Bombings and Blast Injuries: A Primer for Physicians

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Abstract

Conventional weapons and explosives continue to be the most commonly employed instruments of destruction by terrorists worldwide. Such attacks are occurring with increasing frequency and ferocity. The effects of bombings and blast injuries are both physically and psychologically devastating. Explosions combine four mechanisms of injury. In addition to these causes of injury and death, crush injury, entrapment, and compartment syndrome magnify the devastation of blast trauma.

By recognizing the unique features of blast injuries and by prioritizing mass casualties to provide maximal benefit for the greatest number of patients, the physician will be better equipped to triage and stabilize these victims.

Bombings and Blast Injuries: A Primer for Physicians

Bombings and blasts have the potential to inflict multiple and devastating injuries to a large number of victims simultaneously and without warning. Because of the variety of circumstances involved in such an event (e.g., indoor vs. outdoor, size of the explosive charge, distance of victims from the explosion, presence of secondary debris and of biological or radiological contaminants, structural collapse), each bombing event is unique.

Also unique to blasts is the range of potential physiological consequences to different human organs and organ systems, ranging from tympanic membrane rupture to impalement, and from burns to traumatic amputations.

Worldwide, bombings are an increasingly effective and frequent terrorism tool. Explosions are the most common cause of casualties associated with terrorism.[1-5] The 1995 Oklahoma City bombing, the 2004 Madrid train bombing, and the explosions of September 11, 2001, in New York City and Washington, DC, and the 2005 London subway bombings have demonstrated the capacity of bombings and blast injuries to kill and to terrify. According to Dennis C. Blair, Director of National Intelligence, "Conventional weapons and explosives will continue to be the most often used instruments of destruction in terrorist attacks."[6]

While biological and chemical weapons are often mentioned and are much feared as terror tools, it is bombs that have actually produced the majority of injuries, deaths, and societal disruptions in the modern era.[1] In addition to deliberately detonated explosions, there are also industrial accidental explosions that occur with regularity at factory and mining operations, in fuel transportation and storage, and in grain elevators.

Because of the constant risk of civilian incidents and the increasing risk of terrorist attacks, health care providers must become familiar with the characteristics of explosives and of explosions and of the nature of the injuries they may inflict.

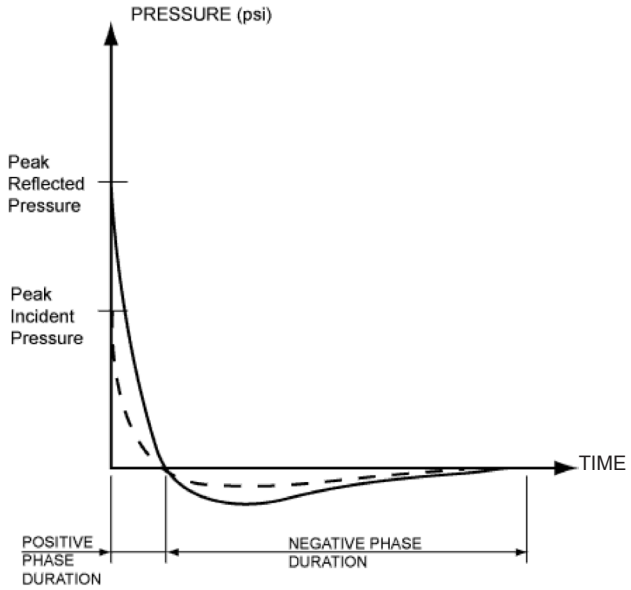
Blast Physics

Explosives cause the rapid conversion of a solid or liquid to a gas, resulting in a sudden release of energy. Explosives are categorized as either high-order explosives (HE) or low-order explosives (LE).[2]

HE produce a supersonic over-pressurization shock wave. Examples of HE include ammonium nitrate fuel oil (ANFO), TNT, C-4, semtex, nitroglycerin, and dynamite.

Air is rapidly compressed, and then, as the blast wave passes, the air is temporarily under-pressurized before returning to the ambient pressure level. The characteristic HE blast wave is presented graphically in Figure 1. HE detonate quickly, producing a blast wave that rapidly expands from the detonation point, filling the involved space within a fraction of a second with the supersonic over-pressurization wave.

Figure 1: Blast Overpressure Wave



HE exert their destruction by several mechanisms: 1) the blast pressure wave, 2) fragmentation, 3) blast wind, 4) incendiary thermal effect, 5) secondary blast pressure, and 6) ground and water shocks for explosions that occur under ground or water.

Fragmentation effect occurs from projectiles that are either included within the container, projectiles that are created by the destruction of the container itself, or from those propelled objects from the surrounding environment and target. The motion of air generated by the blast waves creates blast wind.

Secondary blast pressure effects result from the reflection of blast waves off surfaces, magnifying their effect, especially in enclosed spaces. Because ground and water are relatively non-compressible media, underground and underwater explosions transfer more energy to the body than do explosions in the air.

Four effects produce injuries from blasts: spalling, implosion, shearing, and irreversible work.[2] Spalling is the result of a shock wave moving through tissues of different densities, leading to molecular disruption. Entrapped gases in hollow organs compressing and then expanding result in visceral disruption by implosion. Shearing is due to tissues of different densities moving at different speeds and leading to visceral tearing. Forces exceeding the tensile strength of the tissue cause irreversible work, and this is currently being researched as the most likely of all of these mechanisms of injury in blasts.

In contrast, LE produce a subsonic explosion without an over-pressurization wave. Examples of LE are gunpowder, pipe bombs, and petroleum-based bombs such as Molotov cocktails, or aircraft improvised as guided missiles. Rather than detonating, LE release energy more slowly, by the process of deflagration. In deflagration, a substance is heated until it burns away rapidly. Thus, LE are generally less destructive than are HE. Incendiary thermal effects differ between HE and LE: while HE produce higher temperatures for a shorter period of time resulting in a fireball at the time of detonation, LE have a longer thermal effect and can cause secondary fires.

Categories of Blast Injuries

HE blast injuries are categorized as primary, secondary, tertiary, and quaternary injuries, and these may occur individually or in any combination.[4,5] The characteristics of blast injury are described in Table 1.

Table 1: Characteristics of blast injury

Category	Characteristics	Body Part Affected
Primary	Unique to HE, results from the impact of the over-pressurization wave with body surfaces.	Gas filled structures are most susceptible - lungs, GI tract, and middle ear.
Secondary	Results from flying debris and bomb fragments.	Any body part may be affected.
Tertiary	Results from individuals being thrown by blast wind	Any body part may be affected.
Quarternary	All explosion-related injuries, illnesses, or diseases not due to primary, secondary, or tertiary mechanisms. Includes exacerbation or complications of existing conditions.	Any body part may be affected.

A primary blast injury is caused by the direct effect on tissue of the blast overpressure wave. A primary blast injury affects air-filled structures most importantly, such as the lung, ear, and hollow viscus of the gastrointestinal tract.[6,7]

Flying objects that strike victims cause a secondary blast injury. Such injuries are penetrating trauma and fragmentation injuries.

Tertiary blast injuries are a feature of high-energy explosions only and occur when people fly through the air and strike other objects.

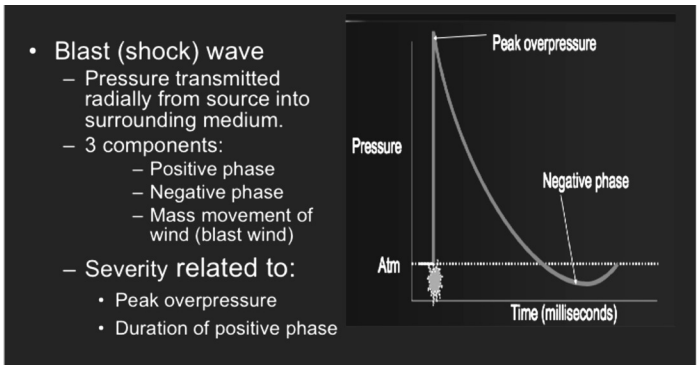
Miscellaneous or quaternary blast injuries encompass all other injuries caused by explosions. This includes burns, crush injuries, toxic inhalations, asphyxia, and exacerbations of victims' underlying medical conditions. The four categories of blast injuries are depicted graphically in Figure 2.

Figure 2: Categories of Blast Injuries

Primary Blast Injuries

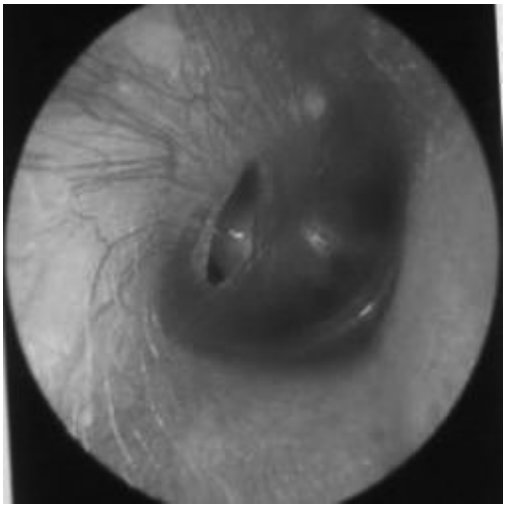
The tympanic membrane (TM) is the organ that is most often damaged by blast injuries, sustaining injury at as low as five pounds per square inch (psi) above atmospheric pressure (1 atm is equal to 14.7 psi, or 760 mm Hg).[3,6] At higher pressures, the ossicles of the middle ear can be dislocated. As can be seen in Figure 3, pressures gradients of 56 to 76 psi (3.8 to 5.2 atm) are needed to cause damage to other organs. Thus, in the absence of rupture of the TM, primary blast injuries on other air-containing organs are less likely. For example, in the Madrid train bombings, of 17 critically ill victims with lung injuries from the blast, 13 had ruptured TMs and four did not.[3,7,8] A graphic depiction of TM rupture is shown in Figure 4.

Figure 3: Effect of peak pressure



The lung is the second most common organ that is injured by overpressure.[2,4,5] Injury results in hemorrhage, pulmonary contusion, pneumothorax, hemothorax, pneumomediastinum, and subcutaneous emphysema. Pulmonary contusion results in the classic "butterfly" pattern of bilateral hilar pulmonary edema seen on x-ray, Figure 5. Acute gas embolism (AGE) is also a form of pulmonary barotraumas that requires special attention. Air emboli most commonly occlude blood vessels in the brain or spinal cord. While body armor protects personnel from most ballistic projectiles to the torso, it does not prevent the lung barotrauma of primary blast injury.[6]

Figure 4: Tympanic membrane perforation

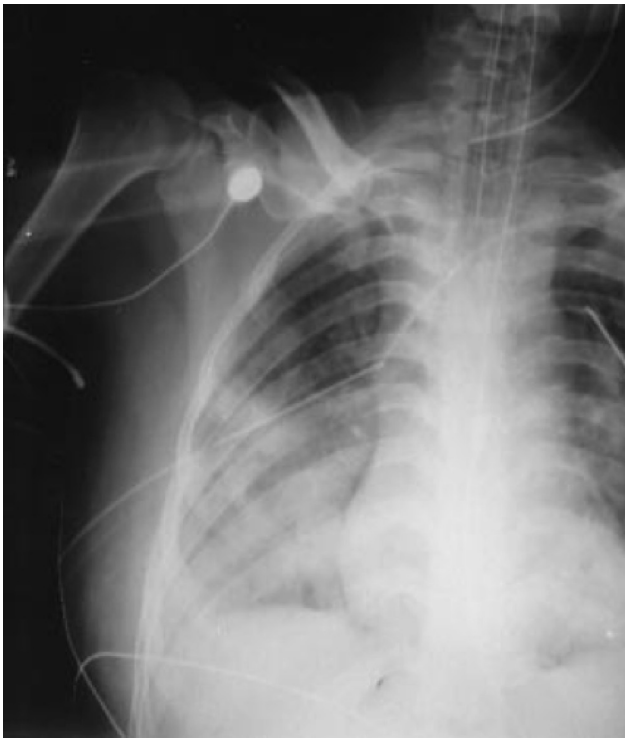


The colon is the hollow viscus most frequently injured by a primary blast injury.[5] Rupture of the colon and mesenteric ischemia or infarct leading to delayed rupture of the large or the small bowel may occur.

Eye injuries from the primary blast include globe rupture, retinitis, and hyphema.[9]

Primary blast injuries to the brain include concussion and barotrauma caused by AGE. The extent of injury from an explosion is affected by the magnitude of the device, the distance from the explosion, whether the medium transmitting the over-pressure is air, water, or solid, and the environment (i.e., open or closed).

Figure 5: Blast lung x-ray



Secondary Blast Injuries

The most common cause of death in a blast event is secondary blast injuries, which result from the effects of projectiles.[1] Projectiles may include objects that were intentionally included in the device or those that were propelled as part of the blast effect. Such objects include nails, bolts, nuts included in the blast mixture, military shrapnel, flying glass, and human parts. Flying debris may injure individuals far from the blast. In the 1998 terrorist bombing of the U.S. Embassy in Nairobi, Kenya, for example, victims up to two kilometers away were injured by flying glass.[6] Penetrating injuries are much more common than primary blast injuries, and they represent the leading cause of death in blast victims, except in the case of major building collapse.[4] The most common types of secondary blast injuries are trauma to the head, neck, chest, abdomen, and extremities in the form of penetrating and blunt trauma, fractures, traumatic amputations, and soft tissue injuries. Foreign bodies follow unpredictable paths through the body and may have only mild external signs. Thus, there should be a low threshold for imaging studies in such injuries. All of these wounds are considered to be contaminated, and they should not be closed primarily.

Approximately 10% of blast survivors will have significant eye injuries, often perforations from high-velocity projectiles, especially glass. Secondary eye injuries include blindness and ruptured globes.[5,8]

Tertiary Blast Injuries

Tertiary blast injuries are caused when the victim's body is thrown into another object by the blast winds of the explosion. Victims may also tumble along the ground, resulting in blunt and penetrating injuries. The most common tertiary injuries are fractures and closed head injuries.[1-6] Other injuries include broken, dislocated, or even amputated extremities. The extent of injuries from this mechanism also depends on what the victim strikes in the environment; injuries can range from simple bruises and abrasions to impalements.

Quaternary Blast Injuries

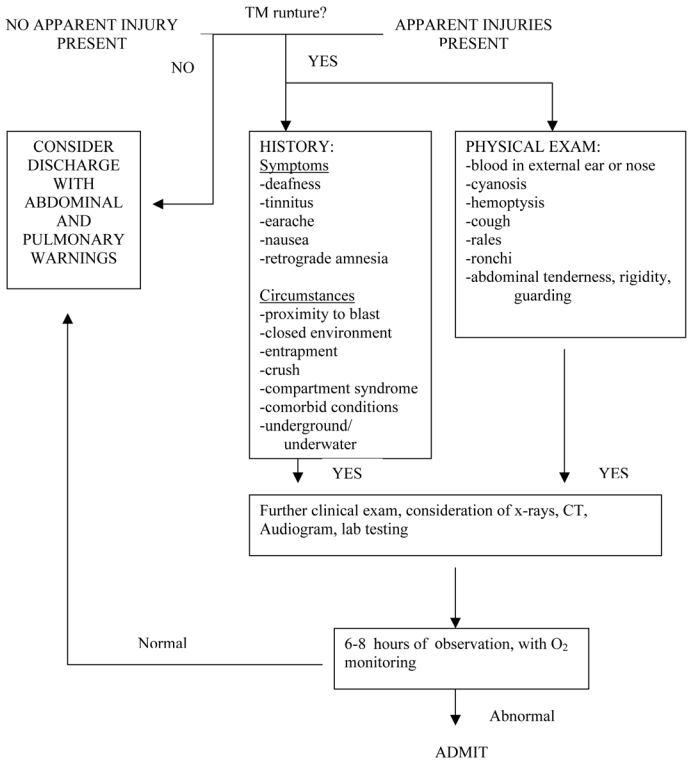
Quaternary injuries include all those injuries not due to any of the above mechanisms. These include burns, inhalation injuries, toxic exposures, poisoning from carbon monoxide, and crush injuries. Quaternary injuries also include exacerbation of chronic medical conditions, such as asthma, chronic obstructive pulmonary disease, and angina.[1,6,10]

Management

Causes of early mortality due to blast injuries are, in decreasing order: multiple trauma, head trauma, thoracic injury, and abdominal injury.[5,6,9] As with any mass casualty incident, effective triage is essential to optimize outcomes. Victims with a reasonable chance for survival receive immediate medical attention. In civilian settings, terrorist attacks tend to have a bimodal distribution of mortality — high immediate death rates followed by low early and late rates. Those victims with lesser injuries receive delayed care, and those with a poor prognosis receive minimal care. Up to 75% of victims self-refer to hospital, arriving by private transportation.[6] Several factors contribute to the blast victims' needs exceeding available resources. Large numbers of patients may make rapid triage impossible and may exceed responder treatment capabilities and cause delay in transport to hospitals.

Patients are divided into urgent and non-urgent categories, and they receive initial resuscitation while other victims continue to arrive. Definitive, optimal care is delayed until victims stop arriving.[3] Expectant management is appropriate for those who are unlikely to survive, such as patients with 100% body surface area (BSA) burns and those in cardiac arrest.[4,11]

Figure 6: Algorithm for the evaluation of blast injuries



Management of blast injuries begins with attention to airway, breathing, and circulation. Ventilatory and circulatory support is initiated, and, if possible, a rapid history is obtained. Important historical details of the explosion include whether it occurred in an open, a closed, or a semi-confined space. Blasts in vehicles, mine shafts, buildings, and subways are associated with greater morbidity. Structure collapse also markedly increases mortality. In a military scenario, whether the victim had on body armor is also pertinent, as body armor increases the severity of primary blast injury.[5,6] History should assess for the presence of tinnitus, deafness, or earache, nausea, vertigo or

retrograde amnesia. The patient should be asked about shortness of breath or chest pain. Other important questions regard eye pain, abdominal pain or urge to defecate, nausea, or blood in the stool. Physical examination should evaluate for blood in the external auditory canal and ruptured tympanic membrane.

Fluid infusion should be initiated to achieve a palpable pulse at a rate of less than 120 beats per minute, a systolic blood pressure of 100 mmHg, and a return of normal mentation.[5] An algorithm for the rapid assessment of blast victims has been proposed, Figure 6.[4,5] Cyanosis, hemoptysis, ronchi, or rales are markers for lung injury. The abdominal exam should assess for tenderness, rigidity, or guarding. The presence of any of these history or exam findings should result in a thorough clinical examination and at least eight hours of observation.

Pulmonary Injuries

Pulmonary blast injury (PBI) has the highest mortality of primary blast effects. Lung tissue is especially sensitive to barotrauma because of the extensive tissue-air interfaces involved. An over-pressure of 40 ATM will lead to lung damage.[6,11] The incidence of pulmonary blast injuries is less than 10% of casualties seen and between 30 and 60% of admitted casualties.[5] Pulmonary injury increases with enclosed space events. Injuries include pulmonary contusions, pneumothorax, interstitial emphysema, pneumomediastinum, and subcutaneous emphysema. The most common lung injury associated with a blast wave, pulmonary contusion, is manifested by alveolar hemorrhage and interstitial edema. Such contusions, resulting in micro-hemorrhages and perivascular and peribronchial disruption, may occur as late as 48 hours after the explosion.

PBI should be suspected in a patient with the diagnostic triad of dyspnea, bradycardia, and hypotension and with wheezing or hemoptysis following an explosion. Other diagnostic clues to PBI are hypopharyngeal petechia, hypoxia, cyanosis, apnea, decreased breath sounds, and hemodynamic instability. X-ray evidence of PBI may present within hours of the explosion, and it usually resolves within a week. A plain anterior-posterior chest x-ray is usually diagnostic for pulmonary barotraumas, producing a characteristic "butterfly" pattern, Figure 5. Such x-rays must also be inspected for the presence of subcutaneous emphysema, fractured ribs, hemopneumothorax, and pneumomediastinum.

Supplemental high-flow oxygen is provided for hypoxemia, either by mask or by endotracheal intubation, if required. Ventilator-associated barotrauma and systemic air embolism are minimized by limiting peak inspiratory pressures (< 40 cm H20), by permissive hypercapnia, and by judicious use of positive pressure ventilation. Chest tubes are inserted as needed for pneumothoraces. Extracorporeal membrane oxygenation (ECMO) has also been used for severe Blast Lung Injury (BLI).[2]

Arterial gas embolism (AGE) is suggested by sudden blindness, focal neurologic deficit, chest pain, or sudden loss of consciousness. Physical examination may show retinal arterial gas bubbles on fundoscopy, and the victim's skin may be mottled. Focal neurological deficits and dysrhythmias may also be present. Immediate treatment for AGE is supplemental oxygen and positioning the patient in the left lateral decubitus position with the head down. Definitive care is treatment in a hyperbaric chamber.

While BLI results in significant scene mortality, approximately 70% of critically injured patients who are admitted with BLI survive, many with near-normal lung function at one year.

Gastrointestinal Injuries

Abdominal injuries include abdominal hemorrhage and abdominal organ perforation and laceration. Blast injury to the gastrointestinal (GI) tract should be suspected in any victim with signs and symptoms that include abdominal pain, rebound, guarding, absent bowel sounds, nausea, vomiting, vomiting blood, rectal pain, testicular pain, or with unexplained hypovolemia.[9]

The colon is the most common site of hemorrhage and perforation due to blast trauma. The clinical signs of injury may be evident immediately, or they may be delayed up to 48 hours and as late as 14 days after the blast.[4] Solid organ lacerations and testicular rupture may also be seen but are less common.

Diagnostic peritoneal lavage (DPL), ultrasound, plain x-ray, and CT are all used in imaging of abdominal blast injury. Plain films may show penetrating foreign bodies and free intraperitoneal air. CT may reveal free air, solid organ injury, hemoperitoneum and retroperitoneal injuries, and mesenteric injury, but it has poor sensitivity in identifying hollow viscus injuries.[3,5,6,10,11]

Neurological Injuries

Severe head injury is the chief cause of mortality in blast victims.[1] The effect on the central nervous system of an overpressure wave includes diffuse axonal injury, skull fractures, coup- and counter-coup injuries, and subarchnoid and subdural hemorrhage. Primary blast waves can cause concussions or mild traumatic brain injury (MTBI), even without a direct blow to the head. Penetrating brain trauma is also seen.

Symptoms of traumatic brain injury (TBI) include headache, nausea, confusion, fatigue, depression, and amnesia, as well as fixed neurological deficits.

Patients suspected of sustaining neurological injury should undergo urgent CT of the brain as well as cervical spine imaging.

Severe head injuries require ventilatory support and neurocritical care. Attention to cerebral protection includes maintenance of cerebral perfusion pressure, body temperature, neuromuscular blockade and sedation, and cervical spine control. Additionally, glucose and seizure control and DVT prophylaxis are addressed.

Auditory Injuries

The auditory system is most sensitive organ to blast injury.[1-7] Overpressure of 5 psi is required to perforate the tympanic membrane, with damage to the cochlea and ossicles occurring at lower pressures.[1-3,6] By comparison, pressure gradients of 56 to 76 psi (3.8 to 5.2 atm) are needed to damage to other organs. Thirty-five percent of survivors in the Oklahoma City bombing reported auditory injury.[1-4] While TM perforation is considered to be an indicator of other, more serious, injuries, it is neither highly sensitive nor specific; TM perforation may be found in victims with severe pulmonary, intestinal, or other injuries, or it may be found in isolation. Its presence does not indicate that more serious blast injuries exist. In an Israeli study of 11 terrorist attacks that caused 145 fatalities and 647 injuries, 142 had isolated TM perforation, 18 had isolated BLI, and 31 had both. No patient with isolated TM perforation later developed BLI.[6]

It has been noted that external ear amputation due to primary blast injury is usually associated with other non-survivable injuries.

Sensorineural and conductive hearing losses are both possible. In addition to hearing loss, symptoms of ear damage include bleeding from the external ear canal, ear pain, tinnitus, and vestibular dysfunction with vertigo. Fifty percent to 80% of ruptured tympanic membranes heal spontaneously, while sensorineural hearing loss is often permanent.[6,7,11,12]

Eye Injuries

Most eye injuries caused by blasts are due to flying debris. While the eye represents only a tiny amount of total body surface area, eye injuries can account for 2% to 16% of bombing injuries.[3,9,11] Flying glass was responsible for most of the eye injuries in the Oklahoma City bombing.[11] One-half of patients with open globe injuries had head injuries as did one-third of patients with any eye injury.[8,9,11]

Symptoms of ocular blast injuries include foreign body sensation, pain or irritation, change in vision, and periorbital swelling. Ophthalmology consultation is appropriate for suspected globe injuries, deep corneal foreign bodies, orbital fractures, retinal detachments, hyphemas, intraocular foreign bodies, corneal burns, and deep eyelid burns and lacerations.

Orthopedic Injuries

Orthopedic injuries may occur by any of a variety of blast effects: 1) blast waves may lead directly to fractures, 2) projectiles may penetrate and injure extremities, 3) bodies tumble and extremities strike fixed objects in the blast environment, and, finally, 4) extremities are crushed, burned, and neurovascularly compromised.

Traumatic amputations due to primary blast injury have a dismal prognosis because victims have been exposed to extreme overpressure.[3] In one series, 11% of blast fatalities had traumatic amputation, and their survival rate was 1%.[9,12] In the Oklahoma City bombings, one-third of survivors sustained musculoskeletal injuries, and one-third of these victims had multiple fractures.[11]

There are several principles that guide the care of orthopedic blast injuries. Significant injuries may result from small entrance wounds, and fragments may not travel in straight lines. Therefore, any victim with entrance wounds in the thighs, perineum, or buttocks should be suspected of harboring an intra-abdominal injury. A hematoma in proximity to an arterial structure may indicate a vascular injury, and compartment syndrome and rhabdomyolysis can complicate musculoskeletal injuries. Tetanus prophylaxis and post-exposure antibiotics are indicated, and these wounds are at high risk for infection and gas gangrene.

Special Situations

Pregnant patients, older, and pediatric blast victims require special mention.[1,2,6] Direct injury to the fetus is not common due to its protection within amniotic fluid. The blast wave can cause placental abruption, however. For this reason, women in the second or third trimester should have fetal monitoring. A Kleihauer-Betke test is also indicated, and women may require administration of Rh immunoglobulin. A positive test requires mandatory pelvic ultrasound, fetal non-stress test monitoring, and obstetrics/gynecology (OB/GYN) consultation.[6]

When children are victims of blast injury, the history of the event and of the patient's complaints may be difficult to obtain. Pulmonary contusion is one of the most common injuries from blunt thoracic trauma in children.[2,6] The injury may not be clinically apparent initially and should be suspected when abrasions, contusions, or rib fractures are present. A chest x-ray is essential in diagnosis especially when blast lung is suspected. Pediatric blast victims may require specialized resuscitation equipment and transfer to regional pediatric trauma facilities.[1,2,6] In the Oklahoma City bombing, which involved a childcare center, there was a high incidence of traumatic amputation, fractures, and head injuries. Experience in Israel has shown that penetrating injuries of the trunk are more common in children who are victims of vehicular bombings than children who have other types of trauma. It has also been noted that children who are victims of terrorism require more ICU resources, have higher Injury Severity Scores, and have longer hospital stays than children who survived traumatic events unrelated to terrorism.[11]

Like children, the elderly are also at a higher risk of mortality, and their hospital stays may be longer and more complicated than other patients.[6] Orthopedic injuries are more prevalent, and blunt chest trauma is of greater significance. Further, decontamination methods may need modification due to limited mobility. Decontamination of medical equipment, such as wheelchairs, walkers, and other walking aides, may also be needed.

Communications difficulties after blast injuries include language barriers and interaction with hearing-impaired patients. Groups of victims who speak a multitude of different languages may complicate effective triage. Interaction with the deaf, hard-of-hearing, newly-deafened, and the deaf-blind are obstacles as well. The history of the event as well as the individual history for the patient may be difficult to obtain. On-scene translation services including medical interpreters, sign language, and telephone translation services should all be available.

Because bombings are events that occur with little or no warning, that result in disruptions of unknown duration, and that create a real or potential threat to personal safety, they have the potential to cause profound and lasting emotional impact. Psychological sequelae among victims of an explosive event include anger, frustration, helplessness, and a desire to seek revenge. Responders to bombings are encouraged to promote a sense of safety, calm, connectedness, and hope.[1]

Summary

Conventional weapons and explosives continue to be the most frequently used instruments of disruption and destruction by terrorists worldwide. Such attacks are occurring with increasing frequency and destructive force. The effects of bombings and blast injuries are both physically and psychologically devastating. Explosions combine four mechanisms of injury that may be combined, adding to the complexity and lethality of injury to victims. In addition to the devastating effects of the primary blast wave and the ensuing flying projectiles, crush injury, entrapment, and compartment syndrome magnify the inflicted injuries.

By recognizing the unique features of blast injuries, the physician will be better equipped to triage these patients rapidly and to stabilize them. By understanding the effects of explosions on each major organ system, the practitioner is ideally prepared to identify and treat these devastating wounds and to save life and limb.

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