA in children than adults.

Direct Site Endovascular Hemorrhage Control and Repair

Direct site endovascular control is a technique that employs similar principles as REBOA for hemorrhage control. However, instead of using a central balloon occlusion to maintain regional blood pressure, direct site endovascular hemorrhage control employs proximal and distal balloon occlusion to control hemorrhage at a specific location once the injury to the vascular system has been identified. Direct site endovascular control has the most immediate applicability for use in pediatric trauma. This technique is generally well-described in the adult trauma literature. In most cases, such methods could utilize existing arterial access equipment for pediatric patients. The adaptation for pediatric use would involve selecting existing adult vascular balloon devices and using them in the smaller vessels of children to occlude flow. An example might include using an adult coronary artery angioplasty balloon to occlude the retrograde flow to a subclavian or axillary artery injury.

Direct site endovascular repair (DSER) is also used once the injury to the vascular system has been identified. This technique involves the use of endovascular stent-graft placement across the site of injury. Several DSER methods are well described in adults and have great potential for adaptation to pediatric cases.

Thoracic endovascular aortic repair (TEVAR) for blunt aortic injury is frequently used in adult trauma centers as an alternative to open thoracic repair of the aorta. This technique adapts endovascular aortic repairs used in elective vascular surgery and confers significant advantages compared to open repair. The first benefit of this approach is the elimination of a thoracotomy and its subsequent comorbidities. An open repair is also associated with significant blood loss, which is mitigated using an endovascular technique. In addition, the overall operative time for a TEVAR for blunt aortic injury can be less than 45 min in experienced hands, whereas an open repair often takes several hours. The principal drawback of this technique is the potential for serious device-related complications [9].

One of the most challenging vascular injuries to address with an open approach is a penetrating injury to the subclavian/axillary artery. The exposure required for open proximal and distal control is associated with significant blood loss and a morbid wound. In adult patients, these injuries are repaired endovascularly by placing a stent-graft across the injury. When a stent-graft repair is not anatomically feasible, it is possible to obtain proximal control with a balloon advanced from the aorta and distal control with retrograde balloon placement from the radial artery. Adan et al. demonstrated comparable success with trans-radial access (TRA) for endovascular interventions compared to femoral access [10]. Both stent-graft repair and proximal and distal endovascular hemorrhage control are well described in adult patients; however, their use has not been adapted for these injuries in children.

Pelvic hemorrhage control in pediatric trauma patients is primarily focused on embolization of distal arterial injury. Larger vessel injuries in the pelvis may be amenable to stent-graft or balloon occlusion control techniques described above; however, these injuries occur with far less frequency in children. In most cases, pelvic hemorrhage embolization is already a frequently used and effective technique at pediatric trauma centers. Adaptation of more advanced endovascular hemorrhage control techniques for this injury group may not be warranted given the effectiveness of embolization at this time.

An additional DSER technique described by Davidson et al. uses current endovascular stent-grafts in open surgical reconstruction to create a "sutureless anastomosis." In this technique, proximal and distal control is obtained, and the damaged vessel is opened to visualize the lumen clearly. A stent-graft is selected and removed from its deployment system with its retention suture, keeping the stent compressed. The compressed stent, only millimeters in diameter, is then advanced into the lumen until the opposite end can also be placed intraluminal. The retention suture, threaded on a free needle, is passed from inside the lumen through the vessel wall. Once the stent is in place with sufficient overlap on the native vessel, the retention suture is pulled to deploy the stent. This technique allows for immediate restoration of flow to the distal extremity. This case series describes using the method for both temporary shunts and permanent repair [11]. Further research focusing on long-term durability in pediatric patients is needed. While endovascular equipment is still undergoing adaptation to children, this technique may be an immediate viable endovascular option in pediatric vascular injuries when rapid control is required.

When evaluating DSER techniques for children, two considerations warrant special consideration: (1) the actual longevity of uncomplicated stent-graft placement and (2) growth following the stent-graft deployment. The expected lifespan for most stent-grafts is not clearly defined. When placing a stent-graft in an adult, the service life of the graft is typically assumed to be sufficient. Compared to the patient's expected lifetime, the benefits of a DSER approach far outweigh the risks of inadequate graft service life. Further, subsequent post-DSER growth is possible, and management of a sizable graft in that circumstance is not currently described. A solution to both concerns is the development of an absorbable stent-graft that will adequately seal and support the vascular injury during the healing process and then dissolve without embolization. A product of this type will also need to be available in a range of sizes adequate for the variation in size of pediatric blood vessels. The development of such products is already underway for use with adults and, when successfully approved, will only require scaling for application with children.

Endovascular hemorrhage control is associated with equivalent or superior control of bleeding when compared to open techniques. It can mitigate the need for large incisions and subsequent surgical site infections. Endovascular hemorrhage control can also be performed in a hybrid suite, allowing for hemorrhage control before required exploratory laparotomy for other indications. Most Level-1 pediatric trauma centers already have high-capacity interventional radiology suites. Pediatric interventional radiologists collaborating with pediatric trauma surgeons could implement an endovascular hemorrhage control program with limited investment. Based on the successes reported in adult trauma care, endovascular hemorrhage control programs should be investigated by pediatric trauma surgeons to advance the complicated care of these patients.

POCUS of ONSD for ICP Monitoring

Traumatic brain injury is the most common cause of mortality in pediatric trauma. The primary goal of managing traumatic brain injury is preventing secondary injury. Elevated intracranial pressure (ICP) is a devastating consequence of traumatic brain injury and a common cause of secondary injury. ICP monitoring is the gold standard; however, it is invasive, requiring an intracranial probe. Lumbar puncture with measurement of opening pressure can also measure ICP. Traditional non-invasive techniques include serial neurological assessments and imaging (CT or MRI) with evidence of intracranial hemorrhage, midline shift, or ventricular compression. These non-invasive methods have their drawbacks. First off, they are surrogate measures. Coordination for off-floor imaging of a critically ill child can be time-consuming and cumbersome. Serial imaging also has radiation exposure risks. Point-of-care ultrasonography (POCUS) of the optic nerve sheath diameter (ONSD) has been recently proposed as a fast, non-invasive, bedside modality for surrogate monitoring of ICP in pediatric trauma patients.

The optic nerve sheath is contiguous with the dura, making its contents contiguous with the subarachnoid space. The ONSD increases with age, with upper limits at roughly 4 mm under 1 year, 4.5 mm for 1–15 years, and 5 mm for adults. Thick fibrous bands connect the nerve sheath to the optic nerve. With increased ICP, cerebral spinal fluid is forced into this trabecular meshwork leading to distension. The optic sheath just behind the globe is loose and creates a bulbous appearance when distended. This pathophysiology is what can be advantageously used to monitor ICP with ultrasonography [12].

Tsung et al. described three pediatric cases in the United States where bedside ocular ultrasound was used to measure ONSD and rapidly assess for increased ICP in head trauma. Measurements of ONSD were obtained through closed upper eyelids using water-soluble ultrasound gel and a 7 MHz endocavity transducer, 3 mm posterior to the globe. One case involved an 8-month-old found to have a significant right subdural and subarachnoid hemorrhage with midline shift secondary to non-accidental trauma. The patient presented obtunded with a fixed and dilated right pupil. ONSD measurements obtained were 4.2 mm on the right and 4.4 mm on the left. The patient was admitted to ICU, and traditional ICP monitoring was deferred due to coagulopathy. The patient clinically improved over 2 weeks with follow-up ONSD measurements of 2.9 mm on the right and 3.3 mm on the left. The two additional cases were less severe with non-focal neurological exams. Unsurprisingly, ONSD measurements for both were within the normal range for the patients' respective ages [13].

A tertiary care teaching hospital in North India conducted a single-center prospective cohort study with 30 children, 2–12 years of age, admitted to the PICU for ICP monitoring. Patients were divided into three groups, case controls with invasive monitoring revealing ICP greater than 20 mmHg, neurologic controls with invasive monitoring showing ICP less than 15 mmHg, and healthy controls enrolled from outpatient clinic visits. They found a mean ONSD of 5.71 mm in case controls, 4.21 mm in neurologic controls, and 3.71 in healthy controls. Additionally, an ONSD of 4 mm had a 98% sensitivity and 75% specificity for elevated ICP greater than 20 mmHg [14].

The literature does report varying sensitivities and specificities of ONSD measurements and their ability to predict ICP. Two different systemic reviews evaluated the efficacy of ocular ultrasonography compared to conventional assessment tools and showed promising reliability. Ohle et al. compared US of ONSD to CT, given it is more often used in practice as a measure of ICP over invasive monitoring. Analysis of 12 studies over 18 years with 478 patients yielded an average sensitivity of 95.6%, specificity of 92.3%, and a negative likelihood ratio of 0.05 [15]. Bhargava et al. reviewed 11 studies performed exclusively in pediatric patients with varied causes of elevated ICP, comparing ONSD measurements to a variety of reference tests. The pooled analysis concluded that US is highly sensitive (93%) but only moderately specific (74%) [16]. While more research is needed to identify universally accepted parameters for precise clinical use, POCUS of ONSD has excellent potential. POCUS of ONSD is a fast, cost-effective, non-invasive point-of-care test to reliably rule out elevated ICP in pediatric head trauma with low clinical suspicion for elevated ICP and rule in elevated ICP for cases with high suspicion. Integrating this technique into the algorithm for pediatric head trauma could lead to faster diagnosis and management of elevated ICP while balancing the potential morbidity of invasive monitoring.

Lung POCUS for PARDS

Pediatric acute respiratory distress syndrome (PARDS) is a significant contributor to morbidity and mortality in children. It is a complex disease process in which disruption of the alveolar-capillary permeability barrier results in dysregulated inflammation, fluid-filled alveoli, and restrictive lung disease. Hallmark clinical manifestations include hypoxia, radiographic opacities, decreased functional residual capacity, increased physiologic dead space, and reduced lung compliance [17]. PARDS is often caused by respiratory illness but can also be seen in trauma. PARDS management aims to provide adequate oxygenation and ventilation while protecting the lungs from ventilator-induced injury. This requires a delicate balance between avoiding both overdistension and repetitive opening and closing of alveoli [18].

The Pediatric Acute Lung Injury Consensus Conference (PALICC) developed pediatric-specific definitions and treatment recommendations for PARDS to optimize diagnosis and management in the pediatric population. The PALICC definition of PARDS requires chest imaging to diagnose new infiltrate consistent with acute pulmonary parenchymal disease. It is also recommended to monitor respiratory system compliance when increasing PEEP closely and during recruitment maneuvers for severe oxygenation failure [19]. Adult literature supports the use of lung POCUS in ARDS. Soummner et al. established that lung POCUS can effectively identify de-recruitment during spontaneous breathing trials preceding extubation in adult patients with ARDS [20]. Bouhemad et al. observed that “the ultrasound aeration score could be appropriate for measuring recruitment resulting from any treatment aimed at increasing lung aeration, such as PEEP, negative fluid balance, positioning, or recruitment maneuvers.” [21] There is now emerging evidence for POCUS as an effective tool to accomplish the same in the pediatric population.

Potter and Griksaitis summarize several POCUS findings and how they can be used in PARDS diagnosis, management, and even identification of complications. Lung POCUS can demonstrate the pleura as a sharp white line sliding back and forth, indicating normal lung movement. Normal lung tissue will also show A-lines, additional horizontal white lines parallel to the pleura. When these findings are obscured, it can indicate disease. The absence of pleural sliding can indicate a pneumothorax. Abnormal thickening or disruption of the pleural line can also be seen. B-lines are dense vertical white lines that obliterate the A-lines, indicating alveolar edema. B-lines can appear on a continuum, with irregularly spaced B lines indicating some loss of aeration, to coalesced lines indicating severe loss of aeration. Consolidation can produce air bronchograms and “tissue-like sign,” giving the appearance of solid viscera. PARDS tends to cause dense consolidation dependently, and a gradation of abnormal POCUS findings can be observed, with normal lung findings present in the most non-dependent regions. Serial assessment can rapidly identify the progression and resolution of these lung pathologies. In addition, POCUS can be used before and after recruitment maneuvers to assess lung aeration, which can guide ventilatory management and optimize PEEP following PALICC guidelines [22].

Lung POCUS is a practical tool for PARDS diagnosis and management. It proves to be highly sensitive, rapid, cost-effective, can be applied serially without invasive techniques or radiation, and does not require deep sedation, paralysis, or transport. This method of evaluating lung aeration can rapidly identify changes in lung inflation with changes in PEEP. Incorporation of this technique could simplify aspects of ventilator management and allow the care team to respond to each patient's needs in a more goal-directed manner.

Pulse Co-Oximetry for Management of Solid Organ Injury

The management of solid organ injury in pediatric trauma has dramatically changed over the last 20 years. The spleen is one of the most frequently injured intra-abdominal solid organs in blunt trauma. Shinn et al. investigated the management of isolated blunt splenic injury nationally from 2007 to 2015. Of 21,128 patients under 18-years of age registered in the National Trauma Data Bank, 90.3% underwent non-operative management, even in grades III–V, with an average failure rate of 1.5% [23]. As endovascular techniques evolve into pediatric practice, a trend is growing towards embolization if an intervention is required. In addition to the benefits of avoiding surgical intervention and its associated morbidities, successful non-operative management of splenic injuries decreases the rate of overwhelming post-splenectomy sepsis [23].

Non-operative management of solid organ injury requires close hemodynamic monitoring, including serial hemoglobin assessments. Frequent phlebotomy is not without its challenges, especially in the pediatric population. It is costly, painful, can worsen anemia, and is time-consuming with lagging results. Non-invasive hemoglobin monitoring uses a finger probe, similar to a standard pulse oximetry sensor. The probe emits multiple wavelengths of light and then calculates the hemoglobin concentration based on specific wavelength absorption in the blood [24]. There are devices for continuous real-time monitoring and "spot" checking, which calculate hemoglobin levels within 1 min of use. Recent literature supports the use of non-invasive hemoglobin monitoring in clinically stable trauma patients.

Kim et al. conducted a systematic review of 32 studies, including over 4400 patients who underwent non-invasive hemoglobin monitoring. They found an overall pooled mean difference between non-invasive and laboratory hemoglobin measurements to be 0.10 ± 1.37 g/dL [25]. Joseph et al. performed a prospective cohort analysis at their level-1 trauma center, performing two spot check hemoglobin measurements with each invasive measurement for 525 patients. Their analysis revealed a mean difference was 0.3 ± 1.3 g/dL, 95.4% sensitivity, 76% accuracy, and a strong correlation with invasive measurements ($R = 0.77$) [26]. Pediatric data emerged shortly thereafter. Ryan et al. performed a prospective observational study with 114 pediatric patients over 2 years at a level-1 pediatric trauma center, comparing i-stat, invasive lab, and co-oximetry hemoglobin measurements on admission. They also found strongly correlating point-of-care measurements and suggested co-oximetry as a valuable adjunct for initial evaluation before IV access is established [27]. Welker et al. exclusively looked at pediatric blunt trauma patients with solid organ injury undergoing non-operative management and found correlating measurements with an average deviation of 0.8 g/dL [28].

There is a drawback to non-invasive hemoglobin monitoring, mainly due to obtaining readings. There is a varying degree of success in obtaining a sensor reading, anywhere from 70.3 to 89% in the above-referenced studies. Phillips et al. conducted a similar comparison in a large PICU at an academic medical center showing a strong correlation between invasive and non-invasive measurements. They also conducted additional analysis given their inability to obtain non-invasive readings in almost 30% of attempts. Hypoxia, hypothermia, and increasing BMI were found to be independent predictors for undetectable readings. Extreme lab values, increasing skin pigmentation, increasing body mass index were predictors of poor correlation of values [29]. These variations may prohibit the use of co-oximetry as the sole method of hemoglobin monitoring, but the positive correlation made it an excellent adjunct for initial assessment and continued monitoring in hemodynamically stable patients. This would reduce the number of invasive blood draws in pediatric trauma patients, with lab measurements reserved for patients with a change in clinical status.

Conclusions and Take Home Points

With blunt traumatic injury being the leading cause of death for children and adolescents, continued research must modernize the tools at our disposal to manage the most common traumatic injuries. This chapter outlines several emerging techniques to deliver practical, less invasive surgical and critical care for pediatric trauma patients.

- REBOA has shown a survival benefit when compared to resuscitative thoracotomy particularly in patients not requiring cardiopulmonary resuscitation (CPR) before its use. A gap analysis performed by Theodorou et al. suggests that 20% of pediatric trauma patients may benefit from the use of the REBOA technique.
- Direct site endovascular hemorrhage control employs proximal and distal balloon occlusion to control hemorrhage at a specific location once the injury to the vascular system has been identified. Direct site endovascular control has the most immediate applicability for use in pediatric trauma.
- Point-of-care ultrasonography (POCUS) of the optic nerve sheath diameter (ONSD) has been recently proposed as a fast, non-invasive, bedside modality for surrogate monitoring of ICP in pediatric trauma patients.

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Index

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