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CHAPTER 11: PHYSICAL TRAUMA: BLUNT AND PENETRATING INJURIES DUE TO EXPLOSIVES AND FIREARMS

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CHAPTER 11: PHYSICAL TRAUMA: BLUNT AND PENETRATING INJURIES DUE TO EXPLOSIVES AND FIREARMS

Knowledge of the effects of blast injuries, on children in particular, is fairly recent, and is based chiefly on reported experiences in the Middle East. As a result, this knowledge is not widely shared by health care professionals who care for pediatric patients. Therefore, this chapter focuses first on what is known of the general causes, nature, and effects of blast trauma on humans before proceeding to brief reviews of the far better known effects of incendiaries and firearms. It concludes with a discussion of specific effects of explosives, incendiaries, and firearms on pediatric patients.

Because the early management of secondary, tertiary, and quaternary blast injuries is somewhat different from that encountered in routine clinical practice, this chapter will begin with a review of the physical science underlying the early management of primary blast injuries, which varies from management of conventional civilian trauma in numerous ways. The clinical findings and diagnosis of primary blast injuries will be discussed in detail as the basis for early management of these fortunately uncommon but potentially devastating injuries.

EXPLOSIVE INJURIES

Blast Physics

Many believe that the harmful effects on the body caused by a blast result from the pressure differentials exerted on tissues by an expanding wave. However, because the peak overpressure decays exponentially, a victim must be relatively close to the detonation for the blast wave itself to induce tissue injury. Several factors, including the following, affect the degree of blast pressure loaded to objects:

- The distance between the object and the detonation.
- The orientation of the object to the incident wave.
- The degree of reflected waves to which the object is subjected.

This latter point is the reason that, given equal peak overpressures, victims found in corners or in underwater blasts suffer greater injury. In both situations, the victim is subject to the incident wave in addition to multiple reflected waves.

Blast Trauma

Many mechanisms of injury are involved in blast injuries.

- Primary blast injury refers to tissue damage by the blast wave itself, specifically in areas with tissue-gas interfaces such as the lungs, the intestines, and the tympanic membrane.
- Secondary injury refers to penetrating or blunt injury that results from the acceleration of fragments or debris, caused by the blast wave or the blast wind. Terrorists often add metallic fragments, such as nails, to devices to maximize the potential for penetrating injuries. Secondary injury is the most common type of injury that occurs, because it does not require the victim to be near the point of detonation.

- Tertiary injuries result from acceleration-deceleration forces imposed as the blast wave or blast wind propels the victim. As the body is tumbled on a rigid surface, it suffers from blunt injury as well as penetrating injuries as it is accelerated over sharp debris.
- Quaternary injuries include crush injuries incurred from structural collapse, flash and flame burns, inhalational injury, and acute stress response to catastrophic events.

Secondary blast injury (SBI) and tertiary blast injury (TBI)—not to be confused in this usage with traumatic brain injury—overlap significantly, and both are more common than primary blast injury (PBI) in the hospital setting. Those close to the detonation of a high-energy explosive are most likely to suffer PBI and to die on scene.

Primary Blast Injury
The effects of the blast wave on structural elements and on human tissues combine to cause complex combinations of injuries in blast victims. Injuries may be variable within a single event. The principal factor that determines severity of PBI is the distance of the victim from the site of detonation (**Table 11.1: Expected Injuries at Relative Distances from Detonation in Open Air**). Injuries also vary depending on the victim's position with respect to incident waves and the degree of reflected shock waves to which the victim is exposed.

A blast that occurs in an enclosed space, such as a bus, is associated with more severe injuries and a higher incidence of primary blast injuries. The number of casualties from PBI would be expected to be more than in an equipotent detonation in open space. Mortality is also higher when a blast occurs in an enclosed space, because the shock wave is contained, reaches a higher overpressure and a longer positive phase, and echoes in numerous directions from the internal structures it encounters.

PBIs are injuries caused specifically by exposure of the body to the blast wave. Pulmonary barotrauma, air embolization, and intestinal perforation are the unique principal causes of death after a blast. Although most injuries in an explosion are secondary, tertiary, and quaternary (crush, burn, inhalational), a person close enough to a detonation would be subjected to the effects of the blast on a microscopic level.

Table 11.1: Expected Injuries at Relative Distances from Detonation in Open Air

Injury	Closest to Farthest						
Body disruption	●						
Burn/inhalation	●						
Toxic inhalation	●	●					
Amputation	●	●	●				
Primary blast injury, lung and bowel	●	●	●	●			
Tertiary mechanism	●	●	●	●	●		
Primary blast injury, ear	●	●	●	●	●	●	
Secondary mechanism	●	●	●	●	●	●	●

The spectrum of PBI reflects involvement of the gas-containing organs and the pathophysiologic effects of these organs on other systems. As in conventional trauma, all victims should be managed with careful attention to the airway, breathing, and circulation. However, in certain patients, complications may arise with respect to positive-pressure ventilation and fluid resuscitation management.

Blast Lung Injury and Air Embolization

The anatomic structure of the lung makes it susceptible to the effects of blast barotrauma. Alveolar spaces are surrounded by a delicate capillary network in a way that maximizes the surface area available for gas exchange.

Clinical findings range from contusion and ecchymosis to massive hemoptysis, severe ventilation/perfusion mismatch, and air leak, leading rapidly to death. Most blast lung injury develops early in the course of treatment, within 1 to 2 hours. Signs and symptoms may progress within 24 to 48 hours to respiratory failure and acute respiratory distress syndrome (ARDS). Respiratory failure is frequently exacerbated by the secondary additive effects of shock, organ failure, or inhalation of smoke and toxic substances.

The most important diagnostic test for blast lung injury is a chest radiograph, which commonly shows bilateral pulmonary infiltrates in a “butterfly” pattern. Computed tomography (CT) can provide important additional information in a patient with respiratory findings but an unrevealing chest radiograph. Pulmonary hemorrhage is the most consistent microscopic finding in blast lung injury.

Management

Blast lung injury is not universally fatal, given aggressive and timely management. Initial management involves maintaining adequate oxygenation and minimizing additional barotrauma. A patent airway free of blood and secretions should be maintained. Control of massive hemoptysis involves tracheal intubation and, whenever possible, selective ventilation of the contralateral lung. The source of bleeding in massive hemoptysis may be from one or both lungs and is often difficult to determine. Having a high index of suspicion for pneumothorax or tension pneumothorax is essential.

The development of systemic air embolization from injured lung tissue is a grave complication. The greater the degree of lung injury, the higher the risk of embolus formation. Although the actual incidence is unknown and is probably underrecognized, air embolization in blast injury is speculated to be the main cause of death within the first hour after a blast. Air emboli in the vascular system carry a high mortality rate, because the air bubbles can potentially cause occlusion of the coronary arteries (myocardial ischemia), cerebral vessels (stroke), or cardiac outflow tracts (shock). Air emboli cause additional morbidity such as blindness (occlusion of retinal arteries) and ischemia of end organs. The ultimate clinical result depends on the site and volume of embolization.

Air emboli pose a challenge in emergency management of blast victims. Air emboli are not only difficult to diagnose but also have a clinical presentation similar to that of other more familiar clinical entities. For example, myocardial ischemia, which is usually easily recognized, is most likely to be secondary to coronary vessel embolization (versus the traditional mechanisms of ischemia) in victims with blast lung injury. Management of these patients should focus on halting the passage of air. However, in patients exhibiting a change in their mental status, more common traumatic causes (eg, intracranial hemorrhage from blunt head injury) should be addressed first, before focusing on embolization.

Air emboli can be confirmed by direct visualization of air bubbles or disrupted air passages via echocardiography, transcranial Doppler ultrasonography, CT scan, or bronchoscopy. Unfortunately, there are no data on the sensitivity of these techniques in detecting emboli in blast victims. Transesophageal echocardiography can detect gas bubbles as small as 2 micrograms, but its availability is limited. Sudden circulatory or neurologic collapse, especially if positive pressure ventilation has been started, combined with a high index of suspicion, is enough to make the diagnosis of air embolization until proven otherwise. Other suggestive clinical findings include possible evidence of bubbles in retinal vessels, aspiration of air from arterial lines, or marbling of the skin or tongue.

Treatment of air emboli might require thoracotomy. However, a temporizing maneuver is placing the patient with the injured lung down, or in the dependent position, to minimize embolization by increasing venous pressures on that side. Hyperbaric oxygen therapy has been successfully used to treat cerebral air emboli from diving decompression injuries by actually causing bubble volume to decrease.

Positive-pressure ventilation (PPV) is a last resort for blast victims because of the risk of further barotrauma. PPV is, therefore, reserved for cases of severe respiratory failure, critical central nervous system injury, or massive hemoptysis or for patients requiring emergency surgery for other reasons. Cardiovascular, respiratory, or neurologic collapse within minutes of PPV being instituted has been reported. In addition, PPV is thought to contribute to the generation of air emboli because of the high airway pressures it causes, and it has been implicated in the reopening of fistulas.

In the spontaneously breathing patient, pulmonary venous pressures are higher than airway pressure, which prevents the passage of emboli into the venous system. During PPV or when pulmonary vascular pressures are low (eg, with hypovolemia), airway pressures are higher, and the gradient is reversed, facilitating the passage of air and debris into the vascular system. Techniques based on experience in ventilating patients with pulmonary contusion and ARDS have been proposed for ventilating victims of blast lung injury who must be intubated. These techniques include low tidal volumes (6 mL/kg), pressure-controlled ventilation with a goal plateau pressure of 25 to 30 mm Hg cm H_2O, positive end-expiratory pressures, permissive hypercapnia, and acceptance of oxygenation saturations greater than 90%. As a last heroic attempt, extracorporeal membrane oxygenation has been suggested.

Gastrointestinal Blast Injury

After lung injury, gastrointestinal (GI) injury is the second most lethal primary blast injury. Abdominal injuries secondary to open-air blasts are less common than blast lung injury, but they are much more common in underwater blasts.

Clinical Findings and Diagnosis

The signs and symptoms of GI injury may be nonspecific and change over time. Evaluation of the abdomen begins with a physical examination, standard trauma screening laboratory tests, and a high index of suspicion for injury. Making the diagnosis of perforation in an area of trauma is challenging for many reasons. First, the findings can be subtle and masked by other, more critical injuries. Second, the patient may be unconscious, making the value of serial examinations limited. Third, diagnostic examinations such as CT, although useful for detecting hemorrhage, may be misleading or insensitive in the early stages of perforation.

Management

The goals of management are to identify and control internal bleeding and to identify and repair any perforated viscus. In stable patients in whom injury is suspected, the abdominal radiograph and diagnostic peritoneal lavage has largely been replaced by CT scan and ultrasonography. CT scan provides useful information regarding intra-abdominal hemorrhage, organ injury, free intraperitoneal air, and intramural hematoma. However, it has a low sensitivity for identifying a hollow viscus perforation. In hemodynamically stable patients with blast lung injury too severe to be surgical candidates, exploratory abdominal procedures may be delayed. In these patients, broad-spectrum antibiotics are recommended pending confirmation of intact bowel. Exploratory laparotomy may be necessary in hemodynamically unstable patients in whom internal bleeding is suspected. Because surgical outcomes in blast victims are poor, surgery, like intubation, is a last resort and should be weighed against the risk associated with missing a perforation.

Cardiovascular Effects

The heart and blood vessels can be directly or indirectly injured by a blast wave. Cardiac involvement during a blast usually manifests as coronary vessel embolization and ischemia. Blood vessels within certain organs have a propensity for injury and may contribute to the generation of microthrombi. Cardiac blast injury that manifests as hemorrhage in the epicardium, myocardium, or papillary muscles is quite rare.

Hypotension in blast victims can be caused by blood loss from major musculoskeletal or thoracic injury or from a blast-related, vagally mediated reflex. This reflex, which is seen immediately after a significant blast exposure, causes hypotension and bradycardia. It is the most common effect on the cardiovascular system by the blast wave itself. The hypotension can be profound but is usually self-limiting.

Traditionally, aggressive volume replacement to support circulation is required in trauma victims with cardiovascular collapse. However, excessive volume replacement can be detrimental, particularly to patients with lung injury. A permissive hypotension resuscitation strategy in which a systolic blood pressure of 90 mm Hg is accepted may help limit the use of fluid and blood products. Research in animals has suggested that fluid replacement actually impairs cardiovascular performance in the setting of a blast. However, inadequate pulmonary vascular pressure has been suggested to promote the passage of air into the pulmonary venous system. Therefore, administration of fluids in increments of 5 mL/kg, titrated to clinical response, has been recommended. Either too much or too little fluid can be harmful, and the judicious use of fluids to maintain euvolemia is probably the best approach. As in all trauma patients, a balanced resuscitation approach that replaces blood loss with similar amounts of red blood cells, plasma, and platelets should be employed.

Traumatic amputations frequently result from a blast. The mechanism for traumatic amputations has been hypothesized to be a combination of the blast wave itself and the effect of propelled fragments on tissues. Tourniquets have been used effectively by the US military and more recently by civilians during the Boston Marathon bombing to limit morbidity and mortality. Uncontrolled hemorrhage is the most preventable form of death in the United States. The "Stop the Bleeding Coalition" has information and kits available to address this issue (https://stopthebleedingcoalition.org/).

Blast Auditory Injury

The auditory system is the system most frequently injured during a blast. Auditory injury is more common than lung or GI injury, because the overpressure necessary to perforate tympanic membranes (5 psi) is well below that expected to cause lung or GI injury. Hearing loss, either with or without a ruptured tympanic membrane, is quite common. It can be debilitating and make communication with the victim difficult, if not impossible. Although some sensorineural hearing deficits improve over the first few hours, deficits are permanent in approximately 30% of victims.

Tympanic Membrane Rupture

Approximately 80% of tympanic membrane ruptures from PBI heal without the need of surgical intervention. However, with larger perforations, as seen in US troops during Operation Enduring Freedom, only about 50% close without surgical intervention.

Management

In general, emergency management of auditory injuries involves clearing the ear canal of debris and minimizing exposure to loud noises or water. Otologic complications such as perilymph fistula and cholesteatoma formation do occur, and all survivors should have an auditory assessment as part of their care.

Sentinel injuries

Sentinel injuries are subtle injuries that can increase the risk of having or developing serious blast injury. These patients should be monitored closely, no matter how clinically well they appear. Sentinel injuries include the following:

- Traumatic amputations
- Hypopharyngeal contusion
- Hemoptysis
- Subcutaneous emphysema

INCENDIARY INJURIES

The chief difficulty in early management of incendiary injuries is that they so frequently coexist with blast injuries. As such, successful fluid management depends on a careful balance between volume resuscitation, needed in severe burns, and volume restriction, needed for blast lung. This is especially problematic in the mass casualty setting, in which numerous patients may require the intensive care resources normally available in burn and trauma centers, but such resources rapidly become overwhelmed during mass casualty events. In truth, the number of available burn center beds on any given day—even given the relatively resource-rich environment of North America—is extremely limited, especially during winter months, mandating that all health care regions develop flexible surge plans for early burn care, typically in regional trauma centers, as burn beds will be scarce, and the physicians and nurses staffing them will be in very short supply.

Incendiary devices, or “firebombs,” are designed to inflict severe burns, and are largely confined to military use because of the high temperatures necessary to ignite them. Historically, white phosphorus was the main component of such bombs, but modern devices rely more often on thermite, a combination of powdered aluminum and ferric oxide, which can burn through, or weld, even heavy armor plate. Their effects on human flesh are obviously devastating. Perhaps the crudest, yet still most commonly employed incendiary device in asymmetric warfare, is the “Molotov cocktail,” a liquid petroleum fuel-based firebomb most often enclosed within a glass container and ignited with a cloth wick that is capable of producing severe burns.

Emergency management of victims of incendiary devices involves identifying and treating the following:

- Severe burns (partial- and full-thickness)
- Respiratory compromise (including inhalation injuries)
- Carbon monoxide poisoning
- Dehydration

These burn victims should be managed according to Advanced Trauma Life Support (ATLS) and Advanced Burn Life Support (ABLS) protocols as for any other burn victim, with special attention to identifying coexisting blast injuries and removing the incendiary agent from the skin. Inhalation of superheated gases associated with the explosion can cause severe burns to the upper respiratory tract, leading rapidly to upper airway obstruction as the mucosa of the upper respiratory tract blisters and swells. Although napalm (petroleum fuel mixed with a gelling agent) is chiefly limited to military uses, carbon monoxide poisoning is of particular concern, because carbon monoxide is a byproduct of napalm combustion. Because of the radiant heat emitted from the combustion of these materials, prolonged exposure may lead to severe dehydration.

Firearm Injuries

Although tragedies such as those at the elementary school in Newtown in 2012 or the concert in Las Vegas in 2017 receive most of the attention, more than 60% of mass shootings occur in private residences. The majority of active shooter incidents involve domestic violence, and in 25% of such cases, a child is a victim. Active shooter events are, however, far more common in the United States compared with other industrialized countries.

Data from US forces in Iraq showed that the most common forms of preventable death were from hemorrhage, and more than 30% were hemorrhage from an extremity. These types of injuries can be treated effectively with direct pressure, arterial tourniquets, and gauze impregnated with topical hemostatic agents, methods that are now in use by many emergency medical services (EMS) systems and police departments and increasingly are being taught to the general public.

Emergency management of victims of firearm injuries should follow Advanced Trauma Life Support (ATLS) protocols. As previously stated, the main difference between routine civilian trauma care and mass casualty trauma care following firearm-related injuries involves the far higher number of both victims and injuries per victim—both of which are facilitated by the use of "assault" weapons that allow both rapid fire and rapid reloading. Because most deaths attributable to gunshot wounds, especially high velocity wounds, result from uncontrolled hemorrhage, the approach to management follows a C-A-B (circulation-airway-breathing) paradigm rather than the more traditional A-B-C (airway-breathing-circulation) model, whereby rapid control of external and junctional (axilla and groin) hemorrhage, employing arterial tourniquets and topical hemostat-impregnated gauze when direct pressure fails to control major bleeding, is addressed first. Otherwise, management is similar to that utilized in routine civilian trauma.

DISASTER TRIAGE

Disasters are operationally defined as occurrences during which patients' needs exceed available resources. Multiple casualty incidents (MCIs) are occurrences typically involving 5 or more injured patients during which patients' needs exceed but do not overwhelm available resources. Mass casualty events (MCEs) are occurrences typically involving 20 or more injured patients during which patients' needs exceed and overwhelm existing local and even regional resources and require that additional resources be mobilized and deployed.

Standard triage methods apply during MCIs. Under standard triage, patients with actual airway compromise take precedence over those with breathing difficulties, who in turn take precedence over those with circulation instability, in that order. Events caused by improvised explosive devices (IEDs) or active shooters require hemorrhage control as the first priority.

TRAUMA SYSTEMS

The medical response to blast terrorism is built on the foundation of the regional trauma system. Approximately 75% of all terrorist events worldwide are blast trauma events. Therefore, regional emergency management, public safety, and public health agencies should include not only regional child health care experts but also regional pediatric trauma professionals in planning for mass casualty events that could affect children. Blast terrorism, like all other mass casualty events, needs to be directed with an incident command structure.

Trauma Hospitals

Most trauma hospitals are full-service general hospitals that provide the highest level of trauma-related health care service in their communities. This includes the timely availability of multiple surgical subspecialties. However, modern trauma system design does not rely solely on such hospitals but integrates all health facilities within the region to the level of their resources and capabilities. Thus, the complete trauma system should consist of an integrated network of health care facilities within a region, designed for safe and rapid transport of injured patients to the health care facilities that best meet their medical needs (eg, surgical, orthopedic, neurosurgical). Many stand-alone pediatric hospitals also serve as "pediatric trauma centers."

Trauma Centers

Trauma centers are general hospitals that are committed, both institutionally and financially, to priority care of injured patients. Trauma center levels are identified in 2 ways—by a designation process and a verification process. The designation process is outlined at the state or local level. Trauma center verification, which is a key element recognized as essential to trauma systems, is an evaluation process conducted through the America College of Surgeons. As of March 2022, there are 578 American College of Surgeons-verified trauma centers. Emergency medicine physicians and emergency trauma surgeons are the primary care providers within the context of the trauma center, and they provide appropriate information and follow-up to each patient's usual primary health care provider. Emergency medicine physicians begin evaluation and management and immediately involve emergency trauma surgeons whenever injuries meet any of the following criteria:

- Are multiple or severe.
- Require support of a full trauma team, based on previously established trauma triage criteria or scores.
- Would benefit from trauma consultation with an emergency trauma surgeon.

Trauma centers should have the following attributes:

- Designated as such by emergency medical and public health authorities within the region, based on self-categorization according to pre-established criteria.
- Followed by on-site peer verification by impartial trauma experts.
- Subject to ongoing review of performance and participation in the regional trauma quality assurance system.

The American College of Surgeons Committee on Trauma publication, *Resources for Optimal Care of the Injured Patient*, offers further detail on the characteristics of trauma systems and trauma centers. The latest edition, released in 2022, includes information on optimal emergency readiness for children.

Treatment

There should be preapproved prehospital triage, treatment, and transportation protocols in place that both represent the consensus of the medical community and are consistent with national recommendations. Treatment of blast trauma involves full integration of the regional EMS system and the regional trauma system, in accordance with plans developed in collaboration with regional public safety and emergency management agencies. Although most blast trauma is caused by explosive or incendiary agents, the possibility of other weapons of mass destruction (WMD), such as biological, chemical, or nuclear weapons, should always be considered.

Trauma and Burn Treatment

The treatment of victims of major trauma, including blast trauma, follows well-established protocols. The American College of Surgeons Committee on Trauma has developed and disseminated such protocols through its support of the *Advanced Trauma Life Support for Doctors Course*. The Emergency Nurses Association and the Society of Trauma Nurses have undertaken like responsibilities for nurses through the *Trauma Nursing Core Course* and the *Advanced Trauma Care for Nurses Course*. All 3 courses focus on a practical approach to the initial care and management of the injured patient, assuming no special knowledge of trauma care, including the steps to be taken during the "golden hour" of trauma care—the critical first hour after injury has occurred.

Major burns and major trauma are often seen together in victims with injuries caused by explosive or incendiary devices. The treatment of victims of major burns also follows well-established protocols. Specific education on the initial resuscitation of these victims is included in both the *Advanced Trauma Life Support for Doctors Course* (American College of Surgeons Committee on Trauma) and the *Advanced Burn Life Support Course* (American Burn Association).

Multiple Casualties

The strict definition of an MCI is an incident involving more than one casualty that overwhelms the capacity of emergency medical providers at the scene. In general, this happens when a local EMS system must care for 5 or more victims who have the same illness or injury at the same place and time. Because local hospital emergency departments may also be overwhelmed by such events, either because of patient self-referrals or ambulance transport, EMS systems usually attempt to transport multiple victims to several hospitals in the vicinity of the event when feasible. Generally, the closest facilities will receive the more critical patients, while the more stable patients will be transported a longer distance to a facility that has the appropriate resources to care for children. In such circumstances, attempts are usually made to transport members of the same family to the same hospital, particularly if ill or injured children are involved. However, the availability of specialized pediatric health care resources, such as children's hospitals, may justify preferential transport of pediatric victims of multiple casualty incidents to these facilities.

Mass Casualties

The strict definition of an MCE is an event involving large numbers of casualties, generally 20 or more, that overwhelms and disrupts the resources and capabilities of the entire regional trauma and EMS systems to provide immediate care for all ill or injured victims. This situation develops when the need for ambulances, hospitals, or both exceeds the emergency resources of the regional health care system. The definition further implies the following:

- The need to activate regional disaster plans that mobilize all available ancillary resources to assist with providing emergency medical care. This includes using the surge capability of both the regional EMS system to deploy extra ambulances (via mutual aid agreements) and of the regional hospital system to maximize the number of victims who can be cared for by opening spare beds, discharging stable patients, canceling elective procedures, and conscripting off-duty staff.
- The need to prioritize care such that those at greatest risk of loss of life or limb are treated first (unless they are unlikely to survive). Switching practice philosophy of doing the most for one patient, to attempting the best possible care for many patients when limited resources are available, is a difficult paradigm to adopt. The standard of care also changes. The most widely used pediatric resource for triage and immediate treatment is JumpSTART,

modified by Romig from the Simple Triage and Rapid Treatment (START) triage system used for adults.

PLANNING AND MITIGATION

The approach to planning for the possibility of blast injury after a terrorist attack should combine knowledge of the epidemiology of blast injury with awareness of the resources available to the regional trauma system. The federal government has adopted a similar approach for routine trauma system planning that allies the regional public health system with the regional health care system to form regional partnerships for the purpose of developing and implementing comprehensive injury control strategies at the community level.

Medical disaster planning should fully integrate regional public health agencies, regional health care organizations and coalitions, EMS, emergency departments, and trauma centers before a disaster occurs. Public health officials and trauma care professionals should collaborate to evaluate, and redesign if needed, each system component for optimal performance.

Current regional trauma system design maintains an artificial separation between the pre-event, event, and post-event phases of injury control. The comprehensive public health approach to regional trauma system design integrates all phases of injury control into a single system. Regional injury control systems that have adopted such an approach (eg, San Diego County, CA) have seen steady improvement in the quality of their injury prevention programs and the outcomes of their trauma patient care.

Public health reasons to apply this approach to blast terrorism include the documented lack of public health preparedness of most regions for terrorist attacks, despite excellent resources that describe the necessary elements for triage, transportation, and treatment of victims.

Planning

The enormous variability in the following characteristics hinders comparative analysis and, hence, accurate prediction of needs and resources for victims of blast terrorism:

- Type, quality, quantity, force, and delivery of explosive
- Environment (closed space versus open air)
- Time (day versus night)
- Distance (proximate versus distant)
- Circumstances (weather conditions, presence of hazardous materials, etc)
- Protection (clothes, barriers, etc)
- Sequelae (structural collapse, structural fire, etc)
- Victims (ages, number, density)

In general, small blasts in open air usually result in less serious injury than large blasts in closed spaces, which historically have resulted in life-threatening injuries.

Regional trauma system planning should also consider the special needs of children who are injured in blast terrorism events and the special resources needed to care for them. Children and young adults are at higher risk of serious injury than adults for several reasons. Specific to blast trauma is that, although blast tolerances in children are poorly defined, there is good reason to believe that children may absorb more blast energy per unit of body mass than adults after blast trauma. This predisposes children to morbidity and mortality rates higher than those of adults as compressive shock waves passing through the body are compacted into a smaller total body mass.

Mitigation

In recent years, many children have been victims of terrorist events, if not physically, then psychologically. Significant personal experience has been gained with pediatric disaster and emergency preparedness and management by child health professionals. Reports in the literature (summarized below) point out many gaps in the state of emergency preparedness for disasters that involve children. They also describe the common problems in pediatric disaster planning and management such that pediatric professionals involved in disaster planning will be knowledgeable about these problems and thus can seek to anticipate and thereby avoid them in future disasters.

Trauma system resources do not always meet the potential needs of the victims. Had the bomb detonated in front of the Times Square Theater where the Lion King was playing in 2010, a study indicated that the bed census in New York City would have been inadequate, even after surge plans were enacted. With only 5 hospitals at the time having operationally ready pediatric surge plans, the total number of beds could have been increased from 29 to 121, certainly insufficient to meet the needs of the number of potential injuries from an explosive event in close proximity to a theater heavily populated by children. The April 1995 bombing at the Alfred P. Murrah Federal Building in Oklahoma City impacted a child care center located on the second floor within that facility directly above the blast site. Nineteen children died and another 47 sustained injuries.

No children were injured in the terrorist airliner attack on the Pentagon on September 11, 2001, because the Pentagon child care center was located on the opposite side of the building from the location of attack. However, as a result of the attack, issues were raised about the regional children's hospital's disaster preparedness. Immediately after the event, the hospital disaster plan was activated, resulting in the discharge of more than 50 patients and the cessation of all nonurgent activities. Although hospital staff had conducted disaster drills, hospital leaders continued to question their actual state of readiness. Emergency preparations were complicated by the fact that all of their news came not from official sources, but from local television, leaving hospital leaders unsure about what to expect.

Experiences highlight a number of vitally important issues regarding blast terrorism mitigation in children.

- After a blast, injuries in children are to be expected with most children injured in closed or confined spaces, which greatly increases the magnitude of forces of injury.
- As with blast injuries in adults, most children will either die at the scene or sustain minor injuries. Only a small number of children in the "penumbra" of the blast wind who sustain major injuries will survive to require hospital care, but typically they will not begin to arrive at the trauma center until 30 to 60 minutes after the blast event.
- Most surviving children with major injuries will require early surgery and subsequent care in a pediatric critical care unit, followed by lengthy hospitalization and rehabilitation, both

physical and psychosocial.
- Pediatric victims may be unaccompanied by a parent or guardian when they present for care and may be unable to self-identify. Systems for the timely identification and reunification of children with family must be in place.
- As has been documented with all disaster types, preparation must also include mitigation and response planning for the mental health impact on children.

Although all of the above can overwhelm even the best prepared systems, optimal outcomes for children and families will be achieved through preparation for all disaster mechanisms, including blast injuries, the concurrent consideration for the unique needs of children of all ages, and the inclusion of pediatric readiness into local planning.

BIBLIOGRAPHY

EXPLOSIVE INJURIES

American Academy of Pediatrics; American College of Emergency Physicians; American College of Surgeons Committee on Trauma; American Trauma Society; Children's National Medical Center, Child Health Advocacy Institute, Emergency Medical Services for Children National Resource Center; International Association of Emergency Medical Services Chiefs; National Association of County and City Health Officials; National Association of Emergency Medical Technicians; National Association of EMS Physicians; National Association of State EMS Officials; National Disaster Life Support Education Consortium; National EMS Management Association; Society for the Advancement of Violence and Injury Research; Health Resources and Services Administration/Maternal and Child Health Bureau Emergency Medical Services for Children Program. Model uniform core criteria for mass casualty triage. *Disaster Med Public Health Prep.* 2011;5(2):125–128

Amir LD, Aharonson-Daniel L, Peleg K, Waisman Y, and the Israel Trauma Group. The severity of injury in children resulting from acts against civilian populations. *Ann Surg.* 2005;241(4):666–670

Bertani A, Mathieu L, Dahan J-L, et al. War-related extremity injuries in children: 89 cases managed in a combat support hospital in Afghanistan. *Orthop Traumatol Surg Res.* 2015;101(3):365–368

Borgman M, Matos RI, Blackbourne LH, Spinella PC. Ten years of military pediatric care in Afghanistan and Iraq. *J Trauma Acute Care Surg.* 2012;73(6 Suppl 5):S509–S513

Creamer KM, Edwards MJ, Shields CH, et al. Pediatric wartime admissions to US military combat support hospitals in Afghanistan and Iraq: learning from the first 2,000 admissions. *J Trauma.* 2009;67(4):762–768

Eber GB, Annest JL, Mercy JA, Ryan GW. Nonfatal and fatal firearm-related injuries among children aged 14 years and younger: United States, 1993–2000. *Pediatrics.* 2004;113(6):1686–1692

Edwards DS, McMenemy L, Stapley SA, Patel HDL, Clasper JC. 40 years of terrorist bombings – a meta-analysis of the casualty and injury profile. *Injury.* 2016;47(3):646–652

Edwards MJ, Lustik M, Burnett MW, Eichelberger M. Pediatric inpatient humanitarian care in combat: Iraq and Afghanistan 2002 to 2012. *J Am Coll Surg.* 2014;218(5):1018–1023

Edwards MJ, Lustik M, Eichelberger MR, et al. Blast injury in children: an analysis from Afghanistan and Iraq, 2002-2010. *J Trauma Acute Care Surg.* 2012;73(5):1278–1283

Everytown for Gun Safety. Mass Shootings in America. Available at: https://everytownresearch.org/reports/mass-shootings-analysis. Accessed February 23, 2022

Hull JB, Cooper GJ. Patterns and mechanisms of traumatic amputation by explosive blast. *J Trauma*. 1996;40(3 Suppl):198S–205S

Irwin RJ, Lerner MR, Bealer JF, et al. Cardiopulmonary physiology of primary blast injury. *J Trauma*. 1997;43(4):650–655

Jaffe DH, Peleg K, and the Israel Trauma Group. Terror explosive injuries: a comparison of children, adolescents, and adults. *Ann Surg.* 2010;251(1):138–143

Katz E, Ofek B, Adler J, et al. Primary blast injury after a bomb explosion in a civilian bus. *Annals Surg*. 1989;209(4):484–488

Kelly JF, Ritenour AE, McLaughlin DF, et al. Injury severity and causes of death from Operation Iraqi Freedom and Operation Enduring Freedom: 2003-2004 versus 2006. *J Trauma.* 2008;64(2 Suppl):S21–S26

Kim D, Mosher BD, Morison CA, et al. A modern analysis of a historical pediatric disaster: the 1927 Bath school bombing. *J Surg Res.* 2010;163(2):309–316

Klimo P, Ragel BT, Jones GM, McCafferty R. Severe pediatric head injury during the Iraq and Afghanistan conflicts. *Neurosurgery.* 2015;77(1):1–7

Lerner EB, Cone DC, Weinstein ES, et al. Mass casualty triage: an evaluation of the science and refinement of a national guideline. *Disaster Med Public Health Prep.* 2011;5(2):129–137

Leventhal JM, Gaither JR, Sege R. Hospitalizations due to firearm injuries in children and adolescents. *Pediatrics.* 2014;133(2):219–225

Liebovici D, Gofrit ON, Stein M, et al. Blast injuries: bus versus open-air bombings—a comparative study of injuries in survivors of open-air versus confined space explosions. *J Trauma*. 1996;41(6):1030–1035

Maxson RT. Management of pediatric trauma: blast victims in a mass casualty incident. *Clin Pediatr Emerg Med*. 2002;3(4):256–261

Pons PT, Jerome J, McMullen J, et al. The Hartford Consensus on Active Shooters: implementing the continuum of prehospital trauma response. *J Emerg Med.* 2015;49(6):878–885

Quintana DA, Jordan FB, Tuggle DR, Mantor PM, Tunell WP. The spectrum of pediatric injuries after a bomb blast. *J Pediatr Surg.* 1997;32(2):307–311

Ritenour AE, Wickley A, Ritenour JS, et al. Tympanic membrane perforation and hearing loss from blast overpressure in Operation Enduring Freedom and Operation Iraqi Freedom wounded. *J Trauma.* 2008;64(2 Suppl):S174–S178

Sorkine P, Szold O, Kluger Y, et al. Permissive hypercapnia ventilation in patients with severe pulmonary blast injury. *J Trauma*. 1998;45(1):35–38

Stuhmiller JH, Phillips YY, Richmond DR. The physics and mechanisms of primary blast injuries. In: Bellamy RF, Zajtchuk R, eds. *Conventional Warfare: Ballistics, Blasts, and Burn Injuries.* Washington, DC: Office of the Surgeon General of the U.S. Army; 1991:241–270

Villamaria CY, Morrison JJ, Fitzpatrick CM, Cannon JW, Rasmussen TE. Wartime vascular injuries in the pediatric population of Iraq and Afghanistan: 2002-2011. *J Pediatr Surg.* 2014;49(3):428–432

Wilson KL, Schenarts PJ, Bacchetta MD, Rai PR, Nakayama DK. Pediatric trauma experience in a combat support hospital in Eastern Afghanistan over 10 months, 2010 to 2011. *Am Surg.* 2013;79(3):257–260

Witsaman RJ, Comstock RD, Smith GA. Pediatric fireworks-related injuries in the United States: 1990-2003. *Pediatrics.* 2006;118(1):296–303

TRAUMA

American Burn Association. *Advanced Burn Life Support Course*. Available at: http://ameriburn.org/education/abls-program/. Accessed February 23, 2022

American College of Surgeons. Committee on Trauma. *Resources for Optimal Care of the Injured Patient 2022 Standards*. American College of Surgeons; March 2022. Available at: https://www.facs.org/quality-programs/trauma/tqp/center-programs/vrc. Accessed April 22, 2022

American Trauma Society. Trauma Center Levels Explained. Available at: http://www.amtrauma.org/?page=traumalevels. Accessed February 23, 2022

Conway E, Flamm A, Foltin G, et al. Had the times square bomb exploded: what about the injured children? *Prehos Disaster Med*. 2011;26(S1):S102–S102

EMSC Innovation and Improvement Center. Pediatric Disaster Preparedness Toolkit. Available at: https://emscimprovement.center/resources/toolboxes/pediatric-disaster-preparedness-toolbox/. Accessed February 23, 2022

National Association of State EMS Officials. Status of State Trauma System Planning and Development: Utilization of the HRSA Model Trauma system Planning and Evaluation Document, 2016. Available at: https://nasemso.org/nasemso-document/status-of-state-trauma-system-planning-and-development-sept2016/. Accessed February 23, 2022

van Amerongen RH, Fine JS, Tunik MG, et al. The Avianca plane crash: emergency medical system response to pediatric survivors of the disaster. *Pediatrics.* 1993;92(1):105–110