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Clinical Review

BLAST INJURIES

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☐ Abstract—Background: Blast injuries in the United States and worldwide are not uncommon. Partially due to the increasing frequency of both domestic and international terrorist bombing attacks, it is prudent for all emergency physicians to be knowledgeable about blasts and the spectrum of associated injuries. Objective: Our aim was to describe blast physiology, types of blast injuries associated with each body system, and manifestations and management of each injury. Discussion: Blast injuries are generally categorized as primary to quaternary injuries. Primary injuries result from the effect of transmitted blast waves on gas-containing structures, secondary injuries result from the impact of airborne debris, tertiary injury results from transposition of the entire body due to blast wind or structural collapse, and quaternary injuries include almost everything else. Different body systems are affected and managed differently. Despite previous dogma, multiple studies now show that tympanic membrane perforation is a poor predictor of other blast injury. Conclusions: Blast events can produce a myriad of injuries affecting any and every body system. All emergency physicians should be familiar with the presentation and management of these injuries. This knowledge may also be incorporated into triage and discharge protocols guiding management of mass casualty events. © 2015 Elsevier Inc.

☐ Keywords—blast; bombing; terrorism; disaster; mass casualty

INTRODUCTION

Perhaps contrary to common perception, blast injuries in the United States are not rare. Seventy percent of disasters causing >20 dead at the scene are secondary to explosions and fires from a variety of causes, and a 20-year retrospective analysis of bombing events by Kapur et al. identified 36,110 bombing incidents, 5931 bomb-related injuries, and 699 bomb-related deaths in the United States during the study period between 1983 and 2002 (1–4).

In addition, the increasing frequency of both domestic and international terrorist bombing attacks in the last few decades has led to blast injuries formerly only experienced in the context of war (5). Conservative estimates from the RAND® Memorial Institute for the Prevention of Terrorism suggest that terrorist explosive events have risen worldwide fourfold from 1999 to 2006, and injuries related to these acts have increased eightfold during the same period of time (6). Compared to military explosions, civilian blasts impact a wide range of humanity whose medical comorbidities can only be expected to impede their ability to withstand and recover from these events (7). These victims frequently suffer from multidimensional injuries involving primary blast injuries, burns, and both blunt and penetrating wounds (8,9). Penetrating wounds are seen more frequently in terrorist civilian bombing attacks than military explosions, largely because of the lack of body armor (7). A recent review of >3000 terrorist blasts victims revealed a mortality rate of 13% on scene, and 30% of those that survive require admission (10). Notable recent blast events include the World Trade Center (New York City, 1993); Argentine-Israel Mutual Association (Buenos

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Aires, Argentina, 1994); Murrah Federal Building (Oklahoma City, 1995); Olympic Park (Atlanta, GA, 1996); the U.S. embassies (Tanzania and Kenya, 1998); Omagh bombing (Northern Ireland, 1998); the September 11 attacks (New York City, Washington, DC, and Shanksville, PA, 2001); Bali (2001 and 2005); Istanbul (2003); Madrid commuter train bombings (2004); Jakarta (2003, 2004, 2009); London Underground bombings (2005), Bangkok (2007), the Boston Marathon (2013), as well as ongoing incidents in the Middle East (Iraq, Afghanistan, Jordan, Saudi Arabia, and Israel) (1,11,12).

Particularly because of the ever-present risk of terrorism in today's society, it is crucial for prehospital providers and emergency physicians to familiarize themselves with the myriad of injuries caused by blasts (12). Blast events can bring about chaos and panic and often overwhelm the capacity of medical facilities, who are generally unaccustomed to caring for multiple trauma patients simultaneously (9). Despite this, victims need to be directed to the appropriate level of care, and life-threatening injuries need to be promptly diagnosed and treated, as early recognition of blast injuries may improve outcomes (13).

DISCUSSION

Blast Physiology

Blasts are created by the instantaneous transformation of solid or liquid matter to its gaseous form, which produces energy in the form of light, sound, heat, and pressure (5,14). When a high-order explosive detonates (defined in section on Types of Explosives), a "blast wave," or significant air pressure elevation is created. The blast wave can travel at a rate as fast as 8000 m/s, and can reach pressures up to 30,000 times atmospheric pressure (11,15–17). The energy of the blast wave dissipates and its pressure decreases as the wave travels. Blast wind, which follows the blast wave, consists of powerful, fast-moving, superheated air that can lift bodies and destroy structures, which can result in both blunt and penetrating injuries (6,7,11).

The blast wave leads to injury through spalling, implosion, and inertia. Spalling is "displacement and fragmentation of the denser into the less dense medium." Alveolar hemorrhage is an example effect of spalling in the lung. Implosion is "displacement of the less dense into the denser medium." Air emboli traveling into the pulmonary circulation is an example effect of implosion in the lung (7,18). The definition of inertia is "shear stress created by the blast wave traveling through tissues of different densities at different velocities." In the abdomen, for instance, this can cause tissue tearing secondary to disparate movement of the abdominal wall and viscera (11,16,18).

Types of Explosives

Explosives are either high-order explosives that create supersonic blasts or low-order explosives that create subsonic blasts with less sheer velocity (12). High-order explosives include C-4, Semtex, trinitrotoluene (TNT), gelignite, dynamite, nitroglycerin, and ammonium nitrate fuel oil; and low-order explosives include gunpowder, pipe bombs, as well as Molotov cocktails and most other petroleum-based bombs (11,12,19). Low-order explosives are generally utilized as propellants and pyrotechnics. Propellants are devised to produce a controlled release of energy, and pyrotechnics are devised to create light, smoke, heat, and sound (20). While homemade bombs are often low-order explosives, this is not always the case, as rogue states and large-scale networks that sponsor terrorism can provide militants with the necessary supplies for the creation of high-order explosives; additionally, ammonium nitrate, which is used in the creation of some high-order explosives, can be easily amassed in the form of crop fertilizers (12).

The damage caused by explosives can be compounded by the addition of hazardous shrapnel (such as nails, screws, or ball bearings) or infectious agents, such as hepatitis B or C from blood debris (21,22). Additionally, evolving technology has allowed improvised explosive devices (IEDs) to be triggered remotely via cell phones and with complex timing for the initiation of multiple blasts (23).

"Dirty bombs" can exponentially increase blast-related destruction through the addition of nuclear materials or chemical agents that are dispersed when the bomb goes off (12,24). Newer thermobaric (or enhanced-blast) weapons emit gas before exploding, which leads to a larger pressure wave that has the ability to extend around corners and cause a much greater path of destruction than with conventional explosives (7).

CLASSIFICATION OF BLAST INJURIES

Primary Blast Injury

Blast injury is typically classified as primary to quaternary, occasionally as primary to quinternary/quinary. Blast waves themselves cause primary blast injuries (PBIs) and generally affect gas-containing organs, most commonly the eardrums and lungs and, to a lesser extent, bowel (25). As mentioned already, PBI develops when a blast wave accelerates and decelerates while traveling through tissues of varying density (11).

Unlike other forms of blast injury, body armor cannot protect against PBI (11,26). Examples of PBIs include blast lung, "hemothorax, pneumothorax, tension pneumothorax, acute arterial gas embolism, gastrointestinal (GI) perforation, blast-induced neurotrauma, eye rupture, and tympanic membrane perforation" (11).

Blast lung is most frequently responsible for death in victims of PBI (11). Of all victims who are killed secondary to blast injuries, 17% to 47% are thought to have signs of blast lung (6,11). The pathophysiology includes capillary rupture within the alveoli, which leads to hemorrhage and pulmonary edema. This ultimately reduces gas exchange, causing both hypoxia and hypercarbia (1,11,27,28).

Secondary Blast Injury

Secondary blast injuries result from the direct impact of airborne debris because of blast wind (11,29). During an explosion, blast-energized environmental fragments or pieces of the explosive device become projectiles and frequently cause penetrating injury (29). The fragments that cause secondary injury can be classified as primary, those that originate from the bomb itself, or secondary, those that originate from the surrounding environment (11,30). Unlike PBI, body armor can protect from secondary blast injury (11).

Tertiary Blast Injury

Tertiary injury results from transposition of the entire body due to blast wind or structural collapse and can result in blunt or crush injuries, depending on the situation (29,31). Tertiary blast injuries include head trauma, fractures, blunt trauma, and traumatic amputations (11).

Traumatic amputations are thought to occur in 1% to 7% of blast victims, but there is some discrepancy within the literature as to its categorization. Multiple sources classify traumatic amputations as tertiary, and others consider them PBIs (1,6,11,32). Horrocks and Harrison et al. suggest a combined primary and tertiary mechanism where bones are fractured by blast wave while surrounding soft tissue is torn by blast wind, resulting in near- or total-limb avulsion (11,14,33).

Quaternary Blast Injury

Quaternary blast injuries include most other blast effects not categorized by primary to tertiary injury. These include burns, radiation exposure, inhalational injury, asphyxia, crush injuries, angina, hypertension, psychological consequences, and others (11,29,31).

Quinternary/Quinary Blast Injury

The majority of literature does not include this category of blast injury, but it is occasionally mentioned and described as a delayed hyper-inflammatory response possibly thought to be caused by chemicals involved in the blast (22,34) (Table 1). One source reports a potential description as "a unique hyper-inflammatory state manifesting as hyperpyrexia, sweating, and low central venous pressure despite adequate fluid input" (22,35).

QUALITIES THAT AFFECT SEVERITY OF BLAST INJURIES

Blast injury severity is determined by numerous factors, including explosive agent, explosion location, amount of explosives used, the victim's prior health, as well as the victim's location and proximity to the blast (9,12,29).

Location of Explosion

Blast location in either open or closed space significantly affects both the quality and degree of blast injury (13,36). In confined spaces, the blast wave reflects off the building structure, slowing the dissipation of the blast wave and consequently amplifying its capacity for destruction (29,37). Confined-space explosions also contribute to greater damage by generating more structural and environmental fragments, which often result in more penetrating blast injury (5,29). Leibovici et al. showed that casualties of closed-vs. open-space explosions have a significantly higher mortality rate (15.8% vs. 2.8%), greater Injury Severity Score (ISS) in those that survive (11 vs. 6.8), and both increased PBIs and notable burns (36).

Additionally, blast waves are also transmitted faster through water than air, leading to greater destruction in the event of an underwater blast (6).

Amount of Explosives Used

Blast force increases as the amount of explosive material is increased, and this range of force results in a wide range of clinical consequences (9). The auditory system can be injured in victims exposed to pressures as low as 2 psi and tympanic membrane (TM) perforation occurs in half of those exposed to 15 to 50 psi. Lung injury develops in half of those subjected to 70 psi, while perforation of the GI tract is generally seen only with higher pressure (9,38). Pressures >80psi are fatal for >50% of victims (9).

Proximity and Position of Victim in Relation to the Blast

The closer a victim is to the center of a blast, the greater the consequences the blast wave will have (6). It has been found that a distance of >16 m is protective from significant PBI for explosions resulting from up to 25 kg of TNT (9,25). The victim's orientation respective to the blast, including the angle and height of the victim in

Table 1. Primary to Quinternary/Quinary Injury

Type of blast injury	Definition	Areas affected	Example injuries	Key points
Primary injury	Injury due to direct effect of blast wave	Gas-containing organs (TM, lungs, less commonly bowel)	Perforated TM, pulmonary barotrauma, hemothorax, pneumothorax, acute arterial gas embolism, GI perforation, concussion without signs of external head injury, eye rupture	Unlike all other forms of blast injury, body armor is not protective
Secondary injury	Injury due to direct impact of airborne debris because of blast wind	Any body part	Blunt trauma, penetrating injury	Primary fragments originate from bomb device, secondary fragments come from the environment (wood, debris, etc.)
Tertiary injury	Injury caused by displacement of the entire body, either from blast wind or structural collapse	Any body part	Head injuries, blunt trauma, fractures, traumatic amputations	Some argue that traumatic amputations are due to a combined primary and tertiary blast mechanism (11,14,33)
Quaternary injury	Injuries not categorized by primary to tertiary injury	Any body part	Burns, radiation exposure, inhalational injury, asphyxia, crush injuries, angina, hypertension, psychological consequences, etc.	Quaternary classification is a diagnosis of exclusion
(Quinternary/quinary injury)	Delayed hyperinflammatory response thought to be caused by chemicals involved in blast (31,32)	Any body part	One potential description: "hyperpyrexia, sweating, low central venous pressure despite adequate fluid input" (32,33)	Majority of literature does not include this category of blast injury

GI = gastrointestinal; TM = tympanic membrane.

relation to the center of the explosion, is also important in determining the extent of injury (12).

BLAST VICTIMS VS. NONBLAST TRAUMA VICTIMS

Blast victims in comparison to victims of traditional trauma tend to have worse injuries, more often require intensive care, and generally necessitate longer hospital stays and recovery periods (7,36,39). Israeli studies evaluating blast injury victims have determined that the number of seriously injured (ISS $\geq$ 16) by blasts is three times higher than those seriously injured in traditional trauma scenarios, and four times higher for victims with a Glasgow Coma Scale (GCS) score $\leq$ 5 (12,34,40,41).

CLINICAL CONSEQUENCES OF PRIMARY BLAST INJURY

Ears

The auditory apparatus is particularly prone to blast injury and is the most frequently damaged organ during blast events, as a relatively low pressure is sufficient to cause damage to the TM (38,42). Although the TM can perforate at a pressure < 0.5 atmospheres, a pressure 8 to 10 times greater is required to directly injure nonauditory organs (43). Many factors contribute to risk of TM rupture, including the pressure amplitude of the blast, position of the head and ear in relation to the explosion, the presence of internal cerumen or external protective equipment, and history of ear infection or injury (7). Patients with TM perforation can experience otalgia, tinnitus, hearing loss, and dizziness. Otoscopy is adequate to confirm diagnosis (7,44).

Traditionally, TM perforation is thought to be an indication of blast exposure that should prompt pursuit of other common, yet less recognizable blast injuries (9). For this reason, blast victims with TM rupture are frequently observed overnight because of concern for delayed respiratory decompensation secondary to occult pulmonary damage (9). The necessity of this practice has not been proven by current data or literature, but continues to guide management protocols in numerous institutions (45). However, a landmark study was performed by Harrison et al. in 2009 in Iraq that evaluated 167 patients with blast injuries at a U.S. military hospital. Of these victims, 16% (26 of 167) had TM perforation. Seven percent (12 of 167) had PBI, but only half of those with PBI (6 of 12) also had TM rupture (22,43). PBI for the purposes of this study was defined as PBI aside from TM rupture, such as "pneumothorax, pneumomediastinum, pulmonary contusion, facial sinus injury, or bowel perforation" (43). This study, the results of which have been reproduced by others, shows that despite traditional belief, TM perforation is a poor marker for PBI (22,43). As a result, some now recommend that blast victims with isolated TM perforation be discharged after a period of observation to free critical hospital resources in the event of a mass casualty scenario (45).

Conservative care is the primary management for TM rupture; although some eventually require operative repair, the important principle for most is simply preventing additional damage, and no antibiotic or other medications are advised (7). The majority of those with TM rupture have good prognosis and experience healing without any intervention, however, up to 30% develop permanent hearing loss (7).

Lungs

Aside from the auditory apparatus, the lungs are thought to be the organ most vulnerable to PBI (44). PBI of the lungs develops due to blast wave transmission across the chest wall and airway structures and is found in 0.6% to 8.4% of those exposed to blasts (46–49). Lung PBI is frequently evident in blast victims killed on scene, but is present in a much smaller percentage of survivors (7,46,50). Common PBIs to the lung are contusions and barotrauma, which can include pneumothorax, pneumomediastinum, and interstitial or subcutaneous emphysema (44). The definition of *blast lung* is PBI of the respiratory system (44). It may also be referred to as pulmonary blast lung injury, and diffuse lung contusions are its hallmark (51). Those with pulmonary blast injuries can have dyspnea, cyanosis, cough, hemoptysis, and chest pain; they often present with hypovolemic shock, respiratory distress, or both (44,45). In general, explosions in closed spaces cause bilateral pulmonary injuries, and open-air blasts cause greater injury ipsilateral to the event (52).

Primary blast injury of the lung is associated with a mortality rate of 11% (10). For those that survive, immediate diagnosis and prompt resuscitative efforts are imperative, but long-term prognosis appears to be good (7,45). Hirshberg et al. conducted a study of 11 patients with lung injuries secondary to a bus bombing in Israel (53). Notably, none of these patients endorsed pulmonary complaints after 1 year, and all had normal lung examinations, normal lung function testing, and resolution of imaging abnormalities at this time. As a result, the study deduced that surviving blast victims with pulmonary injuries generally experience resolution of lung damage within 1 year (12,53).

Much of the conventional thinking that those with TM perforation should be hospitalized for observation comes from the idea that the development of blast lung may be delayed for 24 to 48 h after exposure (54). This impression was questioned by Leibovici et al. and Pizov et al. in 1999 (45,55). Pizov et al. studied 15 victims with blast-related injury to the lung. Intubation was necessary for each of these victims either on scene or upon presentation to the emergency department; notably, none of the patients without mechanical ventilation for 6 h after the initial event subsequently developed blast lung (54,55). Similarly, none of the patients with pulmonary blast injuries in the report by Leibovici et al. had damage to the lung that manifested over time, all had a fulminant clinical course that was apparent not long after presentation (45). Current thinking is that evidence of acute lung injury after 48 h post-explosive event is most likely related to systemic inflammatory response syndrome or sepsis rather than PBI, and standard management algorithms should be followed for these patients (54).

GI Tract

Primary blast injuries of the GI tract are uncommon and occur in only 0.3% to 0.6% of survivors (56). Blast injuries of the GI tract are generally less common than TM or lung injuries, but their rate of occurrence is actually similar to that of lung injuries in open-air blast settings free of obstacles (11,16,44,57). Like other forms of PBI, GI injuries are seen more often in blasts that occur in confined spaces (7). These injuries are also more likely in underwater explosions, as blast waves travel more easily in water than air (7,25).

Hollow abdominal organs are more commonly damaged by PBI than solid organs. Gas-containing organs can develop edema, hemorrhage, intestinal contusions, intramural hematomas, and frank hollow organ rupture (9,44). Case studies have shown that even delayed bowel perforation can occur in these patients from evolving mucosal damage (diagnosed at laparotomy) (58). Solid organs like the liver, spleen, and kidney are rarely affected by PBI, but when they are, subcapsular hematomas often develop (44,59).

Patients with blast injury to the GI tract can have "clinical signs of absent bowel sounds, bright red blood per rectum, guarding, and rebound tenderness, and symptoms of abdominal pain, nausea, vomiting, diarrhea, and tenesmus" (44).

Eyes

Blast injuries to the eyes mainly fall into two categories. Primary injuries result from shear forces and manifest as hemorrhages, detachments, or even globe rupture. Blast-induced projectile fragments cause secondary injuries and are generally more common than primary ocular injuries (60,61).

The incidence of ocular trauma after an explosion is surprisingly high, given the relatively small surface area of the eye (approximately 0.1% of total body surface area) (1). Up to 10% of all surviving blast victims are thought to have notable ocular injuries (12). Those seen most frequently are intraocular foreign bodies, corneal abrasions, lacerations of the lid or periorbital region, retinal detachment, orbital fractures, and globe rupture (1,61–63).

Brain

Blast-induced brain injury may be more common than previously believed (7). Dougherty et al. conducted a retrospective cohort study in 2011 of 2254 blast-injured American personnel in Iraq and concluded that 37% had sustained some amount of blast-induced neurotrauma (11,26). Furthermore, a recent review of 3000 victims of terrorist bombings found that head injury is a major reason for both early and delayed blast mortality (7). In general, the high mortality rate of secondary penetrating injury to the head makes this injury less likely to be seen in victims who survive to seek medical treatment (64).

Blast-related brain injuries can vary from minor to fatal. More significant injuries include subarachnoid hemorrhage, subdural hemorrhage, and hyperemia of the brain and meninges (28,65). Symptoms of blast-related brain injury include headache, tinnitus, hypersensitivity to noise, retrograde and anterograde amnesia, and findings of post-traumatic stress disorder (7). This constellation of symptoms has been labeled with various terms previously, such as *shell shock, shell concussion,* and *combat fatigue*; its clinical presentation can range from subtle dysfunction to complete unresponsiveness, but most of these patients present with a normal GCS (1,66).

It is not fully understood how exactly blast leads to traumatic brain injury (TBI) (17,67), but it may be due to rupture of cortical vessels leading to diffuse axonal shearing and intracerebral, epidural, and subdural hemorrhage formation (1). It is suggested that mild TBI might be due to free radical release and neuronal cell death (68).

Cardiovascular System

Cardiovascular dysfunction can manifest in a small subset of patients after close proximity blast exposure (64). Literature on this subject is sparse, but a study by Irwin et al. in 1997 conducted on rats reported a bimodal cardiovascular response after blast injury; the primary effect takes place within seconds, while the secondary effect takes several hours to develop (7,69). In general, blasts can cause cardiac damage comparable to that caused by blunt trauma; there are many resultant contusions and microscopic injuries, which can predispose to dysrhythmia (70). Animal studies in particular have demonstrated vagally mediated bradycardia and hypotension as a result of blasts (22,56). The belief is that blast casualties might be in profound shock without signs of hemorrhage or other common causes for hypotension, and their low blood pressure is frequently refractory to resuscitative efforts (64). Shock in these patients is thought to be a direct effect of the blast wave: there is a decrease in cardiac index without a compensatory increase in systemic vasoconstriction. In addition, PBI to the lung is also likely to cause alveolar-capillary derangement, which can lead to pulmonary hypertension and resultant cor pulmonale (64). It is important to note that blast-related hemorrhage can contribute to hypotension in blast victims with cardiovascular injury; medical providers should be aware that a patient can have blast-related hemorrhage but might lack compensatory tachycardia because of blast-induced bradycardia and other direct blast effects on the cardiovascular system (71).

Another cardiovascular complication of blasts, though rare, is air embolism of the systemic or coronary vasculature (7). Coronary air emboli manifest with coronary ischemia (electrocardiogram changes and dysrhythmias), and cerebral air emboli can manifest as motor weakness to seizures, loss of consciousness, or coma (1). The greatest risk of air emboli is within the first 24 h after injury, unless casualties are receiving positive pressure ventilation (PPV), in which case this risk increases (72). The combination of hypotension, notable air leak, and decreased end-tidal CO_2 are diagnostic signs of air embolism (51).

Another rare cardiovascular complication of blast injury is thoracic compartment syndrome (51). It is characterized by a significant decline in blood pressure every time PPV is applied; in essence, edematous tissue or hematomas within the mediastinum cause constriction of the heart and prevent its normal function (51). Thoracotomy is the advised management for thoracic compartment syndrome (51).

Musculoskeletal System

Musculoskeletal injury is exceedingly common in victims of blast events and accounts for >80% of all surgical procedures in those that survive (10). These soft tissue and bony injuries can result by any of the four blast mechanisms, but secondary musculoskeletal injury is believed to be more common than primary (7).

Crush injuries from blast injuries are particularly significant because untreated, they can progress to rhabdomyolysis, renal failure, and death from acidosis and extreme metabolic derangements (64). Rhabdomyolysis can also occur without overt crush injury and can arise from prolonged forced positions, such as those encountered by blast victims trapped in enclosed spaces after structural collapse (64,73). The diagnosis of rhabdomyolysis is confirmed with elevated creatine kinase in serum or the presence of myoglobin in urine (64).

Traumatic amputations or limb avulsions occur in 1% to 3% of blast victims (74,75). These injuries, particularly blast-associated amputation proximal to the wrist or ankle, signify poor prognosis, as they suggest likely serious concomitant internal injury (12). As few as 1% to 2% of these patients live long enough to receive hospital care (10,45). Furthermore, the amputated parts, if present, are rarely salvageable (12).

CLINICAL IMPLICATIONS OF SECONDARY BLAST INJURY

Penetrating secondary blast injury of the chest and abdomen are common blast injuries, particularly in urban bombings (9). Suicide bombers often plan to maximize injury by adding various items such as nails and screws to their explosive charge (9). These projectiles can result in a myriad of consequences, ranging from superficial to lethal wounds, depending on their velocity and shape (9). These fragments generally fly with great force and can cause occult penetrating wounds concealed by hair or clothing (76). These victims may walk in to the ED apparently well, yet have penetrating injuries that can threaten their life (76).

Another consideration involving secondary blast injury is that blast fragments can carry environmental debris into a wound (77). Human shrapnel is another consideration, particularly for suicide bombings; bone chips generally behave as other projectiles, but can additionally create numerous emotional, ethical, as well as infectious consequences for both patients and health care providers alike (9,78).

CLINICAL IMPLICATIONS OF TERTIARY AND QUATERNARY INJURY

Generally, tertiary blast injury is similar to other mechanisms of blunt trauma, but in combination with other categories of injury associated with blasts, caring for these victims can be more complex than those with isolated blunt trauma (9).

Burns are a common presentation of quaternary injury. They can vary from superficial burns to deep second- and third-degree burns (9). The superficial “flash” burns are typically caused by the explosion flame and can affect large body areas at once. Deeper burns are typically caused by fires ignited by the explosion and generally affect variable amounts of body surface area, depending on exposure time to the flames (9).

Another common, nonphysical form of quaternary injury is acute stress reaction, which is thought to affect approximately 20% of casualties in terrorism-associated blasts (9). Acute stress reactions are a normal reaction to intense stress and are characterized by impaired response to external stimuli; victims can experience tremors, hyperventilation, sweating, decreased awareness and ability to listen, overwhelming depression, anxiety, anger and guilt, and might frequently re-experience the traumatic event (9). Symptoms of acute stress reaction may or may not proceed along the continuum toward acute stress disorder or post-traumatic stress disorder. Early psychiatric support can prevent this progression (9).

GENERAL MANAGEMENT OF BLAST INJURIES

In general, all blast injury victims need to be managed first following standard advanced trauma life support (ATLS) algorithms (44). After the patient is stabilized, the organ systems specifically affected by blast injury should be more specifically evaluated, with particular attention paid to the lethal manifestations of PBI of the thorax and abdomen (44).

Ears

Because acoustic trauma is a common blast injury, routine otoscopy is mandatory for all blast casualties (9). Specific treatment of TM rupture consists of sterile irrigation and the removal of internal debris. While surgical closure is recommended if the rupture is greater than one third of the TM, the treatment for most eardrum perforation is simply conservative care and the prevention of additional damage (44,79).

Eyes

Routine ophthalmologic evaluation is also mandatory for all blast casualties as eye injuries, even minor ones, such as foreign bodies and smoke particles, are common after blasts (9). Liberal referral for more extensive screening is encouraged with any findings of decreased visual acuity (12).

Lungs

Pulmonary blast injuries are notoriously difficult to manage, as they can present with characteristics of acute respiratory distress syndrome (ARDS) as well as air embolism (12). Generally, lung contusions can be treated with supportive care. Intubation is indicated for those with blast injuries who are unstable or who require emergency surgery (1). PPV is beneficial in that it can correct respiratory distress and ameliorate hypoxemia, but it can also cause barotrauma or arterial air embolism (44,80). Blast victims with severe lung injury also commonly require elevated positive end-expiratory pressure (PEEP) in addition to PPV (51). High PEEP, however, can aggravate already friable lung parenchyma and may result in pneumothorax or other complications (51).

If mechanical ventilation is utilized for primary blast lung injury, it is critical that a lung protective strategy is employed (7). Peak airway pressures should be minimized by adjusting respiratory rate, tidal volume, I:E ratio, and inspiratory flow rate (7). In general, low inspiratory pressure with avoidance of PEEP is ideal, but patients that are difficult to ventilate may require higher airway pressures (1,55). Permissive hypercapnia can also be considered as a means to decrease peak inspiratory pressure, but cannot be used in patients with neurologic injury (1,81).

When conventional mechanical ventilation is unable to maintain adequate oxygenation in a blast lung injury victim, advanced ventilator support technologies that have been helpful for treating primary blast lung injury include different types of pressure-controlled ventilation, jet ventilation, nitric oxide, and high-frequency oscillatory ventilation (9,55,82). These modes confer the benefit of overcoming hypoxemia without increasing PEEP excessively (55). However, there is a paucity of data to determine which mode is preferable, and benefit has only been suggested through case reports (7,51,54). Prone position has also been suggested to improve oxygenation, but is likely impractical during the management of blast victims in the emergency department (51). Extracorporeal membrane oxygenation (ECMO) provides an alternate method of providing cardiac and respiratory support to patients who are severely ill. However, its use requires caution, as the only case report documenting the application of ECMO in this setting also detailed the patient's death due to pulmonary hemorrhage attributed to the required systemic anticoagulation (55).

Although not commonly suggested in current literature, the placement of empiric bilateral thoracostomy tubes was advocated previously for primary blast lung injury as a preventive measure, and benefit has reportedly been seen in specific cases (22,54,83). However, current thinking is that this practice is unnecessary in the absence of pneumothorax, but may be considered before air transportation of lung PBI victims (7).

When resuscitating blast victims, it is important to be aware that aggressive i.v. hydration can cause pulmonary edema in those with blast injury of the lung (6,7,11).

GI Tract

The emergent management of GI blast injuries is similar to the management of general abdominal trauma; patients should be resuscitated after standard ATLS protocols and assessed for possible surgical intervention (71).

While evidence of intestinal perforation can be noted on x-ray study, ultrasound, or computed tomography (CT), none of these modalities are able to diagnose other primary GI blast injuries, such as intestinal contusion (7). Contusions of the bowel are notable as they can occasionally result in delayed "secondary perforation" of the intestine (7,44). Studies suggest that most of these secondary perforations develop 3 to 5 days after initial injury, but occasionally develop up to 2 weeks later (84). For this reason, a high level of suspicion is essential to making this diagnosis.

Esophageal perforation should also be considered in blast victims who present with chest pain, dyspnea, or subcutaneous emphysema (85). Diagnosis of this injury would be made by esophagram, and primary repair, although not always required, is the most common treatment (85).

Brain

The ideal treatment of blast brain injury is at this time (7). A 2007 study by Earle et al. suggests that cerebrovascular resuscitation is optimized when i.v. fluid is limited (49). This study used anesthetized swine with blast injuries to the head and chests due to blot guns. While longer-term studies are still required, this study found that limiting i.v. fluid after resuscitation to standard mean arterial pressure and cerebral perfusion pressure targets with mannitol and pressor therapy after polytrauma attenuated intracranial hypertension and allowed maintained brain oxygenation (49).

There are multiple areas of controversy regarding secondary penetrating injury to the head, including indications for removal of bony or foreign fragmentation and extent of debridement (64).

Cardiovascular System

When blast-related cardiac dysfunction is suspected, inotropic support should be provided in lieu of overly aggressive fluid infusion, as associated lung injury is common (62).

Optic fundoscopy, echocardiogram, and CT head are unfortunately all frequently nondiagnostic for air embolism, so treatment can be initiated empirically if there is clinical concern for this diagnosis. Treatment is generally supportive in nature, and its goal is primarily trapping of the responsible air within the left ventricular apex to prevent subsequent air emboli. This can be done by placing the patient in simultaneous left lateral decubitus and Trendelenburg position (head down, feet up, on left side) (7). It is for what length of time this position should be continued (7). Patients with air embolism typically reach their nadir of oxygenation within the first 24 h, and it is important to have 100% oxygen administered; hyperbaric oxygen can also be used to decrease the size of the gas bubble, although this therapy has not been studied extensively (1,7,86,87). If the patient requires PPV, further embolization may be limited by minimizing peak inspiratory pressure (7).

Musculoskeletal System

The management of blast-induced skeletal injuries includes plain films to evaluate for fracture and foreign bodies, tetanus prophylaxis, and broad-spectrum antibiotics if the fracture is open (88). For the many blast victims that present with fractures, early fixation (typically external) is advocated (64). Like with an extremity injury of any cause, it is also important to consider the possibility of compartment syndrome (7).

The treatment of small fragment wounds due to blasts remains a controversial subject (1). Several studies have assessed a conservative approach to wound management consisting only of irrigation, tetanus, and antibiotics (1,89–91). These studies suggest that wounds may be cared for conservatively if they involve only soft tissue without violation of peritoneum, pleura, or major vascular structures, are <2 cm in diameter, are not obviously infected, and are not the result of a mine blast (as these are often grossly contaminated) (1).

In a blast-related mass casualty event, each victim can suffer from multiple penetrating fragments. While some advocate comprehensive imaging to recognize occult entry wounds secondary to metal fragments, currently there is no consensus regarding the optimal use of x-ray study or pan-CT in those with multiple small projectile-induced penetrating wounds, many of whom remain asymptomatic (9,76). In this situation, it is reasonable to hospitalize hemodynamically stable victims with fragment penetration for observation and later exploration and reassessment (51). As with other trauma, repeat physical examinations are generally reliable (51,92–95). Imaging such as chest x-ray study and CT should be considered for those with penetrating wounds to the head, neck, or trunk.

Renal System

As mentioned previously, blast injury patients can develop rhabdomyolysis. Similar to treatment of rhabdomyolysis of other causes, the treatment for these patients includes aggressive hydration, alkalinization of urine, forced diuresis with mannitol, as well as possible hemodialysis for renal failure (64).

Infectious Disease Considerations

Blast victims will often have multiple soft-tissue lacerations. Unlike simple thermal burns that do not require prophylactic antibiotics, blast-related lacerations require antibiotics to cover environmental contaminants, particularly gram-positive organisms (54,96). Those with wounds breaching the abdominal cavity also require coverage for gram-negative and anaerobic organisms (54).

Blood-borne infections, such as hepatitis B virus, hepatitis C virus, and human immunodeficiency virus, pose a potential hazard for blast victims as well as prehospital and hospital providers, given the large amount of bloodshed and secondary fragments associated with blasts (22). The U.S. Department of Health and the UK Health Protection Agency currently recommend standard individualized assessment for those splashed with blood as well as an accelerated vaccination schedule for victims of penetrating blast injuries who are unvaccinated against hepatitis B (22,97).

Radiologic Considerations

In approaching the care of victims of a radiologic-dispersal device, or “dirty bomb,” medical personnel are advised to take standard precautions as well as wear personal protective equipment (PPE), including scrubs, gown, surgical mask, waterproof shoe covers, eye protection, and double gloves (1). There is no direct radiation risk to providers if appropriate precautions are taken; consequently, critical injuries should be treated before victims are formally decontaminated (1,98,99). Dust on the victim is the primary source of contamination and consequently undressing and disposing of the patient’s clothing removes approximately 90% of contamination (1,100). If a potentially radioactive fragment is present, providers should use forceps to remove it while limiting their exposure time, keeping as much distance as possible, and utilizing PPE and a body shield if possible (1).

EXTERNAL SIGNS TO GUIDE TRIAGE: ARE THERE PREDICTORS OF BLAST LUNG INJURY AND INTRA-ABDOMINAL BLAST INJURY?

Significant blast injuries can occur with minimal external injury, which has raised interest as to whether there are external signs that can predict blast lung and intra-abdominal blast injury (11,14). It was previously thought that because lower pressures are required to perforate the TM than to damage other internal organs, that TM perforation could predict patients who potentially had more serious forms of PBI. Cadaver studies indicate that the average pressure required for perforation of the adult TM is 137 kPA, while other organs are often injured in the 400 kPA range (31). However, multiple studies have now shown that TM perforation is actually a poor predictor of blast injury, possibly because many explosions today (particularly combat explosions and those from IEDs) have pressure increases at an uneven rate (31). It has been shown that serious PBI can occur without TM perforation. As mentioned previously, in one sentinel study in 2009 by Harrison et al., the absence of TM perforation missed detection of up to 50% of those with lung PBI (43). Furthermore, several studies, including that by Leibovici et al. in 2009, show that lone TM rupture in blast victims does not suggest occult PBI of the lung, or necessarily poor outcomes for the patient (45). As a result, they recommend that in resource-limited situations, those with isolated TM perforation be discharged after chest x-ray study and a brief observation period (45). The appropriate amount of observation time is not determined.

One caveat to this is that findings involving TM rupture as a poor predictor for PBI may not apply to victims of conventional blasts (43). Traditionally, bombs and explosions extend outward as a sphere from a central source. IEDs, on the other hand, and other newer forms of blasts, are continually changing and often have shaped charges; for instance, the energy from an IED extends outward as a cone (43). For this reason, with IEDs and other new explosives it is feasible for the TM to encounter less blast energy than other organs, and in these scenarios, TM rupture is understandably not a reliable predictor of occult blast injury (43). Another limitation of some of these studies is that several involved professional soldiers, who generally have protective equipment, unlike the average civilian; this might spare injury to the TM in a way that is not directly translatable to the average blast victim (43).

Aside from a ruptured TM, other specific signs that have been hypothesized to signify potentially significant blast exposure include “hypopharyngeal petechiae or ecchymoses, fundoscopic evidence of retinal artery air emboli,” and subcutaneous emphysema (44). Recent studies suggest that more accurate indicators of serious internal blast injury include external injuries to 4 or more body areas, “greater than 10% total body surface area burns, skull and facial fractures, and penetrating injury to the head and torso” (7,13,101).

Much of the interest in identifying predictors of serious blast injury stems from the idea that blast victims might harbor life-threatening internal injuries that are not apparent during initial assessment, such as blast lung. However, several studies show that this rarely happens (45,51,55). For instance, Alfici et al. in 2006 found that primary and secondary survey in the ED was only unable to identify the gravity of injuries in 2 of 63 severely injured blast victims in the Israeli terrorist bombing incidents they studied, both of whom suffered from significant distracting injuries at initial presentation (51). It is now generally believed that most patients with PBI of the lung develop associated signs and symptoms that become apparent shortly after presentation (45).

IMAGING FOR BLAST INJURIES

General Imaging Considerations

Generally, it is suggested in the literature that all critically ill blast victims receive routine x-ray studies of the cervical spine, chest, and pelvis, as well as additional imaging as needed for penetrating injury (12,102). These sources do not specifically address it, but presumably as with other trauma scenarios, cervical spine CT is preferable to plain films if there is a high likelihood of injury.

Chest Imaging

All blast victims thought to have PBI of the lung warrant a chest x-ray study, particularly if surgical intervention is required for concomitant secondary or tertiary blast injuries (7). As mentioned earlier, blast lung appears both on chest film and CT as bilateral fluffy infiltrates that resemble a “butterfly” or “bat wing,” areas of opacity that initially begin and extend out from the hilum but spare the margins of the lung (1,7). While the development of these abnormalities may be delayed, they are traditionally thought to develop within 2 h of blast exposure, while newer evidence (as mentioned here) suggests that delayed presentations are unlikely (71). Blast lung findings on chest x-ray study are usually abrupt in onset and rapidly clear; persistent pulmonary findings on imaging suggest a more significant underlying disease such as ARDS, pneumonia, or aspiration (44). Ecchymosis between intercostal spaces (called “zebra stripes” or “rib overprint”) may be encountered with injuries caused by large blast loads, where rib markings are visible on the injured lung compared with the unaffected side (1).

Although it is important to do a chest x-ray study in any patient suspected of having primary blast lung injury, it has not been found necessary to perform a screening chest x-ray study in asymptomatic patients. It was previously thought that a screening chest film could anticipate respiratory failure in asymptomatic patients, but this has never been proven in the literature (51). Furthermore, as mentioned here, it is no longer commonly believed that blast injury evolves over many hours, rendering this clinical question of anticipatory x-ray study less relevant (51,103).

Brain Imaging

Blast injuries to the brain are generally not visible with routine imaging and Bochicchio et al. in 2008 found that only half of the patients with this pathology have an abnormal CT of the head (66). Consequently, it is advisable to entertain a diagnosis of PBI of the brain based on clinical presentation, regardless of CT results (7,66).

Eye Imaging

CT is regarded as the gold standard to assess the blast-injured globe, particularly for penetrating trauma, but it has limitations; in cohort studies, the sensitivity of CT for clinically occult open-globe injuries ranged from 71% to 75% (60,104,105). Explosive debris is also often nonmetallic, which may further reduce sensitivity (60,106). That said, CT should always be performed before a possible magnetic resonance imaging (MRI) to assess the globe, as a metallic ocular foreign body may cause severe injury with MRI (22).

Ultrasound can also provide rapid assessment of the globe. A case series by Ritchie et al. in 2012 that assessed 29 patients with suspected intraocular blast injury in Afghanistan suggests that ultrasound may be as good as CT at detecting ocular blast injuries, although the CT used in the study was a lower resolution than that typically used in the United States or United Kingdom (60). Overall, ultrasound appears to be a cheap possible alternative to CT to assess ocular injury. Ritchie et al. report that limited use of ocular ultrasound for penetrating blast injury may be due to concerns about pressure on an open globe causing further damage, but they advise that the study may be appropriately performed with minimal pressure to the globe (60).

Multiple Casualty Incident Imaging

The primary difference between the management of patients in traditional trauma settings vs. a mass casualty setting is that laboratory tests and radiology studies are generally not freely available; consequently, in an multiple casualty incident (MCI) these services should be used wisely and kept free for victims with the most critical injuries (51).

Many of our recommendations for MCI management comes from Israel, where blast incidents and other MCIs are all too frequent. In the Israeli experience, few imaging studies are performed in the ED during an MCI (9). For instance, many recommend obtaining a chest x-ray study at key diagnostic junctures only, when a patient's clinical picture is not explained by physical examination alone (9). The idea of "minimal acceptable care" is utilized during an MCI, where presumed hemothorax or pneumothorax are treated empirically with a thoracostomy tube with plans for a later chest x-ray study unless the patient's condition does not improve or worsens (9). Similarly, CT use should also be limited for use in making critical management decisions, specifically for those with presumed intracranial injury with low or declining GCS, and for only select chest and abdominal injuries. All others should be admitted and obtain delayed studies as needed (9).

One of the more tedious tasks after blast injury is assessing numerous limb fractures and shrapnel penetrations in generally nonurgent trauma patients after MCI (9). For the most part, suspected fractures can be managed initially with coverage of open wounds, temporary splinting, antibiotic prophylaxis, and tetanus immunization until more thorough assessment is possible (9). Like other stable patients who are awaiting studies, these patients can also be transferred to the floor for delayed definitive care; during an MCI, this will assist in freeing much-needed resources in an overburdened ED (9).

While it is generally important to ration imaging and other studies during MCIs, it is also important to be wary of concealed injuries, particularly after suicide bombings, which tend to be associated with large numbers of penetrating metallic charges. One case report of a 14-year-old blast victim was notable for a nail found buried within the girl's brain, resulting from a completely concealed penetrating wound hidden within the mouth (76).

PROCEDURES

Chest Tubes

Blast victims who respond inadequately to intubation and mechanical ventilation, particularly in MCI situations where imaging is not readily available, should have bilateral chest tubes placed for presumed pneumothorax (51). Some providers go farther than this to suggest that all severely injured blast victims who require PPV should have bilateral thoracostomy tubes placed empirically, however, this practice has never been supported in literature (9).

Extreme caution must be taken in the event of tube thoracostomy. Contused lung, which characterizes blast lung injury, is friable by nature and can easily bleed (51). Even successful tube placement can lead to delayed lung injury through the form of pressure lacerations (51).

ED Thoracotomy

While ED thoracotomy is sometimes indicated for patients who present in extremis, this procedure is discouraged in those with severe blast injury to the lung, as the damaged lung parenchyma and associated bleeding will prevent successful aortic clamping (51,93). Alfici et al. suggest that in a blast victim who is a candidate for ED thoracotomy, blood in the endotracheal tube can predict severe blast lung and may dictate whether ED thoracotomy should be attempted (51). That said, an ED thoracotomy should not be performed during an MCI as it would likely represent “futile care” and misallocation of resources (9).

CONCLUSIONS

Blast injuries are more common than many realize. In addition, the increasing frequency of terrorist bombing attacks has led to a high volume of blast injuries previously seen in military conflicts only. These injuries are multidimensional and can affect every organ system. Particularly because of the ubiquitous risk of terrorism in today’s society, it is crucial for prehospital providers and emergency physicians to be familiar with the identification and management of blast injuries. Knowledge of serious blast injury and its associated signs and symptoms can also be incorporated into triage and discharge protocols guiding management of mass casualty events.

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ARTICLE SUMMARY

1.Why is this topic important?

Partially due to the increasing frequency of both domestic and international terrorist bombing attacks, it is prudent for all emergency physicians to be knowledgeable about blasts and the spectrum of associated injuries.

2.What does this review attempt to show?

Describe blast physiology, types of blast injuries associated with each body system, and manifestations and management of each injury.

3.What are the key findings?

Blast injuries are typically divided into primary to quaternary injuries. Different body systems are affected and managed differently. Despite previous dogma, multiple studies now show that tympanic membrane perforation is a poor predictor of other blast injury. More accurate indicators of serious internal blast injuries include injuries to four or more body areas, "greater than 10% total body surface area burns, skull and facial fractures, and penetrating injury to the head and torso." Contrary to previous belief, those with primary blast injury of the lung seem to manifest associated signs and symptoms shortly after presentation. Routine prophylactic bilateral chest tube insertion, previously advocated by some, is generally unnecessary in the absence of pneumothorax, but may be considered prior to air transportation of lung PBI victims.

4.How is patient care impacted?

In a mass casualty situation, those with isolated eardrum rupture may be discharged after a brief period of observation. As those who develop primary lung injury generally manifest symptoms earlier than previously thought, asymptomatic patients do not need admission to observe for development of pulmonary symptoms.