1 Overview of Blast Injury

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Blast incidents and the resulting trauma are an unfortunate and real threat to health. It was first proposed in the late eighteenth century that changes in air pressure from explosions could produce injury or death. More nuanced, modern understandings of blast injury date from observations during the First World War [1]. Blast incidents occur in military conflict from both military and improvised munitions. Acts involving bombings and explosions are by far the most common types of terrorist acts. Blast injuries also result from nonintentional events such as industrial explosions. Although blast incidents are rare outside of areas of military or social conflict, when they occur, the scale in terms of number and types of injuries can range from mild to catastrophic. This chapter briefly reviews the various types of injuries that result from blast trauma, introduces the settings in which blast injuries occur and the epidemiology of blast injuries in different settings, and provides a summary of health preparedness and response strategies for incidents involving blast trauma. These topics will be expanded upon in subsequent chapters.

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Types of Blast Injuries

Blast injuries can be particularly challenging because of the severity of the often-multisystem injuries and also the unique characteristics of blast injuries. A number of excellent review articles provide a broad overview of these issues [2–4].

Blasts and explosions are complex events that can cause injury through multiple mechanisms. Future chapters explore the mechanisms of injury in greater detail; however, the most common way of characterizing blast injuries is mechanistic:

- *Primary* – barotrauma, where striking changes of atmospheric pressure directly resulting from the blast particularly affect air-filled organs or air/fluid interfaces in the body
- *Secondary* – penetrating injuries primarily related to shrapnel, bolts, screws, and other added metallic objects from the blast device
- *Tertiary* – bodily effects from being thrown by the wind or due to injuries sustained from collapsing structures
- *Quaternary* – other direct effects such as burn injuries or inhalation of toxic chemicals
- *Quintenary/Quinary* – some but not all sources add this fifth category, described as a delayed hyperinflammatory response

Blast Injury Scenarios

Blast injuries can result from explosions in a wide range of settings involving diverse types of explosive agents and devices. For this overview, we divide these into three general scenarios: exposure to explosions in military conflicts; exposures related to acts of terrorism using explosive devices; and exposures to accidental explosions, including explosions in industry in which the resulting injuries or fatalities are considered occupational injuries.

Blast Injuries from Military Conflicts

Military conflicts long have involved the use of explosive munitions, originally entailing a hollow metal casing into which was packed explosive powder and a fuse to ignite that powder. This led to the development of specialized exploding military munitions, including bombs, rockets, grenades, and mines. Exploding munitions can be used against materiel, personnel, or both. The injuries resulting from explosive munitions are the consequences of blast effects from the explosive force, thermal effects of the explosion, and ballistic effects of fragments from the detonating munition. Originally, the dispersed fragments were pieces of the munition casing, but starting in the nineteenth century militaries added primary fragments to their munitions to increase the number of projectiles resulting from the explosion [5].

In more recent combat theaters, including the wars in Iraq and Afghanistan, service members increasingly have been exposed to blast injury from improvised explosive devices (IEDs) (Fig. 1.1). IEDs vary in construction, deployment, and types of explosives and shrapnel used in the device [6]. Current IEDs can be divided into three categories: roadside explosives and mines, often constructed from military munitions, usually 122 mm or greater, and sometimes with hardware including ball bearings, nuts or bolts, or nails added (Fig. 1.2); explosively formed projectiles (EFPs), which use an explosive charge to deform a metal plate, usually copper, into a penetrating weapon (Fig. 1.3); and suicide bombings using weapons including human-worn devices (person-borne IEDs, or PBIEDs) and explosives packed in cars or trucks (vehicle-borne IEDs, or VBIEDs) or onto pack animals [7, 8]. IEDs are defined by their components including the casing used, the type of main charge, and the initiating system used to trigger the detonation [8].

Fig. 1.1 Remains of an armored Humvee military vehicle after being struck on the right side by single man-driven, forward-loaded suicide vehicle–borne improvised explosive device, Iraq, 2005. (Photo: Staff Sgt. John B. Francis, USMC. Courtesy US Department of Defense)

Fig. 1.2 IED detected in Iraq, 2005. Three 124-mm artillery rounds wired together with a single 126-mm round, the total combined payload approximately 400 lbs. of explosives (photo edited to remove personal identifying information). (Photo: Major Arnold Strong, Oregon National Guard. Courtesy US Department of Defense, Oregon National Guard)

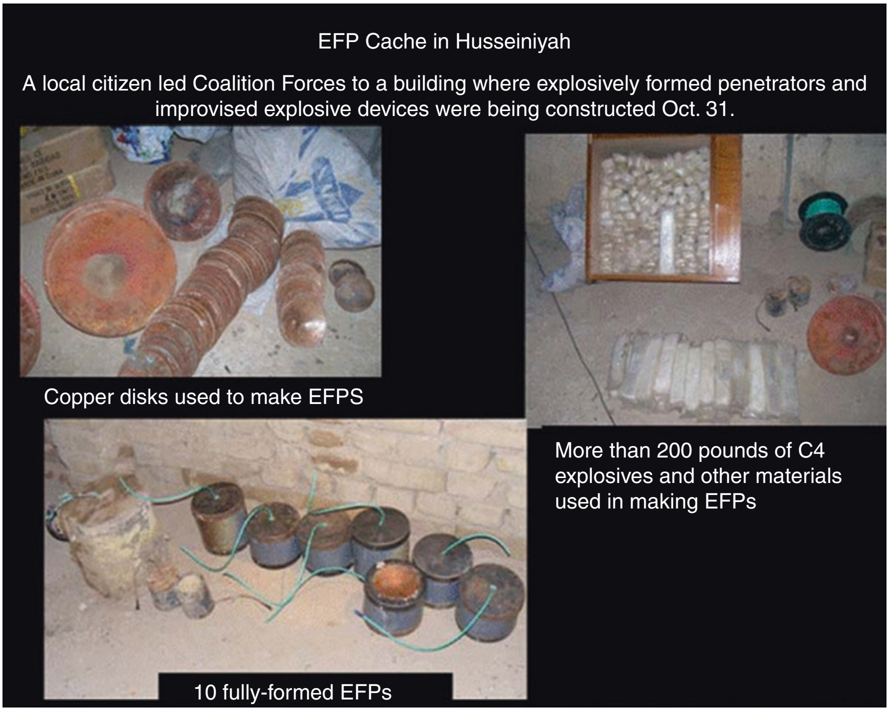

Fig. 1.3 Cache of explosively formed penetrators (EFPs) found in Iraq, 2007. (Courtesy US Department of Defense)

Recent epidemiologic assessments of blast injuries in military combat operations, using US service members as a representative population, were summarized in a literature review of blast injuries among the combat cohorts participating in Operation Enduring Freedom (primarily Afghanistan), Operation Iraqi Freedom (Iraq), and Operation New Dawn (Iraq). Among 1,992,232 soldiers deployed to Afghanistan or Iraq during 2005–2009, there were 5862 injuries from explosive devices. These accounted for a majority (74%) of all injuries at a prevalence rate of 30.5 per 10,000 deployed. Explosion-related musculoskeletal injuries accounted for 82% of musculoskeletal wounds and were experienced by 22.9 per 10,000 deployed. Explosion-related spinal injuries accounted for 75% of spinal casualties and were reported among 3.3 per 10,000 deployed. Major amputations (loss of a limb proximal to the wrist or ankle) caused by IED detonation were reported at a rate of 38.3 per 100,000 troop years in the Iraq theater (Operations Enduring Freedom and New Dawn) and 87.8 per 100,000 troop years in the Afghanistan theater (Operation Enduring Freedom) [9]. These rates are presented as examples, and comparable rates from other militaries may vary as they employ different equipment and tactics against different adversaries in different theaters.

As conventional and unconventional weapons and the tactics of their deployment evolve, so do protective technologies employed against them, resulting in changes to specific rates and patterns of combat-related blast injuries. Different exposure mechanisms may lead to different injuries; for example, combat thoracolumbar burst fractures are a unique pattern of injury that occurs as a result of vertical forces imparted by an explosion beneath an armored vehicle [9]. Protective technologies also alter patterns of injury. In a study of US combatant wounds incurred during Operations Enduring Freedom and Iraqi Freedom from 2001 to 2005, the percentage of thoracic wounds among was 6% (this included wounds from all mechanisms, not limited to blast injuries). Contrasting with a reported 13% in Vietnam, the difference was attributed to the use of personal protective equipment (PPE) such as body armor, in the two recent conflicts [10]. Additionally, though the protection provided by personal gear, including helmets and body armor, has increased survival, a significant proportion of service members who were close to a detonation of high explosives, such as IEDs, developed persistent neurologic and behavioral symptoms despite appearing to be relatively unharmed [6]. Beyond improved PPE, some have suggested that patients with massive blast injuries have survived due to advances in first responder care and forward surgery implemented in these recent conflicts [11].

Military personnel are not the only victims incurring blast injury in conflict zones. Civilians living, working, or transiting the area also are at risk. An injury, death, and disability survey conducted among 900 households in Baghdad, Iraq, found that for the period 2003–2014, injuries from blast or explosion were the most common type of intentional injury in 2008–2011 and in 2013–2014. Although gunshots accounted for more deaths, the majority of disabilities resulted from blasts or explosions. The sources of the blasts and explosions accounting for these injuries (e.g., military use of munitions vs IED) were not reported [12]. A 2015 United Nations report from Afghanistan showed that in the first 6 months of 2015, IEDs resulted in 22% of civilian deaths and injuries related to the conflict. A majority of these (846 of 1108 IED-related deaths and injuries) were civilian casualties of attacks targeting military forces [13].

Additional civilian casualties result from explosions of unexploded ordnance remaining after military forces have departed the area. The threat arises when parties to the conflict depart without marking or clearing unexploded ordnance from the former battlefield. In addition to inadvertently triggering the ordnance, civilians may become casualties when collecting scrap metal, tending to livestock, or farming. The same 2015 United Nations report documented that casualties from exploding remnants of war in Afghanistan accounted for 4% of reported civilian deaths and injuries. Children were put at particular risk by naively playing with recovered devices [13]. The problem extends to most of the globe (Fig. 1.4). In 2016, at least 2089 persons globally were killed and 6491 injured by landmines, cluster submunitions, and other explosive remnants of war. Seventy-eight percent of victims with known status were civilians, 20% were members of the military or security forces, and 2% were deminers. At least 42% of the civilian casualties were children. Rather than declining, the global incidence of such casualties has been increasing in recent years (Fig. 1.5) [14].

The problem is by no means new or recent. Unexploded ordnance from both World Wars still are uncovered in Europe, some causing fatalities upon explosion

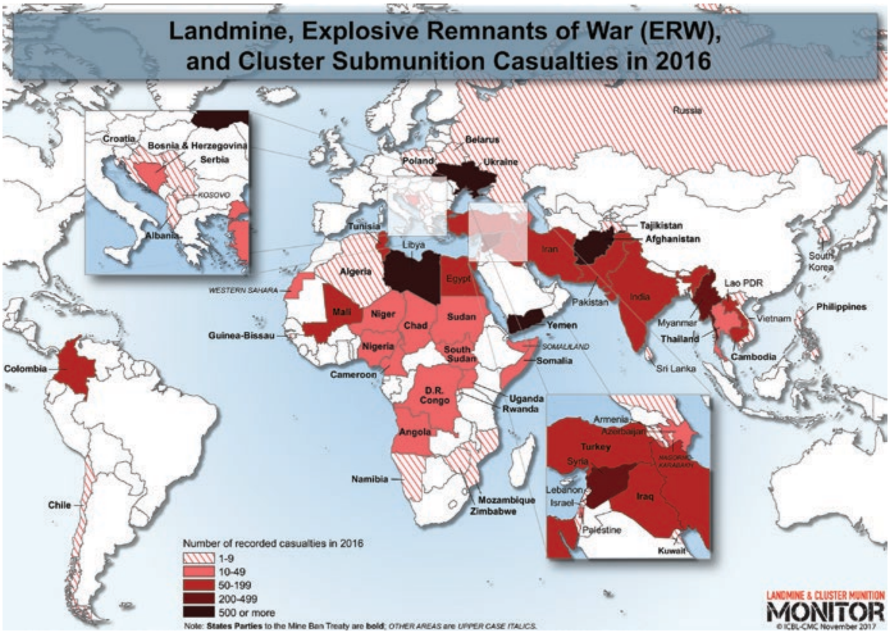

Fig. 1.4 Global reports of casualties from landmines, explosive remnants of war (ERW), and cluster submunitions in 2016. (Source: Landmine Monitor 2017. Courtesy of International Campaign to Ban Landmines – Cluster Munition Coalition)

[15, 16]. In 1988, one of the authors (SD) visited the Palauan island of Peleliu. Residents warned him against picking up unexploded munitions left over from the American invasion of the then Japanese-held island, 44 years earlier, saying that inadvertent detonations of these aging munitions accounted for several recent deaths.

Blast Injuries from Terrorism

Blast incidents are the most frequent type of terrorist attack. The suggested reasons for this preference for blast attacks include: difficulty obtaining the materials and expertise required to implement sophisticated biological, chemical, radiological or nuclear attacks; a contrasting relative ease of construction, materiel availability, and destructive capacity for IEDs; and the success of explosive devices for creating social, economic, and psychological instability in a community [17–19]. The explosives used by terrorists include commercial and homemade explosives in addition to the military explosive IEDs described in the previous section.

Data in the Global Terrorism Database, an open-source database including information on terrorist events around the world from 1970 through 2017, describe that of 181,691 incidents recorded during this time period, there were 88,052 (48.5%) attacks in which a bombing or explosion was the attack type. Explosives, bombs, or

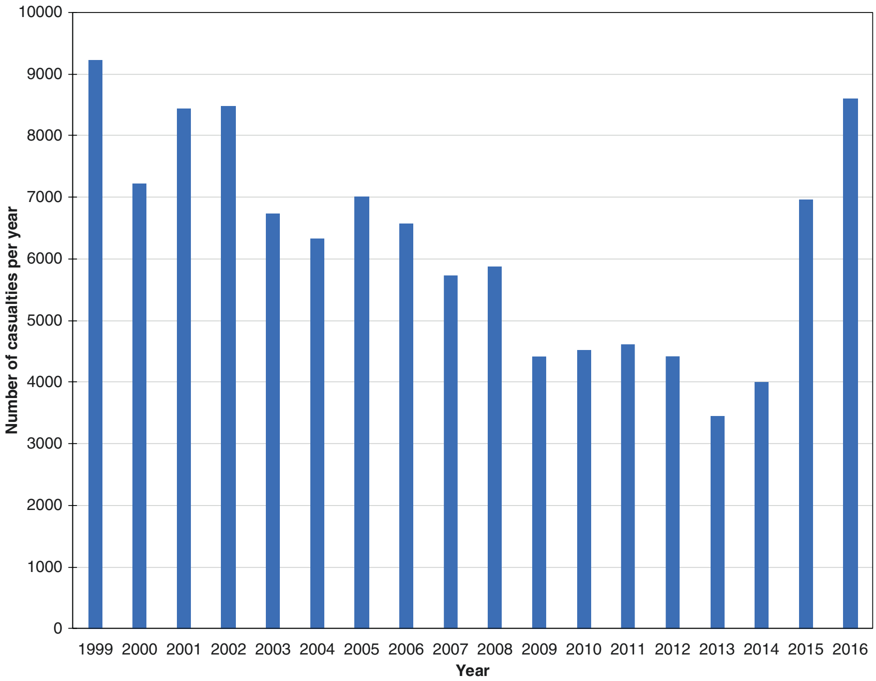

Fig. 1.5 Global number of reported casualties from landmines/explosive remnants of war, 1999–2016. (Source: Landmine Monitor 2017. Courtesy of International Campaign to Ban Landmines – Cluster Munition Coalition)

dynamite were the primary attack weapon. Of these, only 6283 (7.1%) worldwide were suicide attacks. These statistics can vary by region. For example, in the subset of 30,922 attacks occurring in the Middle East and North Africa, 3667 (11.9%) were suicide attacks. Of the global incidents with reported casualties, 36% resulted in one or more fatalities and 45% resulted in one or more nonfatal injuries. The most catastrophic incidents were relatively infrequent, with only 0.1% of incidents resulting in 101 or more fatalities and 0.4% causing 101 or more injuries [20]. Chapter 9 describes one such large event.

Whatever the reason for their selection, terrorist bombs can have truly destructive effects. Blast victims as a group tend to be more severely injured than victims of other types of trauma. Kluger et al. compared injuries among 906 victims of terrorist bombings to injuries of 55,033 individuals injured by nonterrorist trauma during the same period. They found that bombing victims were more likely to be severely injured (injury severity score 16 or higher), have Glasgow Coma Scale scores of 4 or less, be hemodynamically unstable upon arrival to hospital, have injuries in more body regions, require surgical intervention, need intensive care, and require longer hospital stays [21]. Despite this impact, during the period 1970–2017, the worldwide annual incidence of these attacks rose to a peak in 2013, and then, for reasons unclear, through 2017 was gradually declining (Fig. 1.6) [20].

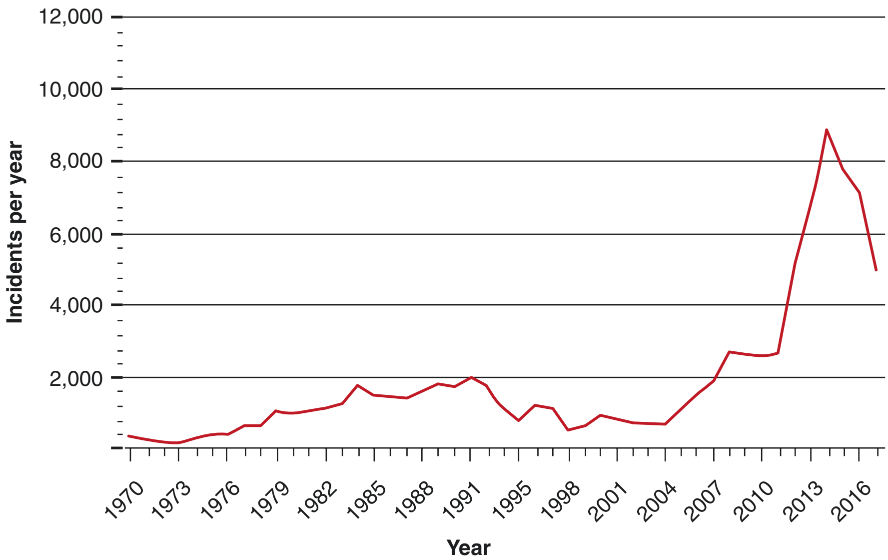

Fig. 1.6 Annual number of global reports of acts of terrorism in which the attack was a bombing or explosion and the primary weapon was explosives, bombs, or dynamite. (Source: National Consortium for the Study of Terrorism and Responses to Terrorism (START), University of Maryland. (2018). The Global Terrorism Database (GTD) [Data file]. Retrieved from https://www.start.umd.edu/gtd)

The nature of injuries from terrorist use of explosives varies with factors such as the size of the device, distance from the detonation, and the materials, including shrapnel, used in device construction. The setting of the detonation also affects the nature and severity of resulting injuries. Outdoor detonations result in different patterns of injury and mortality rates than do detonations in confined spaces. Injuries from indoor detonations are more severe due to the amplifying effect created when blast waves deflect off solid surfaces, and indoor victims additionally risk injury from resulting structural failures [22]. Golan et al. suggested, this confined space effect accounted for the difference in injury patterns seen in bus bombings when comparing persons inside the bus to persons outside of but adjacent to the bus. Victims inside the bus had higher injury severity scores, had more body regions injured, were more likely to require surgery or intensive care, and had higher mortality rates [23].

The nature of terrorism blast injuries also varies by victim age. An Israeli study assessed 837 hospitalized civilian and nonactive military victims injured by terrorist explosions. Children 0–10 years old were more likely than adults 16–45 years old to sustain severe injuries, to have traumatic brain injury, undergo at least one surgery, or require intensive care. These variations may be due to physical or anatomic differences between age groups and also may be affected by differences in medical protocols for different age groups [24].

Multimodal attacks (i.e., combining bombs, small arms attacks, or fire) are increasing in frequency. Attacks may include bombings in one location and concurrent or near-concurrent armed assault in others, as occurred in the attacks in Paris on November 13, 2015 [25]. The assailants in Mumbai attack starting on November 26, 2009 each carried a combination of automatic rifles, handguns and two types of explosives: hand grenades, and IEDs containing the high-grade explosive RDX (cyclotrimethylenetrinitramine) and ball bearings for shrapnel. These terrorists left IEDs with delay timers at some locations, hurled hand grenades at others, and attacked with firearms in still other locations [26]. Combined attacks of this type are regrettably effective. A review of incidents through 2014 found that attacks using both explosives and firearms caused 2.8 times more deaths than those involving only explosives [27].

Other Sources of Blast Exposure

While the previous sections have described blast injuries from devices intended to cause harm, blast injuries also occur in unintended circumstances. These can result from accidental detonations involving explosives used in nonmilitary settings, including mining, building demolition, fireworks, pyrotechnics, etc. In the United States, for example, the Bureau of Alcohol, Tobacco and Firearms (ATF, part of the Department of Justice) received reports of 687 explosions in 2017, of which 180 (26%) were accidental (of the remainder, 335 [49%] were bombings and 157 [23%] were undetermined, while 15 explosions were still under investigation at the time of the report). These resulted in 58 injured victims, seven injured suspects, and two injured fire service personnel or law enforcement officers. The victim injuries primarily were caused by accidental explosions. These explosions also caused 16 victim fatalities and one fatality to a suspect. In these incidents, the most common reported devices were pyrotechnics and fireworks (70 incidents, 31%), flash powder and other pyrotechnic mixtures (44 incidents, 19%), and black powder (nine incidents, 4%).The ATF report does not detail how many casualties, nor which devices, were associated with accidental vs deliberate events [28].

Accidental detonations can involve substances other than explosives. Dust explosions can occur in industrial settings when combustible dust particles are dispersed in sufficient quantity, concentration, and confinement in the presence of an ignition source and atmospheric oxygen. A primary dust explosion may disperse more dust, resulting in a larger secondary explosion. The combustible dusts can be diverse, including flour, sugar, metal dusts, plastics, and, in general, any combustible material reduced to a finely divided state [29]. These can be massive events; a 2009 sugar dust explosion at a sugar refinery killed 14 and injured 36 (Fig. 1.7) [30].

Other potentially explosive substances used in the industry can result in occupational blast exposures. Again using US examples, data collected from the Bureau of Labor statistics indicate that in 2016, there were 680 nonfatal injuries, and 55

Fig. 1.7 Aftermath of a sugar dust explosion at a sugar refinery, 2008. (Source: Chemical Safety Board, Wikipedia)

fatalities, from explosions reporting in goods-producing industries and service industries combined [31, 32]. Some of these can be catastrophic. A 2013 detonation of fertilizer grade ammonium nitrate at a Texas fertilizer plant injured 252 persons, including members of the public thousands of feet away, and killed 12 emergency responders and 3 members of the public. Most fatalities resulted from fractures, blunt force trauma, or blast force injuries. Among survivors, blast injuries included pneumothorax, blast lung, blast abdomen, fractures, closed head injuries, traumatic brain injuries, and skin burns [33].

Preparing for Blast Events

The response to a blast event with associated injuries, especially a large event with many victims, must be driven by extensive prior planning. The specific elements contributing to preparedness for responses to blast incidents will be described in detail in subsequent chapters and are only summarized here.

Preparedness begins with individual preparation. Prepared persons, whether victims or bystanders, can contribute to their own survival. In the 1996 Khobar Towers bombing, the affected population (victims and bystanders) were military personnel trained to administer immediate first aid and self-treatment. Over 39% of injured persons received such treatment [34]. Individual training programs are available, such as *Stop the Bleed*, a national awareness campaign to encourage bystanders to help in a bleeding emergency [35].

The next level of preparedness is community preparedness to respond to the incident, stabilize the scene, provide prehospital care to victims, and distribute victims for definitive care. These preparations include provisions for interagency communications, on- or near-site triage, ambulance dispatch and staging, casualty distribution, and decontamination as needed [36].

Preparedness in emergency departments and their parent hospitals is likewise essential. Because the organizational system used for daily activities frequently cannot meet the needs of an emergency, hospitals can define emergency roles for personnel in advance [37]. A solution with broader application, preparing for diverse emergencies not limited to blast incidents, is to organize using the Hospital Incident Command System (HICS) [38]. The need for surge planning goes well beyond the emergency and surgical departments and includes other high-demand programs such as nursing, intensive care units, radiology, blood bank, pharmacy, and medical supply [36]. Because surgical specimens may contain valuable forensic evidence, surgical and pathology programs should be prepared to process and store samples in a manner consistent with forensic standards [39].

Staffing surge capacity is critical. A terrorist bombing of a train in Madrid in 2004 happened to occur at one hospital's overlap between shifts, so the hospital had more than usual staff on scene [40]. Health care facilities cannot rely on such a fortuitous coincidence and should have advance plans for summoning additional staff as needed. This planning particularly requires participation of hospital administration, although they support the other functions as well [36]. Other surge activities include: cancelling elective surgeries to free up operating rooms and staff, moving intensive care unit (ICU) patients to lower level care units as appropriate to free up ICU beds, using the recovery room beds as a supplementary ICU, discharging hospitalized patients when possible, designating an area for families, and preparing a designated information center [41].

The health care response to a terrorist bombing can be emotionally and physically difficult. Israeli intensivists experienced in terrorist bombing responses suggest emergency staffing plans should include provisions to relieve nurses and physicians after 8–12 hours [42]. As with any emergency event, having trained behavioral health personnel available to support responders, families, and patients benefits all who may be affected by the event or its response [36].

Conclusion

Blast injuries, both fatal and nonfatal, can result from explosions occurring in diverse settings and involving various explosive materials. Military personnel and nearby civilians can be injured by explosions of military munitions used in combat or of improvised explosive devices. The same devices, when left on former battlefields, can injure civilians who encounter them. Blast incidents also are the most frequent type of terrorist attack, whether using explosives alone or in combination with other weapons. Accidental detonations of explosives can occur in nonmilitary settings, including mining, building demolition, fireworks, and pyrotechnics, while dust explosions and explosions of industrial materials such as fertilizers can occur without conventional explosives. Health care systems must be prepared in advance for the large-scale consequences of some blast incidents.

Pitfalls

- Victims of blast exposure may incur any of a constellation of injuries, some obvious and other subtle. Vigilant clinical assessments are essential.
- Blast injuries outside of combat setting frequently represent failures of prevention: failure to clear unexploded military munitions, failures to prevent accidents involving civilian use of explosives, and failure to control dust concentrations and ignition sources in industrial and agricultural settings.
- Absent explicit preparation for mass casualty incidents, health care systems risk being overwhelmed by casualties from large-scale blast events.

Disclaimer The appearance of US Department of Defense (DoD) visual information does not imply or constitute DoD endorsement.

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