Terrorist Homicide Bombings: A Primer for Preparation

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Contemporary planning for disaster response to terrorist events usually assumes the use of chemical, radiological, or biological weapons. Historically, most victims of terrorist attacks are injured by the use of conventional explosives rather than weapons of mass destruction. Such attacks will likely produce victims who have suffered burn injuries along with conventional trauma. Alternately, the large number of patients sustaining conventional soft-tissue or crush injuries will benefit from burn center expertise. This study summarizes the current state of knowledge related to the management of terrorism mass casualty incidents caused by the use of conventional explosives. A review of pertinent medical, technical, and popular literature relating to terrorism and explosives, along with instruction received at Hadassah Hospital, Jerusalem, Israel on the management of mass casualty terrorism events was undertaken, and the pertinent medical and scientific literature relating to bomb delivery methods, blast mechanics, blast pathophysiology, and medical response to a terrorist bombing is presented here. Although terrorist use of chemical, radiological, or biological weapons is possible, historical analysis consistently demonstrates that the most likely terrorist weapon causing a mass casualty event is a standard explosive device detonated in a crowded area. The medical basis for management of such casualties is herein described. (J Burn Care Res 2006;27:576–588)

The attacks of September 11, 2001, have increased focus in the American medical community on response capabilities to a terrorist attack. Significant improvements have been made through development of strategic national stockpiles and various federal grants programs to fund training and equipment for medical response to a chemical, biological, or nuclear event. Although the terrorist use of such specialized weapons remains a possibility, any historical or geographical analysis consistently demonstrates that the most likely terrorist weapon that would result in a mass casualty event is a standard explosive-type device detonated in a crowded area. Medical preparation to manage this category of event has not been a priority.

Nearly all of the mass-casualty terrorist events in the United States to date have involved the use of conventional explosives. On October 1, 1910, a large amount of dynamite was placed in a roadway near a building owned by the Los Angeles Times newspaper, at the time engaged in a fight against employee unionization. The resulting explosion collapsed a wall and caused the second floor to fall into the basement, where it ruptured gas mains and created an inferno, killing at least 20. On September 16, 1920, a horse-drawn cart filled with hundreds of pounds of explosives along with iron shrapnel from window sash weights was detonated in the financial district of New York City, killing 30 and injuring 300. In 1963, a civil rights-related bombing took place in Birmingham, Alabama, in which four girls died while attending Sunday school as a result of a bomb placed under a staircase. In 1993, the first attack by foreign terrorists on American soil was directed against the World Trade Center and involved a truck bomb of conventional explosives placed in an underground parking garage. Six people were killed and more than one thousand were injured. In 1995, a rented truck filled with ammonium nitrate fertilizer and fuel oil was detonated in front of the Alfred P. Murrah Federal building in Oklahoma City, Oklahoma, killing 167 and injuring 509. Burn injury was present in 8.5% of the children who survived and 21% of the children who died as a

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result of this blast.[1] In 1996, a terrorist bomb exploded in Olympic Centennial Park in Atlanta, Georgia. The convicted perpetrator, Eric Robert Rudolph, also was responsible for bombings of health clinics and gay nightclubs, resulting in the injuries of more than 150 people. His devices consisted of conventional explosives packed with loose metal items such as nails to act as shrapnel, which were remotely detonated at elevated locations to maximize their blast effects against vital body areas.

International experience, particularly in Israel and Northern Ireland, is similar. Violence in Northern Ireland has killed 3000 people since 1968, many as a result of bomb blasts. Between September 2000 and December 2002, Israel experienced 70 bombing attacks, a rate of approximately 2 per month. The Liberation Tigers of Tamil Eelam (LTTE, or Tamil Tigers), a separatist group fighting the government of Sri Lanka, has conducted some 200 suicide bombings since the late 1980s, including attacks on mass transit, at Buddhist shrines, and in office buildings.

Unfortunately, exercise planners continually sidestep this reality, with most drills focusing on nuclear, biological, or chemical events. In July 2004, the Homeland Security Council released 15 planning scenarios for use in preparedness activities. Only one of these scenarios involved the use of uncontaminated explosive material.[2] Although it is important to prepare for response to a weapons of mass destruction device, it is even more important to prepare for response to an attack involving conventional explosives, as this has already occurred in the United States and is the most likely future terrorist scenario.

The burn team can play a pivotal role in the management of casualties from a terrorist attack involving conventional explosives. When an explosion results in secondary ignition of a building or vehicle, the potential for burn injury is immense. In the absence of a fire, the multiple trauma patients produced by a blast will have associated lung and soft-tissue injuries, including crush injuries from building collapse. As the trauma services become overwhelmed, it is likely that many of these patients will end up in the burn center, where the burn team expertise in resuscitation, ventilator management, and wound care will be put to good use. Therefore, the purpose of this article is to provide a comprehensive review of what is known and unknown about the medical aspects of terrorist homicide bombings that are based upon the use of conventional explosives.

METHODS

An extensive review of the international medical, technical, and popular literature was conducted. To focus on the medical aspects of terrorist attacks using conventional explosives, this study combined the Federal Bureau of Investigation (FBI) definition of terrorism with a standard definition of a bomb. Terrorism is defined as "The unlawful use of force or violence against persons or property to intimidate or coerce a government or civilian population in the furtherance of political or social objectives" (28 CFR Section 0.85). For the purposes of this article a bomb is defined as "A device intended to explosively release large amounts of burning, gaseous material in a manner that is intended to cause injures and death through baro-trauma or direct physical contact between objects disrupted by blast forces."

The literature search was augmented by training received by the author at the Hadassah Hospital in Jerusalem, Israel. This Level 1 trauma center receives more terrorist victims per year than any other medical facility. Seminars on the management of mass casualty incidents resulting from acts of terrorism are offered at this facility.

This study did not consider the effects of intentional blasts or explosions related to mining or military activity (such as land mines or grenades), accidental industrial explosions, or explosions related to vehicular accidents. This research also did not focus on "letter bombs," as the targets are generally a single victim, who would be normally managed through existing trauma systems.

RESULTS

Terrorist homicidal bombs are designed and detonated in a manner that will maximize destructiveness against persons rather than against property. They are detonated in areas that are known to be occupied and often crowded and commonly are engineered to release metallic fragments for the purpose of increasing injury severity. As a method of delivery, the terrorist often intentionally dies in the attack (suicide bomb), making attack detection and prevention difficult.

Bomb-Delivery Methods

Terrorist homicide bombs are of three varieties: car (or vehicle) bombs, package bombs, and suicide bombs. Technical differences between the three types concerns both the security personnel who are engaged in preventing attacks and, to a lesser extent, the medical personnel who will treat the resulting blast injuries.

Car bombs typically involve hundreds to thousands of pounds of explosive material and produce huge blasts. The detonation of a car bomb often results in building collapse, producing the associated problems of heavy technical rescue and management of patients with crush injury or crush syndrome. The sheer size of a car bomb explosion implies the potential for producing hundreds of victims. The delays inherent in collapsed building rescue and extrication can act as de-facto triage, moderating the flow of patients into the medical system. A car bomb is also the type of device that is most likely to result in an incendiary situation, where a secondary fire also produces burn injury.

Package bombs are designed to be carried into the attack site and, for this reason, will always have a smaller amount of explosive material as compared with vehicle bombs. They are much easier to deliver and explode inside of confined spaces such as the inside of buildings or buses. The smaller size of package bombs means that the blast will not result in a building collapse, but the fact that the blast detonated inside of a confined space will significantly impact the injuries that result. Package bombs commonly include metallic objects such as screws, nuts, or ball bearings intended to act as projectiles.

Suicide bombs are similar to package bombs in that they are generally carried into the attack location, but different in that to avoid detection, the bomb materials are attached to the bomber's body. Detonation results in the intentional death of the bomber, presenting a tremendous problem for the prevention of such attacks as most security measures are designed to protect against a person who intends to survive the assault.

From a medical response standpoint, a suicidal bomb attack is more likely to be successful and to result in production of casualties. The Israeli Security Agency reported in 2004 that suicidal attacks represented only 0.6% of all terror attacks, but 66% of all fatalities.[3] For political and deterrent reasons, the death of the bomber(s) is usually not included in the final casualty report.

Blast Mechanics

It is not necessary for medical personnel to thoroughly understand bomb design or the many different explosive compounds that can be used. The information that needs to be understood is that after being activated, the explosive chemicals that comprise a bomb quickly convert from a solid or liquid state into a gaseous state. The volume of space that the reacted chemicals want to occupy after the explosion is significantly greater than the volume occupied before the explosion, which produces a rapidly expanding overpressure wave and winds that then move outward in all directions. The entire process of overpressurization and blast winds occurs in milliseconds. Depending upon the chemicals used, this expansion can happen at supersonic speeds (the definition of "high explosives") or subsonic speeds (the definition of "low explosives") and is related to whether the chemicals were detonated (a true explosion) or deflagrated (burned quickly). Under some conditions, low explosives can be made to behave just like high explosives.[4]

When treating victims from a homicidal bombing it is not necessary for medical personnel to know what exploded but it is very beneficial to understand where the device exploded.[5,6] The differences in number, type, and intensity of injuries produced are based upon factors including whether the blast occurred in an open area or a confined space, the number of potential victims in the area, and the use of shrapnel.[7–9] The type of explosive material that was used in the explosion (high or low) cannot be determined by patient physical examination, and this information is not important to the medical practitioner in diagnosing or treating blast injures.

The high-pressure blast wave emanating from a detonation produces both a compression and a movement of the molecules of air as it passes through the environment. The compressed air at the leading edge of the blast wave exerts a crushing external force from an increase in ambient pressure, but the air molecules also can be compressed to such a density that the pressure wave itself acts more like a solid object striking a surface. This high-pressure wave is followed by a vacuum or low-pressure area, which is created when the air molecules were compressed. After this high-/low-pressure wave passes, the ambient air pressure returns to normal. The baroeffects from being in the path of a blast wave is that of being first compressed, then exposed to a low-pressure vacuum, then being returned to a normal pressure or a squeezing, releasing, and resqueezing mechanism.[4,10]

When this blast wave moves against a human body or objects in the environment, an initial rapid transient increase in atmospheric pressure is followed by a high-speed wind, both of which can result in significant injuries. The extent of these injuries is directly related to the distance between the victim and the seat of the explosion. An explosive pressure wave decreases with the cubed root of the distance from the explosion,[11,12] so that a person 20 feet away from a blast receives 9 times less blast force than somebody who is 10 feet from the explosion. Furthermore, blast waves may be reflected back by walls and ceilings. Where these waves meet, the overpressure effects can be either canceled out or (more commonly) amplified. Orientation of the victim to the blast, the body mass of the victim, and any shielding present between the victim and the blast will all impact on the resulting injures.[13–16] The height of the ceiling in a room can affect the overall pressures generated, with a blast in a standard room producing higher pressure than a similar explosion in a large sporting arena. Leibovici et al[17] compared four different bombings that included two in the open air and two inside a bus. Mortality was 7.8% for the open-air blasts 49% for the bus bombings. Direct blast injury was observed in 34% of the open-air survivors and 77.5% of the victims from the busses. Saravanapavananthan[18] reviewed 86 victims of small homemade bombs common to Sri Lanka and India (similar to letter bombs) and found that blast injuries occurred only at close range. Stein and Hirshberg[6] concluded that the proximity of the device was more predictive of injury than the size of the bomb. In situations involving 1 to 20 kilograms of TNT, people at distances greater than 6 m will probably not experience significant blast-induced injury. Victims located at these greater distances would more likely be injured by missiles or by being thrown against objects.

Injuries caused by the explosive blast mechanisms have been commonly referred to as primary, secondary, and tertiary injuries. Primary injuries result from over pressurization. Secondary injuries are caused by the winds or other objects striking the patient. Tertiary injuries refer to the wounds received from falling or striking objects.

This classification system is of little diagnostic utility. After a terrorist homicide bombing, the treating clinician needs to look for and expect both blunt and penetrating wounds over the entire body. There is also a fourth mechanism of injury involved in homicide bombing situations: heat and burning. Military explosives are commonly designed with incendiary chemicals, as fire is a desired outcome of detonation. Terrorist bombings, on the other hand, are primarily intended to kill and injure people, and rarely are used with main intent of destroying infrastructure. Terrorists are not arsonists, and terrorist devices are rarely of an incendiary design. One only needs to watch news images or media photos of recent terrorist bombing to see that the blast scene is rarely charred.

Blast Pathophysiology

Bomb blasts occur in milliseconds of time, with exposure to ambient pressure changes, rapid winds, and the heat wave perceived by the victim as being simultaneous. Despite their differences in arrival time, each component of the explosion produces its own injury pattern to specific body systems. For the purposes of better understanding explosion phenomena, each component will be discussed separately. In clinical practice, multiple injuries often are produced, complicating management. The classic example is a patient with a burn injury who requires intravenous fluid resuscitation, along with a pulmonary contusion or pulmonary edema requiring fluid restriction.[19] Homicide blasts involve multiple body areas and systems and result in significant injury severity scores regardless of method of determination or analysis.[19–22]

Primary Blast Overpressure

Contemporary trauma surgery focuses on the rapid assessment of solid organs. Victims of blast overpressure need to be assessed from a different perspective because it is the air-filled organs that suffer the worst damage when exposed to the high external overpressures of an explosive blast.[8–11,23–35] At greatest risk are the lungs, gastrointestinal tract, and auditory system. The rising external pressure compresses the body surface and is then transferred to internal spaces, where organs become compressed. Solid organs have a high fluid component, making them essentially uncompressible. They are not readily injured from the overpressure forces because of their tendency to vibrate as an entire unit. Hollow organs have their internal air space compressed between the outside blast force and both the incompressible internal structures (that include solid organs) and the incompressible fluids of the circulatory system. As the compression forces pass through tissues of different densities, spalling occurs. Spalling refers to fragmentation at the surface of the denser tissue caused as the compressive force is reflected back into it. As the air in hollow cavities is compressed and subsequently re-expands, shearing forces are produced. Further damage occurs as the gasses in the previously compressed tissues reexpand, resulting in smaller secondary "explosions." Injuries are primarily seen on the side of the body exposed to the blast in open-air situations and on both sides of the body in enclosed blast situations, where the blast wave is reflected back from walls and ceilings.[36] Body armor does not offer protection from these compressive forces and, in some situations, may actually amplify the mechanism.[37]

The lungs are the most air-filled organs within the human body and are among the organs most sensitive to blast injury, with injury threshold seen at an approximate overpressure of 4.2 pounds per square inch (PSI) of pressure.[35] During a sudden compression of the lungs, the alveoli can rupture and a pneumothorax can develop, however it is the less obvious mechanisms that can result in greater diagnostic difficulties.

As the external blast pressure compresses the air-filled spaces, (eg, alveoli) they occupy less space whereas the fluid in the capillaries retains the same volume (fluid being incompressible). This pressure differential forces the fluid out of the vascular space (capillary rupture) and into the air-filled spaces, resulting in pulmonary edema and contusion. The sudden blast-induced compression also can directly produce lung contusion or damage to the pleura. The striped contusions present on the lung surface appear to be rib imprint injuries but actually correspond to the intercostal spaces.[38] Determining the degree of injury can be difficult, because the symptoms of respiratory failure can appear immediately after the blast or can be delayed for 12 to 24 hours. Pizov et al[39] reviewed blast 15 victims from two bus explosions and proposed a blast lung injury severity score for predicting outcome. The best single indicator of damage was the PaO_2/FIO_2 ratio, with a ratio less than 60 indicating severe injury, a ratio between 60 and 200 indicating moderate injury and a ratio greater than 200 indicating mild injury. Other useful indicators included extent of infiltrate on chest radiograph and presence of bronchopleural fistulae. Almogy[21] studied 15 bombing attacks in Israel and found that blast lung injury was more common among survivors who had skull and facial fractures, burns greater than 10% BSA and penetrating wounds to head or torso.

The heart is also susceptible to blast injury in a manner similar to blunt trauma, with contusions and microscopic injuries predominating. Blast injury to the heart can result in arrhythmias. Ventricular fibrillation, ventricular tachycardia, bradycardia, and asystole have all been described.[40] In animal models,[41] bradycardia is the primary response. Blast injury may result in severe hypotension related to bradycardia and lack of compensatory vasoconstriction.[42] Cardiac monitoring is indicated when cardiovascular injury is suspected.

Damage to auditory structures is the most common injury directly attributable to blast overpressure with an injury threshold of approximately 5 PSI pressure.[33] The inability to quickly equalize pressures across the tympanic membrane results in tears and ruptures. Tympanic membrane rupture usually occurs at pressures below that required to damage other organ systems.[31] The majority of tympanic membrane tears heal spontaneously, with only 25% requiring surgical closure.[43] Fracture and/or dislocation of the ossicles also can occur. Inner-ear injures can result in tinnitus or permanent hearing loss, representing a potential lifetime disability.

The most interesting question regarding tympanic membrane rupture is the triage utility of this injury in predicting overpressure injury to other organs. This axiom, although universally taught, is poorly supported by the literature. Leibovici[44] in a review of 647 civilian blast survivors determined that eardrum perforation is not a useful indicator of concealed blast injuries and that concealed internal blast injury can occur in the presence of intact tympanic membranes. Chest radiographs and patient observation for symptoms were better indicators. Intact tympanic membranes do not rule out occult overpressure injury and the rapid otologic examination should not be the sole determinant of hospital admission for observation.

Blast injury to the gastrointestinal system occurs at a threshold of 6 PSI[35] and is much more common in underwater blasts. Unlike lung injuries, which may be immediate and apparent, gastrointestinal injuries frequently are occult. The intestines and colon are the organs that are most susceptible to injury because of their high air content. Overt bowel rupture can occur. The ileocecal region has been identified as the portion of the human gastrointestinal tract most susceptible for rupture.[9] A blast abdomen syndrome has been described. Blast injury may rapidly compress hollow structures, producing a smaller cross-sectional diameter of the lumen. Unlike peristalsis, where this process is coordinated and slow, the sudden overpressure of a blast constricts different gastrointestinal tissues at different rates, disrupting the continuity of the epithelium, mucosal and submucosal tissues. The thicker smooth muscle layer is normally unaffected. After the pressure is relieved, the colon diameter returns to normal, but the different layers of the intestinal wall now separate, resulting in hemorrhage, possible thrombus formation, and necrosis from hypoperfusion. Necrosis is followed by perforation, with resultant spill of intestinal contents, abdominal free air, infection, and peritonitis. A diagnostic challenge is differentiating between those lesions that are destined for perforation and those that are capable of spontaneous recovery.[27] Current imaging modalities are not particularly accurate in this situation. A technique used at the Hadassah Hospital, Jerusalem, Israel, is long-term diagnostic peritoneal lavage in which the peritoneal catheter is left in place for 24 or more hours and repeated washings are performed as a method to identify subtle changes that allow for earlier interventions. Delayed development of gastrointestinal perforations have been reported.[27,45,46]

The neurologic system can be damaged by overpressure, although an injury threshold has not been established. Normally, blast head and neck injury results from direct blunt or penetrating trauma; however, the compression/reexpansion of fluids and tissues elsewhere in the body can potentially result in intracranial air embolism. The exact incidence has been difficult to establish at autopsy.[9] It is generally assumed that the air embolism begins in either the lungs or the coronary arteries and is transported to the brain. In theory, mechanical ventilation used to support pulmonary insufficiency after a blast might worsen the effects of air emboli. Transient flattening of the electroencephalogram in response to blast waves has been experimentally demonstrated in pigs[24] but has not been documented in humans. Blast related trauma to the head or neck may result in sudden death from a direct injury, but does not seem to pose a management problem for survivors.

Fragment (Shrapnel) Injuries

The blast winds that result when explosives detonate can produce blunt or penetrating trauma by turning objects in the vicinity of the blast into projectiles. The severity of fragment injury that would result from randomly existing objects at the site of a homicide bombing cannot be relied upon by terrorists to produce the consistent patterns of death or injury that they seek. For this reason, terrorists routinely include metallic objects in the construction of bomb packages. The use of ball bearings for this purpose was first described by Teare in 1976,[47] when Irish terrorists started adding them to their bombs. Today, terrorists can be routinely expected to add nails, screws, bolts, or nuts that will be propelled in all directions when the blast occurs. Eric Robert Rudolph, the serial bomber convicted for the Olympic Centennial Park attack, was known to construct bombs with nails and a steel plate on the back side of the device to direct the blast forces and nails primarily in the direction of the crowd.

In a bombing incident, these metallic pieces behave in a manner similar to multiple small arms fire in producing multiple penetrating injuries. The presence or absence of metallic objects in a bomb is a better determinant of injury than whether the metallic objects are inherently sharp or dull.[16,21,47–50] Although the ballistic characteristics of fragments used in military bomb design is well researched, there is very little information regarding the ballistic characteristics of improvised shrapnel from terrorist devices. Although it is known that greater-mass (density) objects travel farther after an explosion than lighter-weight bomb components,[4] it is not correct to automatically correlate the speed of the explosion with the velocity of these missiles. The hardware used in terrorist bombs is not propelled down a rifled barrel but rather is thrown by the blast overpressure and the resulting winds. The objects themselves have dubious aerodynamic characteristics, and wind resistance causes them to lose velocity rapidly. Ball bearings are known to travel faster and farther than bolts. What these objects lack in velocity is made up for by increased mass. Projectiles from civilian weapons are commonly small-mass bullets with a diameter ranging from 0.22 inches to 0.4 inches. When compared to the mass of a 5/8-inch nut or a 3-inch long bolt that a terrorist might use in bomb construction, the potential for significant injury becomes clear.

Unlike military high-velocity bullets, high mass metallic fragments from bomb blasts typically do not pass thru the victim and are retained in the body. Multiple fragments typically are observed. Although impressive on a radiograph examination, these metallic projectiles will most likely not produce the same type of penetrating injury that results from a high-velocity rifle round. Resulting injuries include lacerated and bleeding internal organs, perforated hollow organs, or collapsed lungs. Neurological injuries in which these objects enter the brain or spinal column are not infrequent. The location of multiple embedded metallic objects may be better identified with computed tomography scanning as compared with anterioposterior and lateral radiographs.[16]

Musculoskeletal injuries from metallic fragments have more in common with Civil War injuries than with contemporary firearms. Civil War soldiers commonly shot low-velocity black powder weapons with projectiles generally a half inch in diameter. A common civil war injury was a comminuted fracture produced by the impact of a high mass object into a long bone. The lack of treatment options for a comminuted fracture in the nineteenth century left amputation as the only option.[51] Although orthopedic procedures have improved greatly, the entry of these bomb projectiles into musculoskeletal anatomy can lead to injuries that can cause lifetime impairment and require significant rehabilitation.[21]

The distribution of fragment injury on the body is not as random as would be expected. Exposed areas of the body such as the head, neck, and hands are injured more commonly than the trunk[13] because, in an explosion, clothing may offer a slight amount of protection. Blast forces and metallic fragments lose their energy very quickly to the point that anything that can shield the underlying body surfaces, even for a short time, can offer some protection. The act of being torn causes clothing to absorb energy that might otherwise result in an injury. This makes the exposed skin surfaces most likely to suffer minor cuts, bruises, and penetrations. There is some minimal protective value to just wearing long sleeves and pants in a blast situation.

Traumatic Amputation

Limb amputation is one of the most dramatic injuries that can occur from a bomb blast. The common civilian concept of people getting "blown to pieces" after an explosion is actually an observation of the various mechanisms that result in amputation. The forces required to produce an amputation injury are associated with significant concurrent trauma and the blood loss from disrupted vessels can result in rapid exsanguination. Patients with traumatic amputations from a bomb blast have a very high mortality rate and are unlikely to survive long enough to get to the emergency department.[52] In some cases, the victim is positioned in such a way that a blast amputation occurs but other body areas are shielded, making survival possible.

In 1996, Hull and Cooper[53] studied the amputations that occurred in 100 fatal bombing victims and found that blast amputations tend to occur in long bones rather than at joints. Most commonly affecting the lower extremities, the majority of amputations occur in the proximal third of the lower leg, followed by separations evenly divided along the length of the femur.[53] Upper-extremity amputations occurred at all levels in both the upper and lower arms; however, none resulted in disruption at the elbow joint. This review noted that in some cases traumatic amputation was caused directly by metal fragments but this mechanism could not explain all injuries.[53] It is tempting to ascribe the other amputations to the speed of the blast winds that potentially tear away at a body part; however, this logic is faulty. Military fighter pilots who eject from troubled aircraft can suddenly transition from the protected space of a cockpit to being hit with winds that are nearly supersonic in speed. These pilots commonly suffer fractures and dislocations but rarely amputations.

Using both computer and animal modeling[53] it was shown that amputation is caused by a combination of both blast overpressure and blast winds. The shock wave puts pressure on the bone shaft, attempting to "bend" it until a fracture occurs. The now fractured limb is then flailed by the blast winds and the tissue is avulsed and separated from the body. The severity and extent of injury precludes replantation, and the amputation site can be expected to bleed significantly. Hemostasis by means of vasoconstriction does not occur because vascular disruption will result from vessels being torn and pulled along their length rather than being neatly transected. When hemorrhage from traumatic amputation is life threatening, tourniquet control may be indicated. A potential weakness in the prehospital medical response to a homicide bombing is that in the United States the proper use of tourniquets is not consistently taught or reinforced in first aid classes or prehospital educational programs.

Burn Injuries

Terrorist homicide bombings normally are not incendiary by nature, and burn injury after attacks usually is not the primary intent of the bomber. Nevertheless, significant burn injuries can be produced. The fireball that emanates from an explosion can reach several thousand degrees in temperature and lasts for approximately 500 milliseconds. This may produce flash burns over large body surface areas. A second scenario resulting in burn injury is a structure or vehicle fire caused by the bomb blast. Hadden et al[14] reviewed the injuries of 1532 explosion victims in Ireland and found that burn injuries occurred in 50 patients. Leibovici et al[44] noted that flash burns after terrorist explosions typically were found on exposed body parts such as face, neck, hands, and the calves of female victims, indicating the protective value of clothing in blast situations. He also reported that burns were more extensive and severe in victims of confined space blasts as compared to victims of open-air explosions because of confinement of the fireball for a longer time period. In 1994, Karmy-Jones et al[7] reviewed seven victims of a blast and identified three that had significant burn injury. The victims with burns were in close proximity to the explosion of a letter bomb. Quintana et al[1] reviewed the pediatric victims of the 1995 Oklahoma City bombing and found a 21% incident of burns among the 19 dead children. Among the 47 children who survived, there were four burn cases (8.5%), including one patient with burns of greater than 40% BSA. A review of all 759 people injured in the 1995 Oklahoma City blast reported that soft-tissue injuries were the most prevalent type of injury seen and were present in 506 patients.[54] In addition, nine patients had thermal injuries covering up to 70% BSA, with seven requiring hospitalization The face and neck were the most frequent area burned.[54] Had the Murrah building caught fire after the explosion, the numbers of burn patients produced would have been staggering. The implication of these studies is that burns can be expected to be seen, and that the most severely injured victims will be those closest to the blast epicenter.

Burns in victims located further away can result from clothing ignition, structure fires caused by the blast, or rupture of vehicle fuel tanks with subsequent fuel ignition. Perhaps the best example of this is the terrorist bombing in Bali, Indonesia on October 12, 2002.[55–57] This attack consisted of a series of three terrorist bombs, including a car bomb detonated in the town of Kuta. In addition to blast injuries, large structural fires were ignited. A total of 66 critically ill patients were evacuated from Bali to Australia using Australian Defense Force (ADF) assets. This air evacuation, termed Operation Bali Assist, was the largest performed by the ADF since the Vietnam War, and required the use of 5 C-130 aircraft along with 34 medical personnel.[56] On arrival in Australia, the patients were stabilized at the Royal Darwin Hospital (RDH).[57] Twenty-eight of 61 patients treated at RDH had major traumatic injury, including severe burns. Fifty-five escharotomies were performed. In addition to those intubated in Bali, a total of 12 patients required emergency intubation at RDH. Most were difficult intubations "because of facial and airway burns and oedema"[57]; a decision was made to redistribute the burn patients to specialist burns units throughout the country because "no single hospital in Australia has the capacity to effectively manage 61 patients with severe burn and blast injuries."[57] The experiences of one center, the Repatriation General Hospital Concord Sydney, has been described previously.[55] Twelve patients with burn and blast injuries were admitted with burn injuries, comprising 15% to 85% TBSA, mostly full-thickness injury. The hospital length of stay ranged from 13 to 91 days.

The Bali experience serves as a warning of what could easily happen in a terrorist bombing. An incident producing "61 patients with severe burn and blast injuries"[57] would overwhelm the resources of most areas of the country and would require secondary triage and redistribution of patients to other burn centers.

Inhalation Injuries

Terrorist bomb blasts involve the detonation of a combustible product. This combustion may or may not result in an overt fire, but it will always produce gaseous material that can be inhaled by the victims in the area. Inhaled materials that could result in a pulmonary pathology include smoke, dust, and toxic gasses. It is expected that these types of problems will present as a less-emergent problem than the preceding mechanisms; however, they also should be included in any patient assessment.

Crush Syndrome

Crush syndrome results when building collapse is followed by a delayed rescue because of entrapment. This was recognized as a mechanism of injury during the London (blitz) bombings of World War II but, interestingly, was not a factor after the Oklahoma City bombing. Mallonee et al[54] found that there was a strong correlation between those who died and their location in the collapsed section of the building (87%) compared with deaths occurring in noncollapsed sections (5%). The deaths occurring in collapsed sections of the building were relatively instantaneous. Only three victims were extricated alive 5 hours after the explosion.[54] From a global perspective, terrorist explosions are consistently smaller and anti-personnel in nature and are therefore unlikely to cause structural damage or collapse requiring lengthy extrication or resulting in crush syndrome.

Pregnancy

Blast forces predominately harm hollow or air-filled organs. The gravid uterus is a fluid filled organ, and crushing overpressures are not a major source of morbidity. Because the fetus is surrounded by amniotic fluid, there is unlikely to be much direct harm. As previously discussed, spalling may occur at the interface where the blast wave energy and vibrations pass between tissues of different densities, causing tissue layers to separate. For this reason, after blast injury to a pregnant patient, an evaluation to determine the possible existence or extent of a placenta abruptio must be performed.[12]

Unusual and Unexpected Infections

In 2000, Wolf et al[58] reported a higher rate of Candidemia among the victims of a terrorist explosion occurring in a marketplace as compared with similarly injured patients from a pedestrian mall. Patients with an inhalation injury were at the highest risk. Follow-up investigations detected the presence of Candida species and a high level of mold spores in the marketplace that did not exist in the pedestrian mall. This is reflective of the mechanisms of an explosion that could make airborne pathogens out of microbes that might otherwise not be an infective source.

Kennedy[55] reported colonization with multi resistant strains of *Acinetobacter baumannii* and *Pneumoniae pneumoniae* among burn victims from the Bali bombing transferred to Australian burn centers A possible source was the fact that, in lieu of ambulances, some victims were transported away from the blast scene in vehicles that typically hauled garbage.

Because victims of homicide bombings have significant exposure to blood and body fluids, transmission of blood-borne pathogens is a concern. The addition of metallic fragments to the bomb materials results in major disruption of the bomber's body and causes penetrating wounds in the victims.[59–61] Fragments of the bomber's body have a strong likelihood of becoming embedded into the victims of such attacks. Although Israeli researchers have not found a case of hepatitis B transmitted in this manner, the potential exists. Concern is warranted because the prevalence of hepatitis B is 10% in the local Palestinian population and only 1% to 2% in the Israeli population. In August of 2001, the Israeli Ministry of Health began routine vaccination of all blast victims against hepatitis B.[61] Despite rumors to the contrary, there is no documented case of a suicide bomber becoming intentionally infected with AIDS (or any other transmissible disease) for the purpose of transmitting that disease to the victims of the terrorist attack but because there is always a background occurrence of transmissible agents, there might be value to drawing baseline blood samples and monitoring victims for seroconversion.

Poisoning

Chemical poisoning is not a typical occurrence in homicidal bombing situations; however, an article in *Newsweek*[62] relates an incident told by Israeli Dr. Avi Rivkind where "rat poison" or coumarin was applied to bomb shrapnel material for the purpose of causing increased or uncontrollable bleeding from the resulting wounds. This incident was later addressed formally in the medical literature.[21] A 14-year-old girl was admitted with multiple shrapnel wounds to both lower extremities, along with fractures and vascular trauma. Bleeding continued after admission to the intensive care unit; she required the transfusion of 57 units of red blood cells and other blood products, along with administration of 100 μg/kg of recombinant factor VIIa to control. Nevertheless, the weapon potential of anticoagulation delivery through bomb fragments is probably overstated. The clotting cascade resists tampering, and any physician who has prescribed an anticoagulant therapeutically knows how difficult it is to achieve the intended response. In the unlikely case that intentional anticoagulation is suspected in a blast victim, standard medical practices should be employed for reversal.

Medical Response to a Terrorist Homicide Bombing

The priorities after a homicide bombing are scene control (especially scene safety), triage at the scene, triage at the hospital, management of available hospital resources, integration with law enforcement, and identification and release of information concerning victims.

The primary objective of a terrorist homicide bombing is to produce human casualties. Placement and timing of detonation can therefore be expected to occur during periods when a location is maximally occupied. Even when preblast warnings have been given to the authorities, it is unlikely that the medical community will be informed until after the blast actually has occurred. The resultant effect upon the health care system is the sudden existence of a mass casualty event. Understanding how patients will enter the system and how many victims to expect can greatly aid the response to a mass casualty incident.

Determining the number of victims involved in any particular terrorist bombing event is difficult because the confusion and chaos of the event does not lend itself to reliable data collection. News services will report on the event and will routinely list the number of killed and injured, but the exact source of their statistics is rarely cited and, oftentimes, the news reports are filed long before victims stop arriving. For this reason, few published studies regarding the size of terrorist incidents are available to aid in planning disaster response. An exception is the 1996 report of Mallonee et al,[54] who actively searched out any victim of the 1995 Oklahoma City bombing, including those who might have fled the scene and sought care at small clinics and doctor's offices long after and a long distance from the event. The authors documented a total of 759 victims of this incident. Before a website redesign in 2006, the Magen David Adom (MDA) ambulance service in Israel routinely posted reports of all major emergency responses, including terror attacks. These reports included the numbers of victims that were transported from each event, broken down by severity of injury. A review by this author of 33 homicidal bombings listed on the MDA website occurring during the second Intifada between October 2000 to August 2002 and that involved six or more casualties, found an average of 57 victims per incident either killed or wounded (range, 6–145). Thus, although some homicidal events may be enormous events producing large numbers of casualties, most terror attacks can be expected to be about the size of a large bus crash.

In planning for response to a large homicide bombing, it should be noted that not all the victims will arrive at the hospital simultaneously. After the Oklahoma City bombing, it was found that victims arrived in two different "waves." The first to arrive were the self-transported with minor injuries followed later by the more critically injured that required transportation by ambulance.[63,64] This bimodal arrival of patients is typical in disasters and was also documented in the Station Nightclub fire disaster, the Madrid train bombings, and the 2005 London subway bombings.[65,66] The Centers for Disease Control and Prevention suggests that one half of the casualties from a mass casualty event will arrive at the hospital within the first hour.[67] The most important lesson is that the least injured usually arrive first and that resources should not be fully committed until the full nature of the disaster is appreciated.

Some hospital disaster plans call for the establishment of a hospital presence at the disaster scene. This is mentioned only to be condemned. In general, hospital-based resources and personnel are not trained, prepared, or equipped to work on the scene. Secondary explosive devices may be set with intent to injure rescuers. To move or allow hospital resources to be moved to the scene is to place inappropriately trained people into a dangerous working environment and to deprive the hospital of staff and resources that will be needed as patients are eventually brought in. The presence of an untrained and unequipped hospital-based medical professional at the scene of the Oklahoma City bombing lead to the death of a volunteer nurse.[68] Medical volunteers wishing to help out should respond to the hospitals and not the scene.[69] The United States has a well-developed ambulance transport system, which should be relied upon to bring patients to the hospital. As mentioned, a substantial number of victims will get to the hospital on their own, independent of the EMS system. News images from New York on September 11th showed hospital employees properly waiting outside their emergency departments with empty stretchers ready to receive ambulance patients transported from Ground Zero. If these hospital employees had moved themselves to the World Trade Center site before the collapses happened, then the losses among emergency responders would have been far greater.

An estimate of the severity of injuries likely to require medical treatment after a terrorist homicide blast can be made from studies of previous incidents. Mellor and Cooper[37] studied 828 soldiers injured in Northern Ireland and found that 216 (26%) were dead before any treatment could be instituted. Cause of death was generally blast lung or head injury. A total of 90% of the victims were wearing body armor and few suffered fatal missile injuries, illustrating the deadly potential of blast loading and barotrauma. Pyper and Graham[70] reviewed outcomes of 482 terrorist victims in Northern Ireland, including 339 bomb victims and 115 gunshot victims and found a hospital admission rate of 42% for bombing victims and 81% for those with gunshot injuries. In this cohort, there were 5 in hospital deaths from bombs and 12 from gunshots. A 1978 study by Hadden[14] of 1532 explosion victims in Ireland found only 9 who died in the hospital. It is unknown how many died at the scene, and it was not noted whether these were open or confined blasts. Chest and abdominal injury occurred in 10 patients, including 5 fatalities. Primary blast lung occurred in only 2 patients, with major limb amputation noted in 16 patients, including 4 fatalities. Injuries generally were to the head and neck, illustrating the protective value of clothing. These studies suggest that the majority of bomb victims that survive to admission would likely have a low acuity. Quintana's 1997 review of the pediatric victims of the 1995 Oklahoma City bombing[1] showed 66 children were involved. Of these 19 (29%) expired and 47 had nonfatal injuries, including 7 victims (10%) requiring hospitalization. Between 1975 and 1979, The Shaare Zedek Medical Center in Jerusalem received 511 casualties from 24 explosions. A total of 87% were admitted with "light injuries," 3% had "medium injuries," and 10% were classified as "severe injuries."[71] Although the wounds of the hospitalized victims were sometimes very severe,[22] these studies also suggest that after a blast, the vast majority of the victims can be expected to have either minor injuries or to be dead on the scene. Fewer than might be expected will require major trauma center care, but those who do will have very significant injuries. This point is a critical one to remember when planning for the proper triage of victims.[72]

Better studies of how many victims a homicide bombing could be expected to produce and the severity of injuries associated with different types of bombs would give an advantage to medical systems preparing to deal with the effects of homicide bombings. However, the study and publication of these factors also might function as an effective research laboratory for those who design and build bombs. Published research in this area can be a two-edged sword with ethical implications.

The collection and preservation of evidence is a job normally performed by law-enforcement agencies. Medical personnel need to recognize that their actions can either protect or destroy this evidence. Because of the nature of an explosion, traceable bomb elements crucial to the investigation may show up anywhere and will likely go unnoticed by medical personnel if they are not alerted to the need to be vigilant. Although most hospitals have appropriate medical-legal procedures for dealing with rape and assault victims, few seem genuinely prepared to collect the myriad of blast scene evidence that could arrive on or even embedded in the victims treated. Important evidence might be recovered while undressing a patient in the emergency department or while performing a surgical procedure. The chain of custody needs to be documented for any such evidence collected. Everyone will want to see the perpetrator(s) captured and punished. In the case of a suicidal bombing, it may seem like this has already happened and that the evidence is of no value. However, learning which terrorist organization(s) caused the crime can result in valuable information that might prevent other attacks. In terrorist situations evidence may be more important as intelligence than for prosecution. Developing strong hospital policies that can collect and protect evidence is an area where much improvement can be made.

Rescuers should anticipate that law enforcement personnel will want statements from all persons who were at the blast event. Some of the observations of these direct witnesses may turn out to be dying declarations. Medical personnel should work closely with law enforcement to obtain and document these statements as needed.

Finally, hospital personnel must recognize that in terrorist situations there is always the possibility that perpetrators may present themselves at the hospital posing as innocent victims with intent to cause more harm within the treatment areas. A routine procedure in Israel is for a law enforcement or security expert to search each person before transport away from the scene and to open and search each ambulance upon arrival at the hospital to ensure that it is in fact a real ambulance carrying an actual patient. These ambulance searches are conducted a safe distance from the hospital building just in case the vehicle is actually a disguised terrorist device, the hospital building itself will suffer little or no damage.

Psychological and Long-Term Issues

It is not difficult to appreciate the high level of psychological stress that occurs to the family of a blast casualty who suddenly may have to deal with unexpected death, changes in family roles, or having to care for a newly handicapped person. The need for family support and counseling services must be anticipated when planning medical response to such incidents. The extended family must also be considered. A 5-year follow-up study of 27 school children who had lost a friend in the 1995 Oklahoma City attack[73] found all but three had symptoms of posttraumatic stress 8 to 10 months after the bombing. These "friends of the victim" may not gain access to the formal treatment that is offered to relatives, but their need for care must be recognized.

Terrorist bombings occur in public areas, including malls, marketplaces, busses, and restaurants. To many of the victims, these locations are work and job locations. Fannery[74] outlined the impact of unrecognized and untreated psychological trauma when violence occurs in the workplace even if those involved were not physically injured.

Perhaps worse than losing a family member or friend is losing personal potential, dreams, and aspirations. A bomb blast normally injures many more people than are killed; however, news accounts after a bombing often report the number killed then give a larger number who were "only wounded" in the attack as an afterthought. Survivors of bomb blasts may have only minor cuts and abrasions, but they often have life-changing injuries such as amputations, paralysis, blindness, or hearing loss. These types of wounds can easily change the life plans of those who experience them. Even when there are no physical injuries, there can be psychological trauma. In Hadden's 1978 study of 1532 explosion victims in Ireland,[14] he found half of those studied suffered from emotional shock with no physical injury.

It should be expected that some survivors will feel that they would be "better off dead." A direct connection between suicide risk and posttraumatic stress disorder has been documented. A medical system preparing for terrorist attacks also needs to prepare for increased utilization of psychological and rehabilitation services. Similar to the need for special care for disabled veterans that follows war, civilian society will need to provide special rehabilitative services for civilians when terrorists attack.

Finally, the psychological effects of terrorist bombings on rescuers and medical personnel must be recognized. Bombings produce extreme disruption of bodies, amputations and massive penetrating wounds of the sort normally only seen in battle. Although many may dismiss this stressor as "just part of the job," it should be recognized that wounds caused by terrorist acts can be expected to produce increased psychological stress among rescuers and hospital personnel dealing with the aftermath of a homicide bombing.[74] It can be expected that personnel who provide aid at the site of a bombing will require stress abatement to prevent future psychological problems. Without being able to put traumatic stress into perspective, it can surface later as job dissatisfaction. The greatest loss to society after a terrorist attack would be for trained medical personnel to cease performing their duties. Over time, this would result in an overall shortage of available rescuers. Increased retirement of New York Fire Department personnel after the attack on September 11, 2001, is an example of this type of loss. This resultant stress has been noted even among Israeli responders who "should be used to such attacks."[75,76]

DISCUSSION

In planning for medical response to a terrorist attack within the United States, the most likely scenarios must receive priority. It is possible that a future attack might involve the use of a chemical weapon, biological agent, or nuclear material. However, it is fact that past terrorist attacks in this country have already involved conventional explosives. Because such explosives are easy to obtain and effective to use, it is highly likely that future attacks will involve this modality. These attacks can result in burn injury, either as a direct blast effect, or by causing secondary fires in vehicles or buildings. In the absence of severe burn injury, the critical care and soft-tissue trauma expertise of the burn team will be highly useful in disaster mitigation. It is incumbent on every member of the burn care team to become proficient in the management of injuries produced by such devices.

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