ABSTRACT

Our objective in this review is to describe the unique features of bombing injury and to outline some special elements of their management. This is to allow the timely improvement and adjustment of existing mass casualty protocols.

Forensic studies, detonation and explosion, mechanisms of injury in explosion and their bodily effects, chemical effects of the explosive, site of the explosion and the wounding potential, the Multidimensional Injury Pattern, diagnostic evaluation of Multidimensional Injury Pattern, and surgical and treatment dilemmas associated with it are described and discussed.

Key words: Trauma; terrorism; explosion; blast injury

INTRODUCTION

Bombing attacks directed against civilians have become the primary weapon of terror groups and rapidly emerged as a worldwide epidemic. They have been perpetrated in many and diverse locations, and apparently no community is immune. The terrorists’ favorite modus operandi is bombing, and this is likely to remain the primary instrument of terrorism because bombs are easily and inexpensively manufactured, simple to activate, and require no more than a motivated and determined perpetrator. With increasing severity and magnitude, much like outbreaks of other plagues, this epidemic strikes the innocent in their most productive years of life.

The aftermath of such terror bombings requires unique management strategies, because, even with high preparedness, the sheer volume of injured patients may challenge the most experienced medical center. Our objective in this review is to describe the unique features of bombing injury and to outline some special elements of their management, in order to allow the timely improvement and adjustment of existing mass casualty protocols.

DETONATION AND EXPLOSION

The explosive can be of military, commercial, or homemade origin, and usually it is trinitrotoluene. Metal particles of various shapes are often added to the explosive to increase its wounding potential; steel balls, nails, nuts, and the like are the most common. The explosive is detonated by an electrical charge activated remotely or through a switch operated by a suicide bomber.

After detonation, the transformation of the solid explosive into gaseous form generates a highly pressurized wave of air that propagates radially from the site of the explosion at the speed of sound and is followed by a wave of negative pressure. The leading front of this massive air movement is termed the “blast front” and it is responsible for the peak of high pressure that will cause varying types of damage according to its intensity. A larger quantity of explosive will prolong the duration of the blast front, adding to its wounding potential. The propagation of the blast front depends on the density of air and the blast...
wind velocity, and higher velocities result in more severe injuries and a greater number of casualties.

The metal additives are energized by the blast, and their injury potential is proportional to the size and nature of the explosive charge, and their shape, weight and the distance of travel.

MECHANISMS OF INJURY IN EXPLOSION AND THEIR BODILY EFFECTS

Patients from bombings may present with a tremendously varied pattern of injuries. In addition to the unique class of blast injuries, these patients may exhibit the classic manifestations of blunt trauma, as well as penetrating injuries and burns.

Explosion induces four classes of injury: primary blast injury is induced by the blast itself; secondary blast injury is caused by the projectiles; tertiary blast injury is caused by thrusting the victim against stationary objects and by wind disruption; and quaternary blast injury results from fire and heat generated by the explosion (1).

PRIMARY AND TERTIARY BLAST INJURIES

The blast wave itself causes the primary and tertiary injury patterns, and perforation of the eardrums and lung injury are the hallmarks of blast wave injury. The blast forces exerted on the tissue are the stress wave, which damages relative to its peak amplitude, and the shear wave, which relates to the peak’s velocity and strain forces. Spalling, implosion and acceleration-deceleration are the putative mechanisms of blast tissue damage.

The elastic properties of the involved tissues, their density and composition determine the nature of injury, and consequently different damage is caused in different organs. The human body is remarkably resistant to the blast wave, and solid or fluid-filled organs are rarely damaged while air-containing organs suffer the most. Although the blast wave has little or no effect on fluid-filled and solid organs, their interaction with it may accelerate the blast wave’s velocity beyond the speed of sound and increase the potential of injury from greater stress forces.

BOWEL PERFORATION AND SOLID VISCERAL DAMAGE

Deceleration forces are the cause of injuries to solid organs, such as the liver, spleen and kidney. One possible mechanism of genuine blast injury is the acceleration of organs upon impact of the blast wave and then deceleration due to their anatomic attachment. However, it is more likely that acceleration and deceleration of solid organs result from the tertiary blast mechanism, namely the bumping of the body against other objects, resembling classical injury of blunt trauma.

In bombing, perforation of hollow abdominal viscera is uncommon (0% to 1.2%), and its incidence depends on the amount of explosive, proximity to the explosion, and the enclosure of the explosion site. Frank bowel perforation may be delayed for hours due to the special mechanism of its development. It was suggested that slow mucin dissection between the wall layers of the bowel could be the underlying mechanism of hollow viscous perforation (2). We suggest that sometimes-delayed bowel perforation is the result of mesentery tears or mesenteric avulsion leading to bowel wall ischemia and eventual perforation. We have treated several cases where mesenteric tears and avulsion about the terminal ileum and cecum were found, suggesting a mechanism of acceleration-deceleration in this type of injury.

The late presentation of some this injury with their occasional lucid interval raises concern about early detection. Ultrasonography and computed tomography may not be of diagnostic assistance at early stages, and we have found diagnostic peritoneal lavage (DPL) much more useful and accurate when treating patients with abdominal wall penetration by multiple metal projectiles. Also, in the intubated or unconscious patient, whose signs of peritonitis may be obscure, or no entrance or exit wounds are found, the use of DPL is encouraged.

BLAST INJURY IN OTHER ORGANS

Other organs suffer true blast injuries as well. Head injuries cause some of the dead-on-scene events. The lucid interval of brain injuries is another manifestation of blast effects. Abrasions of the sclera and lens dislocations are rare, yet representative of blast injuries of the eyes.

Eardrum perforation occurs at very low peak overpressure, with 50% likelihood of eardrum perforation between 1.05 and 3.5 kg/cm² ≤ (15 and 50 psi), and therefore it is considered an indication of the patient’s exposure to the blast. However, because cerumen filled auditory canals and eardrums of younger patients are relatively resistant to the blast, intact eardrums are not indicative of the exposure in these patients, and other signs of injury should be sought.

Blast lung is a more severe infestation of blast injury, and can develop with elapsed time. Overpressure between 3.5 and 7 kg/cm² ≤ (50 to 100 psi) results in 50% likelihood of blast lung injury. Difficulty in ventilation that necessitates innovative ventilatory techniques and massive air leaks are some of the problems encountered by medical teams treating blast lung patients.

Also, the blast wave can sometimes create coronary air emboli, and they can lead to cardiac ischemia and death.

LIMB AMPUTATION

In some patients, the dynamic pressure from the blast wind may result in limb amputation, and major limb amputation is a positive predictor for the severity of injury. Indeed, most injured suffering major limb amputations succumb to their injury in the field, while few will reach the hospital alive. Their severe injury pattern and the knowledge that amputation is a grave prognostic sign should not discourage teams from treating such patients in mass casualty events,
since our experience has shown the most of them survive and are eventually discharged.

SECONDARY BLAST INJURIES

Projectiles embedded in the explosive are the source of secondary blast injuries, which reflect their velocity and shape. Indeed, different injury patterns have been defined for spherical missiles, nails and screws. Such multiple penetrations to the human body demand special awareness during evaluation, and all means of evaluation should be used to exclude cardiac or vascular injury in such patients.

FORENSIC STUDIES

Forensic studies provide information about the cause of death in terror bombings, especially for victims without distinctive injuries. In some of them the explosion caused cardiac dysrhythmia or air emboli that induced cardiac arrest and death, and such hidden injuries are often related to the impact of the blast.

Because most victims dead on the scene suffered the combination of blast, ballistic and thermal effects of the explosion, the recognition of these differing death patterns and their correlation with the underlying mechanisms of injury could help to develop strategies for diagnosis and treatment.

CHEMICAL EFFECTS OF THE EXPLOSIVE

Our group has recently described an apparent new pattern of blast injury that we have termed the quinarian injury pattern (3). In several victims of a recent Tel Aviv bombing, a hyperinflammatory state was observed without any other injuries that could explain it. Tachycardia, fever, low central venous pressure, and an excessive demand for fluids to maintain adequate tissue perfusion were noted in these patients. Considering the special explosive used by the terrorists, DETA-Sheet or pentaerythritoltetranitrate (PETN), which possesses vasodilatory properties, we have postulated that the bizarre hyperinflammatory state, unrelated to the severity of injury, resulted from absorption of this explosive.

SITE OF THE EXPLOSION AND THE WOUNDING POTENTIAL

In the civilian setting, sites of bombing have been classified as open, closed or ultra-confined spaces. When the same explosive charge was detonated in closed quarters and not in open air, a distinctive increase in morbidity and mortality was identified (4). In open-air explosions, a rapidly expanding sphere of gas at high pressure travels from the center of the explosion, propagates through and around the objects in its path, and intensifies by the reflection of the shock wave from the ground to form the “Mach stem”. The quick dissipation and slowing of the shock front in open spaces leads to low immediate and late mortalities and to predominantly non-critical injuries. In confined spaces, the blast is bounced off the walls and consequently immediate and late mortalities and morbidities increase, and higher incidence of blast lung occurs. In ultra-confined spaces like buses, the localized area of overpressure from the explosion is instantly amplified by repeated reflections from the enclosing walls, and therefore bus bombings are highly lethal.

THE MULTIDIMENSIONAL INJURY PATTERN

When different classes of injury occur simultaneously in the same patient, a Multidimensional Injury Pattern (MIP) is recognized. In this sub-group of bombing patients the severity of injury is not adequately projected by the classic injury severity scoring (ISS) system, and therefore their diagnosis and management must differ from that of the conventional severe trauma patient. The multiple injuries in MIP challenge diagnosis, decision-making and treatment. These patients are more likely to require surgical intervention, to stay longer in intensive care and the hospital, and their in-hospital mortality is significantly above that of other patient groups, emphasizing the unique nature of this subgroup of bombing victims.

Because visceral injuries in bombing can occur from multiple wounding mechanisms, the conservative selective management that is commonly practiced in stable patients from conventional trauma must be applied cautiously, especially since delayed tissue breakdown in these injuries may result in missed injuries.

DIAGNOSTIC EVALUATION OF THE MIP

Triage protocols of bombing mass casualty events differ from those of other trauma situations (5). Virtually all local and regional hospital facilities are recruited to handle the large volume of injured patients. Patients who are triaged to smaller facilities may require transfer to trauma centers for definitive care.

The initial most obvious clinical issue in these events is the lack of diagnostic capabilities. Prioritization of computerized tomography (CT) and ultrasonography (US) must be established; such tests must be reserved for immediate, life threatening decision-making. CT is usually made available only for the most severe head injuries that need immediate intervention decisions. Bedside US is of limited use. While a clearly positive finding could expedite diagnosis of hemothorax or hemoperitoneum, negative results in some situations calls for expert clinical judgment and use of other invesigatory tools in such scenarios. Repeated US in stable patients may add to early detection of abdominal injuries.

Previous negative imaging results require careful second review because of delayed injuries. For this reason, the tertiary survey has assumed a new level of importance in these events, and if it suggests
missed injuries further tests should be conducted once the majority of casualties have been admitted and triaged.

DPL has surfaced as an important diagnostic tool in mass casualty events. It can be rapidly performed at bedside and provides immediate diagnostic information to accompany triage decisions. In the absence of other diagnostic maneuvers, this minimally invasive technique is valuable in the immediate evaluation and in the follow-up evaluation after the tertiary survey. Sometimes, in patients presenting with delayed injuries, DPL has been the only positive test, even after an initial negative CT. It is recommended to set for DPL a threshold of 10,000 erythrocytes/ml in such visceral injury.

We recommend liberal use of total body fluoroscopy to identify all potential projectiles; their mapping is mandatory for documentation and future reference. A high index of suspicion must be maintained when multiple shrapnel pieces are identified on X-ray or fluoroscopy. The missile trajectory in secondary blast injury may parallel classical penetrating injury, as described in stab or gunshot wounds.

SURGICAL DILEMMAS IN MIP

The MIP represents the ultimate challenge to the clinical judgment of the trauma surgeon. Consider a scenario with limited diagnostic capabilities and patients with multiple body areas injured, such as severe head injury, potential abdominal or chest hemorrhage, coincident burns, and trauma to an extremity or the vasculature. Therefore, multiple teams are frequently involved, each anxious to treat their particular injury complex. This requires careful coordination and implies need for strict supervision of the trauma surgeon as the captain of the team (5). Prioritization of treatment regimens is life saving in such patients; definitive treatment must be delayed while the patient is stabilized with liberal use of damage control strategies.

TREATMENT DILEMMAS IN THE MULTIDIMENSIONAL INJURY

Blast lung versus lacerated lung represents another clinical challenge. While lacerated lung may result from secondary blast injury by penetrating missiles, blast lung injury is the classical injury of explosions. Both may develop significant respiratory difficulties with persistent air leakage and creative ventilatory practices are required. Fluid management in the early phase of injury may be quite different in these two lung injuries, because blast lung requires restrictive management while lacerated lung mandates resuscitative therapy. Swan-Ganz catheterization is therefore recommended for ideal tailoring of fluid management. Lacerated lung may occasionally require operative therapy, while the mainstay of blast lung therapy is non-operative respiratory support.

Patients are often transported to the intensive care unit after damage control protocols with profound acidosis and hypothermia. Aggressive warming must be employed, recognizing the coagulopathy associated with the “bloody viscous cycle”.

SUMMARY

World terror represents a true modern epidemic that threatens the very survival of the free world. Until politicians can resolve its causes, the medical establishment must prepare and improve current protocols. Meticulous coordination of manpower and medical resources are the first and most important requirement of protocol delineation for bombing events. A thorough understanding of detonation and blast dynamics is required of the treating team to better correlate the injury patterns presented. This is critical for revision of current mass casualty protocols.

The Multidimensional Injury Pattern, a new injury pattern apparently unique for bombing events, has been identified. It escapes accurate description by the conventional ISS system and awaits evolution of a better scoring system that will account for its uniqueness and so enable to improve the treatment of these patients.

REFERENCES

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