

CONVENTIONAL EXPLOSIONS AND BLAST INJURIES

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Objectives

- Describe the mechanisms of injury associated with conventional explosions.
- Outline triage strategies and markers of severe injury in patients wounded in conventional explosions.
- Explain the general principles of critical care and procedural support in mass casualty incidents caused by conventional explosions.
- Discuss organ-specific support for victims of conventional explosions.



Case Study

Construction workers are using an acetylene/oxygen mixture to do some welding work in a crowded nearby shopping mall. Suddenly, an explosion occurs, shattering windows in the mall and on the road. The acetylene tank seems to be at the origin of the explosion. The first casualties arrive at the emergency department in private cars and cabs. They state that at the scene, blood and injured people are everywhere.

- What types of patients do you expect?
- How many patients do you expect?
- When will the most severely injured patients arrive?
- What is your triage strategy, and how will you triage these patients?
- How do you initiate care in victims of conventional explosions?

I. INTRODUCTION

Detonation of small-volume, high-intensity explosives is a growing threat to civilian as well as military populations. Understanding circumstances surrounding conventional explosions helps with rapid triage and recognition of factors that contribute to poor outcomes. Rapid evacuation of salvageable victims and swift identification of life-threatening injuries allows for optimal resource utilization and patient management.

II. CHARACTERISTICS OF BLASTS

A. Epidemiology

Blast injuries can occur as a result of handling petroleum derivatives, accidents during the manufacture or transport of dangerous goods, or terror-related events. Currently, blast injury is by far the most common terror-related event. It is estimated that 98% of terror-related operations include explosives. Explosives are legally produced in large quantities: 2.4 million tons of various explosives are produced officially each year. Moreover, how-to information about bomb-making is readily available on the Internet. Explosive devices usually require very minimal technology; they are scalable from 100 g to 1 ton and are easy to guide and deliver by mail, foot, car, truck, aircraft, ship, or train.

From 1973 to 1999, authorities recorded 45,573 criminal bombings in the United States, an average of 5 bombings per day. The incidence of bombings has almost doubled in the last 10 years, from 2,000 per year in 1999 to 3,445 in 2006. Terrorist bombing targets include individuals, private and commercial groups, and governmental figures. In 2001, excluding the September 11 deaths and injuries, casualties included 81% civilians, 17% US government workers, 2% military personnel, and 0.3% business employees. In 2001, the US Department of State counted 348 attacks against US concerns; 74% involved bombs. Excluding the events of September 11, 2001, there were 830 bomb deaths and 4,063 bomb-related injuries in the US over 10 years. This represents the second highest cause of disaster-related lethality over 10 years after flooding, and it exceeds deaths by lightning (712), tornadoes (437), earthquakes (276), and hurricanes (224) as causes of disaster-related mortality.

Bombings may be mixed with other violent activities, as illustrated in the 1999 Columbine High School shootings in Littleton, Colorado. Ninety-nine bombs were recovered from the high school after 2 students shot and killed 12 students and 1 teacher, wounding 21 others, before killing themselves. Delayed or secondary explosions can also add new casualties and delay and jeopardize medical intervention, as illustrated by the 2005 London bombings. In this terrorist attack, 56 people were killed, including the 4 suicide bombers, when 3 bombs exploded within 50 seconds of each other on 3 commuter trains, and a fourth bomb exploded on a bus nearly an hour later.

The history of modern terror-related bombings can be traced over several periods. In the 1980s, the initial Irish Republican Army attacks usually included advance warnings to limit casualties.

The 1990s were characterized by more deadly tactics, including Irish Republican Army secondary bombings, solo suicide bombers, and more technologically complex explosive weapons. More recent attacks have been aimed for the maximum number of casualties and target defenseless civilians. During this period, explosives have been more powerful and the addition of adulterants more prevalent. Adulterants include mechanical objects (shrapnel, nuts, bolts, glass) or chemical/biological agents (cyanide, hepatitis virus, HIV, nitrate, super-warfarin, chlorine, ammonia). The goal of adulterants is to increase the lethality and total number of injuries per explosion. After 1998, even more complex patterns developed, including multiple bombs and multiple, often suicidal, synchronized attacks. The synchronized multiple bombs were often aimed at soft but vital targets such as transportation systems (eg, simultaneous bombings of the US Embassy buildings in Nairobi and Dar es Salaam in 1998, as well as the 2004 Madrid and 2005 London coordinated train bombings). This evolution in terror bombings is characterized by an increasing success rate for the bombers and an increased number of casualties.

B. Physics

An explosion is the rapid release of thermal energy by a chemical reaction. This is caused by a very rapid consumption of fuel that leads to gaseous end products, and the reaction produces large amounts of energy, high temperature, and excessive pressure. The perfect gas law describes all explosions:

$$PV = nRT$$

where P = pressure; V = volume; n = number of moles; R, a constant = 8.31 USI; T = temperature.

Explosives can be classified as low or high according to their initial shock wave (**Table 7-1**). Such descriptors do not necessarily refer to the amount of explosive but rather to its effect. In conventional explosions, the total mass of the explosive is detonated in a single moment, and the blast wave radiates from a single point in all directions until it encounters an obstacle. In an enhanced explosion, there is a 2-stage detonation. First, a small charge disperses the explosive, and then the disseminated material is detonated. This leads to a larger impact zone and a longer positive pressure phase. Enhanced-blast explosives cause more severe damage than conventional explosives.

Different materials explode in different ways. Explosives are compared using the concept of TNT equivalent, which corresponds to the amount of TNT required to produce the peak overpressure of the blast wave produced by a specified explosive. For example, C4 plastic explosive has a TNT equivalent of 1.37, meaning that 1 kg of C4 produces the same peak overpressure as 1.37 kg of TNT.

1. Blast Waves

Explosions produce several effects: blast waves, blast winds, and thermal injury. Blast waves occur when the compression of air in front of the pressure wave heats and accelerates air molecules, leading to a sudden increase in overpressure and temperature, which are transmitted into the surrounding environment as a propagating shock wave known as the blast wave (**Figure 7-1**). Blast waves travel at supersonic speeds, between 4,000 and 8,000 m/s in air and even faster in water

or metal. This wave is very thin, measuring between 50 and 500 μm thickness. A single kilogram of dynamite can yield overpressure effects measured at more than 1,200 kPa (174 psi) at 1 meter and 280 kPa (40.6 psi) at 2 meters. The blast wave expands in all directions unless reflected or channeled by a structure. With expansion in 3 dimensions, intensity decreases in relation to the distance by a power of 3. For example, in open space, doubling the distance decreases the blast wave and reduces overpressure by a factor of 8.

The 3 main factors characterizing the blast wave are the peak rate of pressure rise, the peak pressure, and the duration of pressure rise. Blast waves are reflected on surfaces, and the reflected wave can add to the pressure of the blast wave. If an explosion occurs inside a closed space, such as a vehicle, the overpressure phase is followed by a quasi-static overpressure due to the expanding gases, and no vacuum phase occurs. Because water, human bodies, and metallic structures are almost noncompressible, blast wave transmission in such structures will dissipate much less energy than it would in air. Therefore, when an explosion occurs in water or is transmitted by water, there is less dampening with distance, and injuries are more severe. Induced noise levels can be extremely high, with a blast wave of 5 kPa (0.7 psi) corresponding to a noise level of 140 dB.

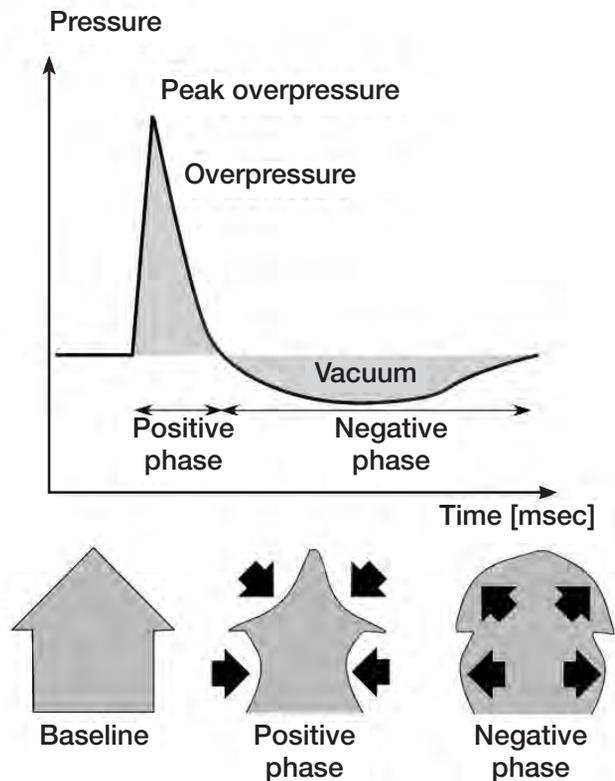
Table 7-1. Classification of Explosives

Class	Low Explosives		High Explosives
	Gas	Powder	Explosive
Examples	Fuel, methane, napalm, fuel, Molotov cocktail	Gunpowder	Military explosives, TNT, Semtex, ANFO, dynamite
Overpressure	Weak	Moderate	Strong
Wave	Wind	Wind	Shock
Speed	Subsonic	Subsonic	Supersonic
Reaction	Combustion	Deflagration	Detonation

Abbreviation: ANFO, ammonium nitrate and fuel oil.

2. Blast Wind

Blast wind stems from the gas generation and expansion during the explosion. It is a displacement of air that can hurl people, objects, and pieces of collapsing structures. The speed of a blast wind is much slower than the speed of sound, and there is no negative pressure phase after a blast wind. An overpressure of 230 kPa (33.4 psi) corresponding to detonation of 1 kg of TNT generates a blast wind of over 240 km/h measured near the point of origin.

Figure 7-1. Blast Wave Physics: Friedlander Blast Wave

^aOriginally described by Friedlander, a blast wave consists of a short, high-amplitude overpressure peak followed by a longer depression phase. Injury potential depends on the wave's amplitude as well as the slopes of its increase and decrease in pressure. X-axis refers to time and Y-axis refers to pressure.

III. EFFECTS OF A CONVENTIONAL EXPLOSION

A. Factors Affecting the Nature and Extent of Injuries

The mechanism of injury may be predicted by an individual's distance from a detonation. Fractures, particularly of the skull and extremities, burns, and penetrating injuries to the head or torso are common in conventional explosions. Because suicide attackers frequently carry explosive devices on their backs or chests, it is likely that victims in closest proximity will absorb high-energy penetrating missiles to the head or the mid-portion of their bodies. Victims at greater distance from such conventional explosions are partially protected by manmade barriers or the bodies of other victims and are more likely to sustain penetrating injuries to the extremities.

Injuries seen in greater proximity to an explosion include burns, blast injury, fragment injury, contusions, superficial lacerations, and relatively minor concussive injury. The sizes of the zones where various types of injuries occur can be predicted by the amount of explosive used. For example, a suicide bomb containing 1-10 kg of TNT has a lethal blast range of 5 meters and a range

for serious injury of 10-30 meters. In contrast, the lethal blast radius for a car containing 455 kg of TNT is 60 meters, with a serious injury range of over 500 meters. Massive explosives, such as fuel trucks, increase the lethal blast range to 150 meters, with the range for serious injury extended to approximately 2,000 meters (Table 7-2).

Table 7-2. Explosive Characteristics and Injury Ranges^a

Bomb	Explosive (kg TNT equivalent)	Lethal Blast Range (m)	Serious Injury Range (m)
Suicide bomb	1-10	5	10-30
Compact car bomb	227	30	450
Sedan car	455	60	530
Passenger car	1,180	80	840
Panel truck	4,545	91	1,150
Fuel truck	13,636	140	1,980
Semitrailer	27,273	180	2,130

^a Reproduced with permission from Centers for Disease Control and Prevention.

The blast wave created by an explosion will affect injuries suffered by a victim as it produces an instantaneous rise in pressure that is several times the atmospheric level, followed by an exponential decline to a subatmospheric degree of pressure. When a blast wave encounters tissue, the resulting stress gradient leads to tissue disruption, which is particularly common at tissue interfaces. For example, compression and decompression at the alveolar level causes tensile stresses that lead to microvascular injury, hemorrhage, edema, alveolar rupture, and changes in alveolar membrane permeability.

Distance from an explosion determines the amount of energy absorbed from penetrating missiles and is the single most important influence on survival. Survival is also affected by the physical configuration of the explosion scene and such factors as the location of the victim and the presence of physical partitions such as passenger seats. When an explosion occurs within a limited space—for example, in a passenger vehicle—the reflection of the blast wave is amplified and the injury to occupants is increased. Blast wave reflection and magnification is less likely in open settings such as restaurants, street scenes, and outdoor markets.

Whether an explosion occurs in an open or a confined space also significantly affects the outcomes of the related injuries. In data obtained from terrorist bombings, victims exposed to explosions in a confined space have an increased mortality (15.8% versus 2.8% in open spaces), higher Injury Severity Scores (11 versus 6.8), higher incidence of primary blast injuries, and, due to the containment of the fireball, more extensive burn injuries (Table 7-3).

Table 7-3. Prognostic Factors of Casualty Outcome After Bombing^a

Magnitude of explosion
 Building collapse
 Triage accuracy
 Time interval to treatment
 Indoor versus open air
 Urban versus isolated setting
 Anatomic injuries
 Immediate presence of surgeons

^aReproduced with permission from Frykberg ER. Medical management of disasters and mass casualties from terrorist bombings: how can we cope? *J Trauma*. 2002;53(2):201-212.



Victims exposed to explosions in a confined space typically have increased mortality, a higher incidence of primary blast injuries, and more extensive burn injuries.

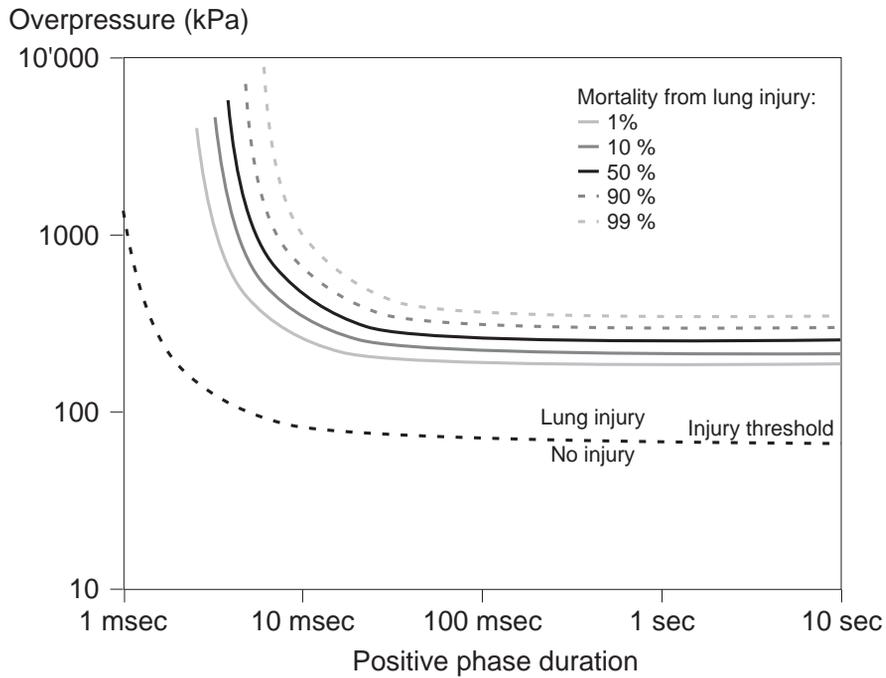


Injuries are further influenced by the amount and type of explosive force. The auditory system is affected with overpressure as low as 14 kPa (2 psi), and 100 to 400 kPa (14.5 psi to 58 psi) will induce eardrum perforation in 50% of cases. Pulmonary damage occurs in 50% of victims exposed to 500 kPa (72.5 psi), whereas intestinal perforation occurs with much higher pressures. Exposure to pressure levels greater than 550 kPa (79.8 psi) is lethal in more than 50% of cases (**Figure 7-2** and **Figure 7-3**).

B. Dimensions of Blast Injury

Injuries inflicted by explosive devices are multidimensional: at least 4 separate mechanisms play a role – primary, secondary, tertiary, and miscellaneous injuries. Primary blast injury results from the dissipation of energy into the tissues. For example, when a blast hits the thorax, the blast load deforms the thorax and crushes the underlying tissues. The damaging wave propagates in the thorax. This creates a micromotion of the thoracic wall and lung known as shear waves (**Figure 7-4**). Because air and tissue conduct blast waves at different speeds, the propagation of a blast wave will induce a pressure gradient and a shearing stress. This explains why the blast wave has such powerful effects on tissue (water)-air-space interface such as the tympanic membranes, the lungs, and the gastrointestinal tract. Pressure gradients and shear stress at those interfaces will be significant and lead to mechanical tissue failure. The orientation of a surface to a blast wave strongly influences the wave's effect: a surface parallel to a blast wave will receive more damage than a surface that is almost perpendicular to the wave.

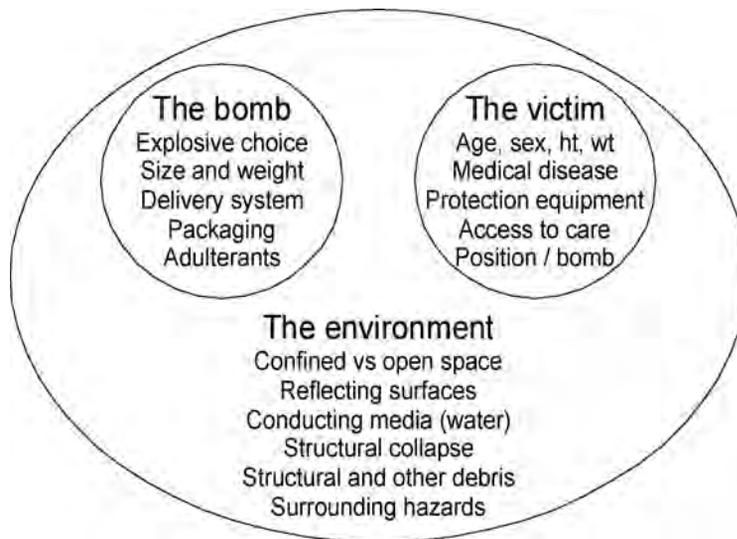
Figure 7-2. Threshold for Blast Injury^a



Simplified relationship between the positive phase duration, the amplitude of the positive phase, and lung injuries in man.

^aData from *A Manual for the Prediction of Blast and Fragment Loadings on Structures*. US Department of Energy. Published August 1981.

Figure 7-3. Triangle of Blast Injury



Blast injury is the result of 3 sets of factors: characteristics of the bomb; personal characteristics, health, and location of the patient in relation to the bomb; and characteristics of the environment.

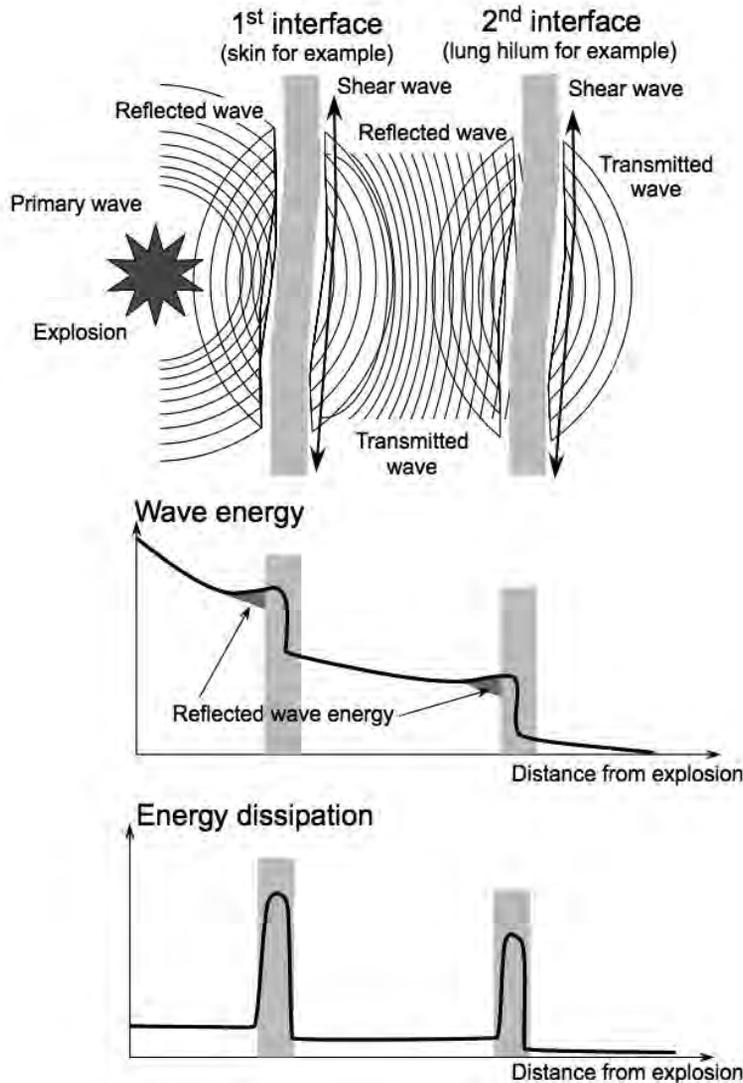
Secondary blast injuries occur when blast-energized fragments of bomb casings and other foreign material, such as glass and masonry, strike a victim. To increase the potential to inflict such penetrating injuries, metal or plastic particles such as steel pellets, nails, screws, and nuts may be embedded in bombs. Depending on their velocity and shape, these projectiles cause injuries ranging from minor subcutaneous deposits of debris to deep, life-threatening wounds of the heart, vascular tree, liver, or brain. Embedded body parts of suicide attackers pose additional infectious risk. Cyanide, HIV, hepatitis B virus, super-warfarin, and hypotension-causing nitrate byproducts have all been traced to projectiles intended to inflict secondary blast injuries. This can be intentionally placed around the bomb or embedded in a body part of the suicide bomber.

Tertiary blast injuries are forms of blunt force trauma caused by the blast winds that sweep people away from the blast and throw them against the ground or rigid objects (**Figure 7-5**). A fourth dimension of injury consists of other miscellaneous injuries, such as burns caused by flash mechanisms (hot gases released by the primary explosion) or by the ignition of clothing or other flammable materials. Although victims of explosions usually sustain a combination of injuries, it is estimated that 47% to 57% of severe injuries in survivors and 86% of fatal injuries result from the primary blast.

The greatest number of injuries after explosions are secondary and tertiary. The majority of victims sustain head injuries, usually in the form of lacerations; traumatic brain injuries including concussion and intracerebral or subdural hematomas are less frequently noted. Fractures and lacerations of the upper and lower extremities, pelvis, and trunk are also common. Crush injuries, amputations, and severe soft tissue injuries may occur, and, as already mentioned, blast fragments may carry environmental and human debris into wounds. Penetrating and blunt trauma of the chest and abdomen may result in pneumothoraces, pulmonary contusions, and penetrating injuries of the intra-abdominal organs. Projectiles may cause injuries to the eye, including globe perforation. Following civilian blasts, cognitive or psychiatric conditions caused by traumatic brain injury may sometimes be overlooked.

There are virtual concentric circles around an explosion site that can help predict potential injuries according to a victim's location. Casualties closer to the explosion will sustain blunt and thermal injuries, whereas casualties more distant from the blast will sustain penetrating injuries from shrapnel. As observed earlier, when a blast wave reaches a surface, its energy is in part reflected, in part absorbed by the surface, and in part transmitted. In the human body, most of the energy dissipates at the air-space interfaces, which leads to the most severe injuries (**Figure 7-6**). With modern weapons, debris can fly over several kilometers. When more than 1 debris element is found per square meter, the area is considered to be in the lethal range. Thus, the range of most serious injury may spread across several square kilometers and include thousands of potential victims (**Table 7-2**). Often these victims present with multiple injuries involving several body regions. The head and neck are the most vulnerable areas, followed by the limbs. Beyond the lethal range are several concentric circles where patients may sustain trauma, burns, or primary, secondary, or tertiary blast injuries. The secondary blast radius is the largest and may enclose several kilometers. The severity and complexity of injuries decrease with distance from the explosion, but the number of potential injured increases.

Figure 7-4. Interactions of Blast Waves With Surfaces



When a blast wave hits a surface, its energy is in part reflected, in part absorbed, and in part transmitted. If the surface is a human body, most of the energy dissipates at the interfaces of the most important organ systems, thus causing serious injuries.

IV. TRIAGE

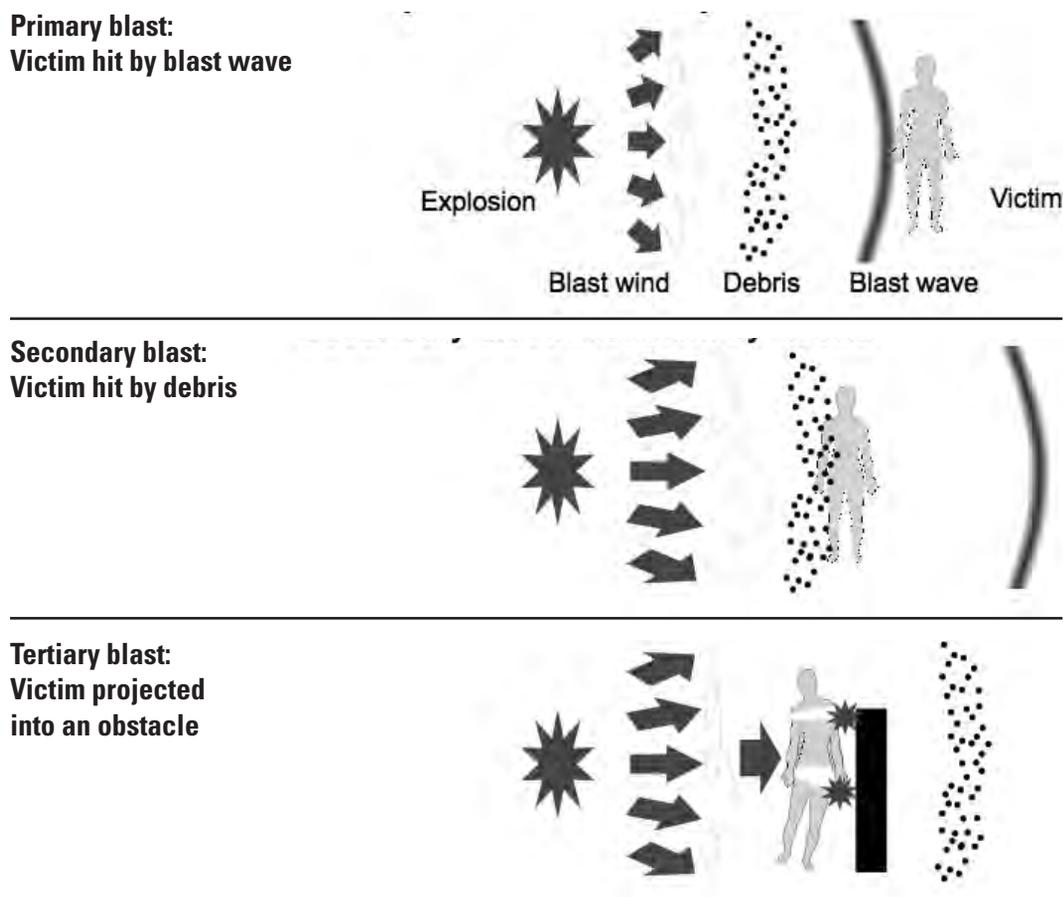
A. Key Considerations

Military medical forces are well prepared and trained to cope with mass casualty incidents (MCIs) even though they deal with such events as infrequently as the civilian sector does. Training and systematic planning for orderly triage, stabilization, and evacuation of casualties through a chain of treatment stations and hospitals in times of war have prepared the military to manage MCIs that would overwhelm ordinary civilian centers. For example, British military medical command in

World War I managed up to 25,000 wounded soldiers in a 24-hour period, with over 5,000 wounded soldiers at 1 casualty clearing station. The victims were handled in an orderly manner, even though the system was severely strained, thus demonstrating the importance of training and preparation.

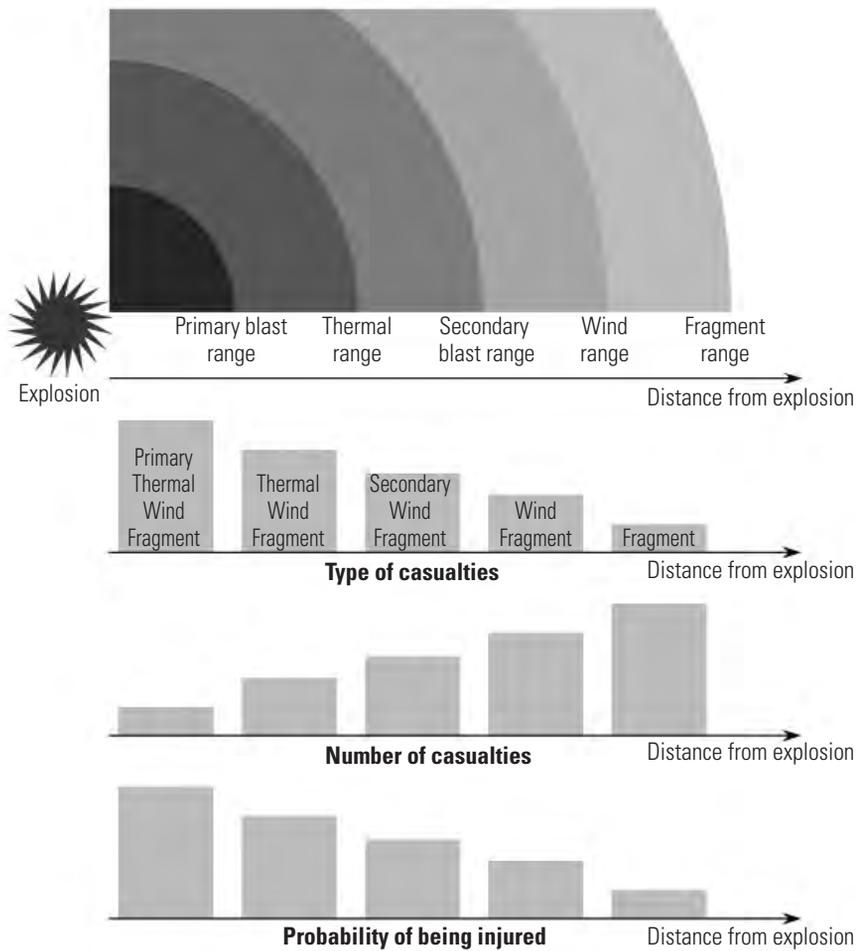
In conventional explosions, the number of people who die immediately or before reaching medical care appears related to the magnitude of the explosion, the occurrence of building collapse, and the event's location. Indoor explosions not only magnify the destructive power of the primary blast shock wave but also promote building collapse, which multiplies injuries and deaths. Rapid dissipation of a shock wave in open air reduces lethality and the number of critical injuries among survivors.

Figure 7-5. Dimensions of Blast Injuries



Primary blast, the effects of the blast wave itself, occurs only with high explosives and mainly results in injuries to the lungs and abdomen. In secondary blast, blast winds project debris that strikes victims and causes multiple penetrating injuries. In tertiary blast, blast winds fling victims against fixed structures such as poles, trees, or buildings, which results in blunt injury.

Figure 7-6. Relation of Blast Radii to Casualties



The area affected by a blast can be viewed as several concentric circles that correspond to the nature of the likely injuries. The secondary blast radius, which is the largest, may enclose several kilometers. The severity and complexity of injuries decrease with distance from the explosion but the number of injured increases.

Most critical injuries to body systems are found among the people killed immediately after conventional explosions. Although all fatalities suffer multiple injuries, head injuries tend to be most common. Among survivors, soft tissue and musculoskeletal injuries and blast injuries to the ears and eyes predominate in up to 80% of cases but are mostly noncritical in severity and contribute little to mortality. Although over 50% of immediate survivors who die have head injuries, most early survivors with head injuries are noncritical and only 1.5% of them eventually die. Chest and abdominal injuries, including blast lung and traumatic amputations, occur infrequently among survivors. Despite medical care, late death can be quite high among patients who initially survive a blast. Mortality varies by type of injury, with abdominal injuries accounting for 19% of deaths; chest injuries, 15%; and blast lung and traumatic amputations, 11%. Such injuries should be recognized as severe and in need of immediate care to optimize survival. Burns are relatively infrequent among survivors of conventional explosions and tend to be mild flash

burns with low mortality. In some settings, however, burns may be more severe and contribute to a higher mortality.

B. Effective Triage

The planning for medical management of casualties must revolve around identification of critical illness and appropriate allocation of medical resources. The greater the number of casualties, the more difficult triage becomes. The more time it takes to find and treat severely injured victims, the higher the potential for preventable deaths.

One of the most consistent patterns noted among survivors of terrorist bombings is the overwhelming predominance of relatively minor, noncritical injuries that are not life threatening. The incidence of critical injuries among survivors varies between 9% and 22%. Rapid and accurate triage—that is, triage that detects and treats the most critical injuries in the shortest time—significantly reduces mortality among survivors of conventional explosions. Undertriage, or the assignment of critically injured casualties needing immediate care to a delayed category, may lead to preventable deaths. This is avoided by training triage officers to recognize life-threatening conditions. Contemporary reviews suggest that undertriage is a relatively uncommon problem.

Overtriage, or the assignment of noncritically injured survivors to immediate care, hospitalization, or evacuation, taxes resources and effort. In an MCI, overtriage may quickly inundate medical facilities and prevent timely detection of the small minority of critical patients needing immediate treatment. Recent experience with conventional explosions demonstrates an overtriage rate from 8% to 80%, with an average of 53%, and mortality of critically injured patients ranging from 0% to 37%, with an average of 12.6%. There is a linear relationship between overtriage and increasing mortality of patients with critical injuries. Overtriage with victims of conventional explosions can result in loss of salvageable lives, as shown in **Figure 13-3** on page 13-7.

Effective triage is necessary to screen out the great majority of noncritically injured survivors who typically are the first to reach hospitals in large numbers. In contrast to usual practice, these casualties must be kept out of hospitals to the greatest extent possible. Overloading of hospitals is most likely in the immediate aftermath of a conventional explosion, when the situation is most chaotic. Leaders must rapidly establish control over the care of victims to avoid unnecessary loss of life. Any biologic, chemical, or radiation contamination in association with a conventional explosion could lead to hospital shutdown if patient flow is not promptly controlled.



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Triage should be conducted in open areas away from the explosion scene and outside the hospital. A second triage site may be at a location away from the hospital to further screen the triaged victims to enhance accuracy and ensure that only those needing hospitalization are admitted. Medical personnel and surviving victims must remain away from explosion sites; only those with specialized combat and disaster training should remain in those areas. Protection of medical personnel and assets must be a priority of disaster management.

The relationship between the accuracy of triage and casualty outcomes illustrates the critical importance of triage. Triage officers must be experienced and have particular expertise in trauma management to rapidly distinguish critical injuries requiring immediate treatment from noncritical injuries. They also need training in the principles of triage and mass casualty management to ensure that limited medical resources will be used efficiently. It has been shown that overtriage is minimized when field triage is performed by physicians and is increased when it is performed by non-physicians. The difference occurs because non-physicians must often rely on mechanism of injury to triage victims, whereas physicians bring in-depth physiologic and anatomic perspective to the assessment. Physiologic and anatomic criteria are superior to the mechanism of injury in reducing overtriage, and overtriage can be minimized without risking undertriage.

V. CRITICAL CARE FOLLOWING CONVENTIONAL EXPLOSIONS

A. General Principles

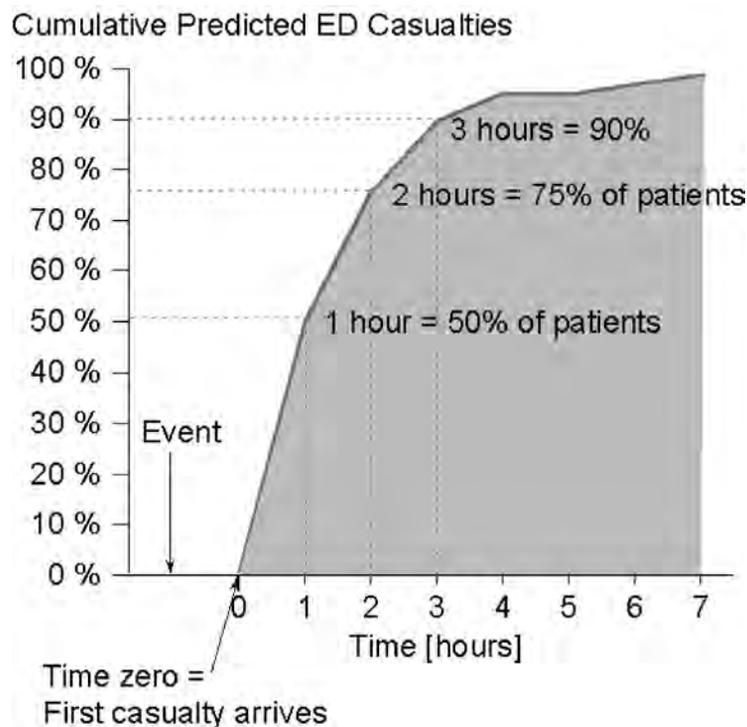
Treatment of casualties from conventional explosions begins at the triage site with rapid stabilization, hemorrhage control, fracture splinting, and cleaning and covering of wounds. Immediate determination of concomitant radiation, chemical, or biologic contamination must be made, and decontamination processes must be initiated before victims reach the hospital. Extensive or definitive treatment should not be performed at this stage. Systematic distribution of casualties from the triage sites to available hospitals and medical facilities is governed by severity of injury and urgency of needed care. Overloading any single facility should be avoided. To ensure that the definitive treatment of patients with critical injuries is given the highest priority, hospitals' disaster management plans should include a backup system for redistributing casualties such as soft tissue and skeletal injuries. Evacuation of casualties to distant facilities by air transport may be necessary with large casualty loads and in isolated environments.

The hospital disaster management plan should rapidly identify criteria for injuries that should not be treated. Criteria should be categorized by the nature of the conventional explosion, the estimated casualty burden, and available resources. In extreme circumstances, unresponsive patients should be assumed to be dead and not resuscitated. Closed chest compressions and emergency department thoracotomies should be forbidden. Serious consideration must be given to avoiding blood transfusions and endotracheal intubation in light of the associated resource requirements. Although urban hospitals usually have adequate resources for airway and ventilatory support, hospitals in rural or isolated settings may not.

After a conventional explosion, casualties arrive at hospitals in a predictable pattern (**Figure 7-7**). Rapid, early arrival of patients should be anticipated. If Time 0 is the time at which the first patient arrives in the emergency department, 50% of casualties can be expected to arrive within 1 hour, and 75% of casualties will be present after 2 hours. Less critically ill patients typically arrive first by

their own means, with critically ill patients arriving later via emergency medical services. Knowing this enables response planners to consider the use of available hospital-based emergency resources versus remote sites for initial patient evaluation. Of patients presenting after a blast, approximately one half will require admission, 20% will have an Injury Severity Score greater than 16, and the majority of the latter group will require critical care. Length of stay is increased both in the intensive care unit and in other parts of the hospital following treatment in the intensive care unit. Differences are significant even in comparison to patients with multiple blunt trauma and other injuries.

Figure 7-7. Hospital Arrival of Patients After a Blast ^a



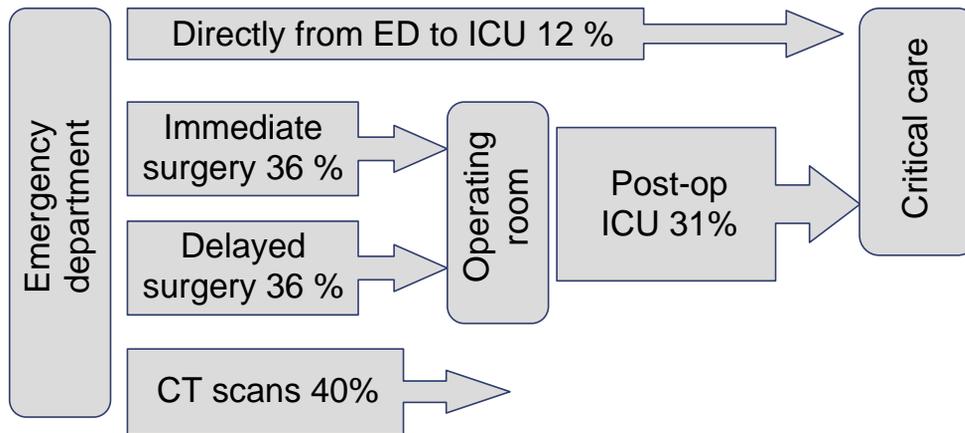
The arrival of patients after a blast follows a predictable course, with 50% presenting in the first hour and 90% presenting by the end of the third hour.

Abbreviation: ED, emergency department.

^aData from from Emergency Preparedness and Response. Centers for Disease Control and Prevention.
<http://www.bt.cdc.gov/masscasualties/predictor.asp>.

Casualties assigned to immediate hospital care are assessed and treated as quickly as possible but receive only minimal acceptable care during the initial phase of casualty influx. When stabilized, patients are moved to new areas to make room for additional casualties. To facilitate rapid turnover of rooms, only patients with life-threatening injuries should be transported to the operating room, and surgery must be truncated according to the principles of damage control. Plain radiographs and laboratory blood work should be restricted, and resource-intensive diagnostic tools such as angiography, magnetic resonance imaging, computed tomographic scanning, and other contrast studies should be avoided. Use of such tools is impractical in the immediate aftermath of a disaster and may hamper efficient casualty evaluation and flow (Figure 7-8). A possible exception is ultrasound, which may be an effective screening tool for abdominal injuries. Cross-matching of blood should be avoided because it is expensive and largely unnecessary in conventional explosions. Many interventions are feasible on the basis of clinical findings alone, such as tube thoracostomy and laparotomy. Only when casualty influx subsides should physicians reassess evaluated casualties more completely and begin considering treatment or evacuation of those in the delayed and expectant categories. At this time, there will be better understanding of available resources.

Figure 7-8. Patient Flow After Blast Injury^a



After a reasonable-size explosion without structural collapse, two-thirds of casualties will require surgery, one-third immediately, and one-third later.

Abbreviations: ED, emergency department; ICU, intensive care unit; CT, computed tomography; Post-op, post-operation.

^aData from Einav S, Aharonson-Daniel L, Weissman C, et al. In-hospital resource utilization during multiple casualty incidents. *Ann Surg.* 2006;243:533-540.

Most victims of conventional explosions are affected by secondary and tertiary blast effects that cause noncritical soft tissue and skeletal injuries. Their wounds may be extensive and if contaminated, they may require substantial debridement and multiple surgical procedures (Figure 7-9). Burns are usually superficial and caused by the brief thermal flash of the explosion. In light of their relation to high mortality, critical abdominal, head, and thoracic injuries warrant early surgery. When a conventional explosion occurs, the crucial need for surgeons and surgical support personnel and facilities cannot be overstated.

Documentation of the findings and interventions for each victim is an essential part of disaster management. It is the only reliable means by which continuity of care can be maintained and redundant triage and treatment can be avoided as patients are transported through successive care areas. To avoid loss or damage, the records should be attached to the patient and protected with plastic lamination. For expediency, the forms used for documentation should be familiar to caregivers.

Accurate records allow retrospective assessment of casualties and outcomes so that administrative and medical management can be critically analyzed and adjusted. Deaths among survivors, particularly in cases of undertriage or among noncritically injured victims, should be analyzed to determine the quality of medical care. Any immediate care beyond comfort measures provided for victims of nonsurvivable injuries should be considered overtriage. Such treatment will result in an inflated mortality rate for critical patients and may contribute to unnecessary deaths among salvageable patients. Deaths of properly triaged victims with nonsurvivable injuries should be categorized as immediate deaths. Because those individuals never received medical care, they are not included in the mortality statistics as a measure of medical management.

B. Organ-Specific Critical Care

Conventional explosions result in a number of typical injuries that correspond to the differing intensities of the shock wave (**Table 7-4**).

Table 7-4. Effects of Blast Wave Overpressure

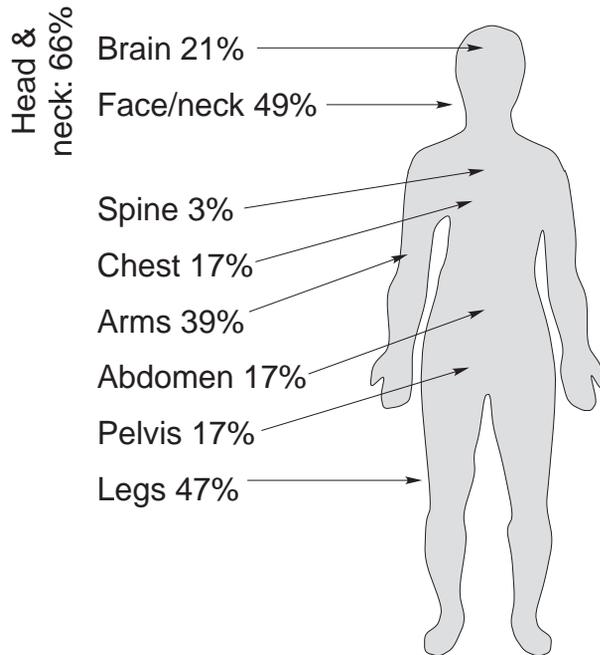
kPa (psi)	Effect on Structure	Effect on Victims
0.2 (0.03)	140-decibel boom	
3-7 (0.4-1.5)	Windows break	Reversible injury limit
7-10 (1-1.5)	Sheet metal falls	Secondary blast injury
15 (2.2)	Plaster walls collapse	
35 (5.1)	Brick walls collapse	Ear lesions
50-100 (7.3-14.5)	Wood siding falls	Lethal threshold
100-175 (14.5-25.4)	Utility poles snap	Lung lesions
200 (29)	Structural collapse	Gut injuries
300 (43.5)	Concrete walls collapse	
800 (116)	Total destruction	99% fatal blast

1. Auditory Injuries

Injury to the auditory system occurs with an overpressure of as little as 14 kPa (2 psi). The auditory system is the most common organ system injured in an explosion. Rupture of the tympanic membrane is a frequent finding caused by the mechanical pressure of the blast wave. The finding of eardrum perforation is evidence that a victim was exposed to a blast and that other blast-

induced problems should be sought actively. A negative exam of the eardrum, however, does not exclude significant blast injury. Ossicular discontinuity, dislocation, and bleeding of the middle ear have been reported, but vestibular damage is uncommon (Figure 7-10).

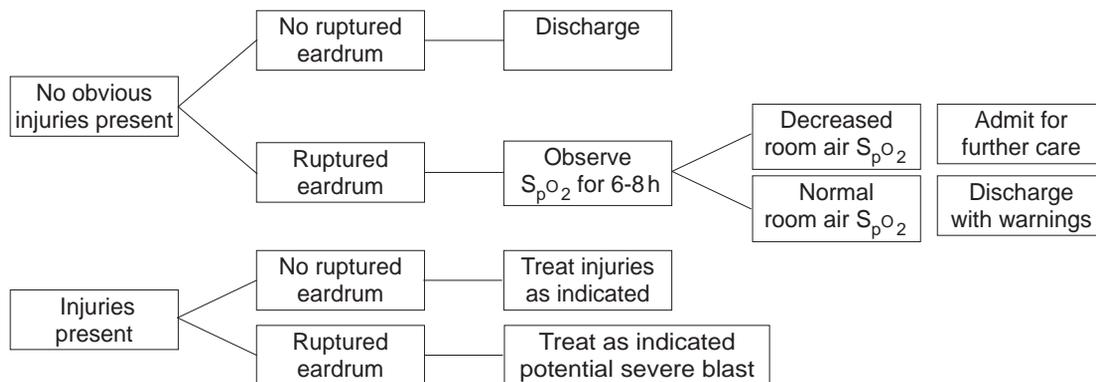
Figure 7-9. Frequency of Blast Injuries to Regions of the Body



^aData from Kluger Y, Peleg K, Daniel-Aharonson L, Mayo A, Israeli Trauma Group. The special injury pattern in terrorist bombings. *J Am Coll Surg.* 2004;199(6):875-879. Peleg K, Aharonson-Daniel L, Stein M, et al. Gunshot and explosion injuries: characteristics, outcomes, and implications for care of terror-related injuries in Israel. *Ann Surg.* 2004;239(3):311-318.

Due to greater exposure, the head and neck as well as the limbs are often injured during an explosion. In the diagram, the combined percentages of the affected regions total well over 100% because multiple injuries are common.

Figure 7-10. Triage Based on Auditory Injury^a



The eardrum is the most blast-sensitive organ. However, because eardrum rupture depends on an individual's position relative to the explosion, such injury is only 1 criterion to consider during triage. S_{pO_2} , pulse oximetry.

^aData from DePalma RG, Burris DG, Champion HR, Hodgson MJ. Blast injuries. *N Engl J Med.* 2005;352(13):1335-1342.

Table 7-5. Assessing Blast Lung Injury**Mild**

- Unilateral or limited infiltrates
- P_{aO_2}/F_{iO_2} ratio >200 mm Hg
- No bronchopleural fistula
- No need for mechanical ventilation

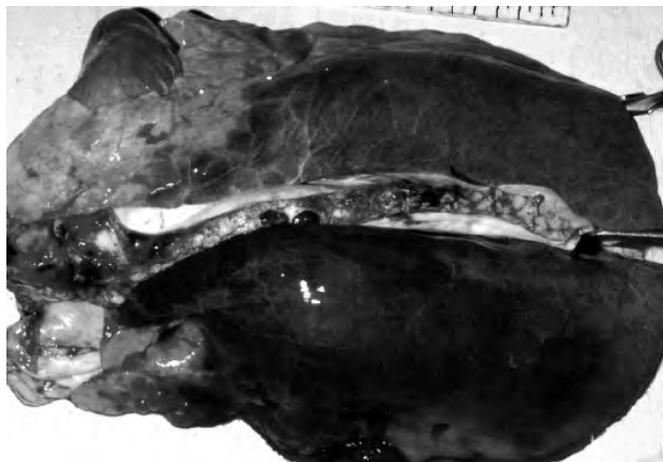
Moderate

- Asymmetric bilateral infiltrates
- P_{aO_2}/F_{iO_2} ratio 60-200 mm Hg
- Moderate bronchopleural fistula, no major bronchopleural fistula
- Requires mechanical ventilation but with routine settings

Severe

- Diffuse bilateral infiltrates, batwing appearance
- P_{aO_2}/F_{iO_2} ratio <60 mm Hg
- Bronchopleural fistula
- All require mechanical ventilation with unconventional methods
- PEEP >10 cm H_2O common
- Extracorporeal oxygenation may be considered

Abbreviation: PEEP, positive end-expiratory pressure.

Figure 7-11. Blast Lung^a

Animal experiment showing confluent lung hemorrhages.

^a Photograph courtesy of Dennis Amundson, DO, MS, FCCM.

2. Lung Injuries

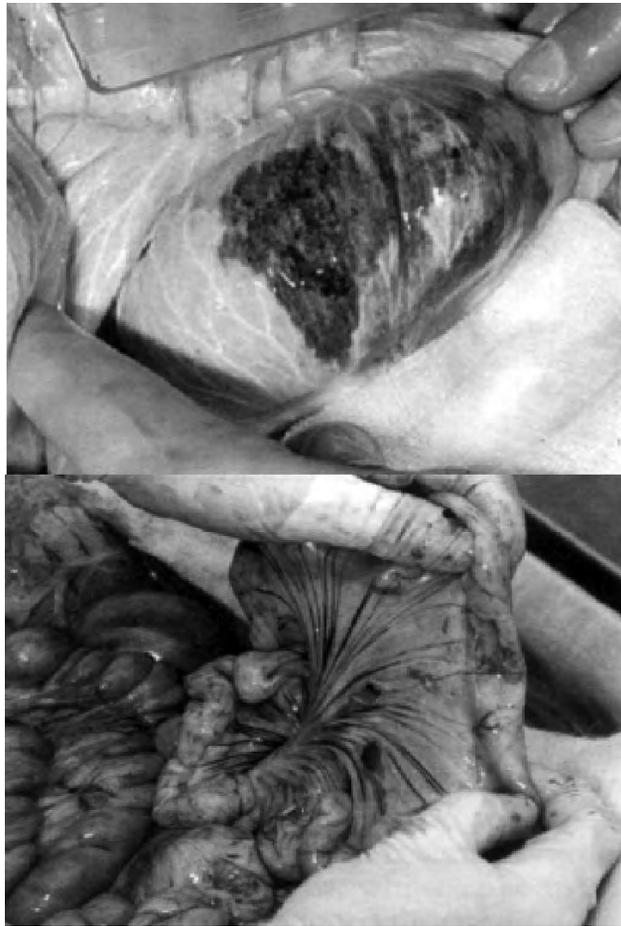
The lungs are particularly vulnerable to primary blast effects, which are reported in up to 38% of victims of conventional explosions. For survivors of the initial blast, the extent of lung injury is a significant determinant of later mortality. Patients who present with severe dyspnea and butterfly infiltrates on chest radiographs have high mortality. Main features of primary blast injury to the lungs include alveolar overdistension with rupture, thinning of alveolar septae, enlargement of alveolar spaces, and subpleural intra-alveolar and perivascular hemorrhage. These pathologic changes manifest clinically as pulmonary contusions. Patients are typically hypoxemic on admission and frequently require intubation within hours of presentation. Pulse oximetry has been advocated as a screening tool if blast lung is suspected. Opacities are frequently seen on chest radiographs, and hemopneumothoraces requiring bilateral chest tubes are common. Bronchopleural fistula is also possible (Table 7-5). When an injury occurs in open air, lung trauma is typically worse on the side of the blast, whereas a pulmonary injury received in an enclosed space is diffuse and bilateral (Figure 7-11).

! Extent of pulmonary injury is a strong predictor of survival. Radiographic changes resemble pulmonary contusions. Patients are typically hypoxemic on presentation. !

Air embolism, a complication of lung injury, may be 1 of the main causes of cardiac dysfunction, stroke, bowel ischemia, blindness, spinal cord injury, and immediate death. Autopsies find air embolism in explosion victims even if they have not been mechanically ventilated, suggesting that disruption of alveolar septae and interstitial vessels is a source of the problem. Air embolism is frequently seen within 30 minutes following a blast. Evidence of fat embolism, which is thought to be a determinant of subsequent acute respiratory distress syndrome, is also reported. Animal studies suggest

that oxidant-induced lung damage may be an important secondary mechanism of injury. The generation of free radical reactions may be the result of hypoxia and mechanical damage to the lung.

Pneumothoraces should be anticipated and aggressively treated. Alveolar hemorrhage and massive hemoptysis may require insertion of double-lumen endotracheal tubes and independent lung ventilation. Given the nature of lung injury seen with conventional explosions, positive pressure ventilation should be avoided, if possible, due to the danger of additional alveolar disruption and systemic air embolism. Careful limitation of alveolar overdistention using low tidal volumes and low plateau pressures is recommended to decrease the risk of barotrauma; hypercarbia is anticipated and accepted providing acidosis is not extreme. When there is suspected or proven head injury, hypercapnia may be dangerous, and other strategies may be required. High-frequency oscillatory ventilation may prevent further overdistension and damage to alveoli and has been used in a small number of cases where severe lung injury was present. Results in the small number of patients are encouraging. In the setting of severe lung injury ($P_{aO_2}/F_{iO_2} < 60$ mm Hg, massive bilateral infiltrates, bronchopleural fistula), mortality may exceed 60%. Bradycardia in these patients may relate to C-fiber-mediated vagal stimulation. Hemoptysis is treated using standard supportive care. Tracheal injury must be excluded.

Figure 7-12. Blast Abdomen^a

Submucosal hemorrhages in the large intestine and patchy necrosis.

^a Photograph courtesy of B. Desbien, Professeur Agrégé du Val-de-Grâce, Service de Réanimation, Hôpital d'instruction des armées Percy, France.

3. Intestinal Injuries

In conventional explosions, intestinal injury (blast bowel) occurs at higher overpressures than do auditory or pulmonary injuries. Underwater blasts seem more prone to produce blast bowel. Nonfatal blast exposure may result in multiple intestinal contusions or intramural hematomas, particularly in the colon, where gas tends to accumulate. If energy transfer is sufficient, there is progressive disruption of the intestinal wall. The presence of serosal injury appears to be evidence of a transmural lesion at high risk for perforation. Because intestinal wall injury may evolve, there may be a delay of 1 to 14 days between the time of injury and the time of clinical presentation. The overall incidence of intestinal perforation is low (0.1%-1.2%) but is increased when large amounts of explosives are used, when the victim is close to the center of the explosion, or when the explosion occurs in an enclosed area. Splenic rupture without perforation of the intestinal wall may stem from tertiary explosion mechanisms resulting in blunt abdominal trauma (**Figure 7-12**).



In blast injury to the intestinal wall, several days between the time of injury and clinical presentation may be anticipated.



When a patient has acute abdominal symptoms, surgery is necessary. Because the intramural hematomas that typify blast injury to the bowel increase the risk for late perforation, there is controversy over whether they should be routinely excised. Macroscopic features predictive of later perforation include an increased size of the lesion, the lesion's position relative to the intestinal mesentery, the extent of intramural hematoma relative to the intestinal circumference (more than 50%), and whether the pattern of hemorrhage appears diffuse or confluent.

Optimal treatment for stable victims exposed to a significant explosion but with no immediate evidence of abdominal injury is not well defined. Because bowel perforation may be delayed and radiologic examinations and even diagnostic peritoneal lavage may be normal if performed early, careful observation is essential. The development of unexplained sepsis or hemodynamic instability should prompt aggressive reassessment of the abdomen as a possible source. Some traumatologists recommend total body computed tomography in victims with multiple shrapnel wounds as soon as the initial stabilization is completed.

4. Neurologic Injuries

Neurologic dysfunction during the early post-traumatic period following conventional explosions has been attributed to air emboli in cerebral vessels. The effects of a blast on the brain are complex. The skull may be considered to protect the brain. However, the skull creates unique patterns of wave reflection and resonance-inducing, brain-shearing injuries. A blast wave does not propagate in a straight path in the skull. Instead, it accumulates and reflects. This produces subtle histological injuries rather than extensive or focal bleeding or hematoma. Small focal hematomas or contusions as well as diffuse axonal injuries have been reported. Ultrastructural findings of swelling in neurons, glial reactions, and myelin debris in the hippocampus of animals exposed to blast injury of the chest with the head protected suggest that kinetic energy of overpressure may be transferred to the central nervous system, where they cause diffuse axonal injury and initiate secondary mechanisms of injury. Electroencephalographic changes are common, and central nervous symptoms, including retrograde amnesia, apathy, psychomotor agitation, and anxiety, are frequently noted in victims of conventional explosions. Sometimes, a patient's symptoms and signs are classified as psychiatric, and some patients may be misdiagnosed as having post-traumatic stress disorder. There is an association between eardrum rupture and loss of consciousness during a blast, which suggests that having a perforated eardrum increases the risk of blast brain by a factor of 2.5 to 3.

5. Skeletal Injuries

Blasts cause great axial stress to the extremities, leading to complex fractures and amputations (**Figure 7-9**). The presence of stress fractures is frequently obvious in patients with flailing limbs and associated neurovascular injuries. Often these fractures require surgery, including vascular repairs. However, the physiologic stability of patients with skeletal injuries is often jeopardized, and a compromise is necessary between restoring cardiopulmonary stability and recovering injured limbs. Extensive repairs should not be tried in unstable patients with multisystem trauma. Due to the complexity of the wounds and associated secondary blast effects, external fixation systems are preferred. Secondary blast injuries occur when a victim is struck by numerous blast-energized projectiles. To assess the position of each fragment, imaging techniques are used to localize all foreign objects in 3 dimensions. Trajectory of fragments through the body must be determined.

6. Infectious Complications

Special consideration must be given to bits of human remains that become embedded in victims because this may have both emotional and disease-related implications. For example, victims of suicide bombings may be struck by bone fragments from an assailant who was positive for hepatitis B or HIV. After the Israeli Ministry of Health identified human remains among the fragments extracted from victims of a terrorist bombing, it made immunization for hepatitis B mandatory for victims whose skin is breached during such an attack. Treatment for HIV is sometimes added.

Infection may also be spread through inhalation injuries. After a conventional explosion in an open-air market, multiple victims developed candidemia characterized by early onset and absence of preexisting candidal mucosal colonization. Air sampling at the site of the explosion detected a significant concentration of airborne *Candida* species that appeared to correspond to the higher incidence of candidemia among victims with inhalation injuries. Those *Candida* infections were associated with increased morbidity and mortality.

CONVENTIONAL EXPLOSIONS AND BLAST INJURIES

- An individual's distance from an explosion determines the amount of energy and penetrating missiles absorbed. This is the single most important influence on survival.
- People exposed to explosions in a confined space have increased mortality, higher Injury Severity Scores, more primary blast injuries, and more extensive burn trauma.
- When a conventional explosion generates a large number of casualties, inappropriate overtriage increases overall mortality.
- In MCIs, interventions such as chest compressions, emergency thoracotomies, blood transfusions, and even intubations may be inappropriate in light of associated resource requirements. The appropriateness of these procedures is based on location and available resources.
- For survivors of the initial blast, the extent of injury to the lungs is a significant determinant of later mortality. These patients frequently require mechanical ventilatory support.
- Blast-induced intestinal perforation is an evolving process with a delay of 1 to 14 days between time of injury and time of clinical presentation.
- Recently recognized complications of terrorist bombings are the rapid distribution of infectious agents at the site of explosion and fragments of human remains that become embedded in victims and may carry infectious disease.



Suggested Readings

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Web Sites

Blast Injuries/Burns. Greater New York Hospital Association. <http://www.gnyha.org/45/Default.aspx>.

Explosions and Blast Injuries: A Primer for Clinicians. Centers for Disease Control and Prevention. <http://www.bt.cdc.gov/masscasualties/explosions.asp>.

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