Introduction and Epidemiology

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1 Overview of Explosive Blast Injury

When high explosives or nuclear weapons detonate, a tremendous amount of energy is released at an instant, and the pressure and temperature at ground zero soar in a dramatic fashion. The explosive force then rapidly spreads in all directions through surrounding media (e.g., air, water, soil, steel sheets), forming a high-pressure and high-speed energy wave, and this is explosion shock wave (blast wave). The abrupt movement of high-pressure gas from the firing of a cannon, supersonic flight, explosions from gas leaks, shock tube experiment, and other instances also generate similar shock waves. Bodily injuries caused by shock waves are hereinafter referred to as "explosive blast injury."

In clinical context, "explosion blast injury" usually refers to primary injury caused directly by shock waves in air or water. Injuries caused by shock wave in a solid (e.g., deck of a warship), or mechanical trauma from objects thrown by shock wave or other indirect effects (e.g., collapse of structures) may be categorized as "blast injuries" but are usually not called "explosive blast injuries."

In modern warfare, belligerents might adopt carpet bombing strategy and drop a huge number of large bombs in densely populated cities, or use bombs that mainly cause destruction through shock wave such as aerosol bomb or fuel-air explosive bomb, which are more likely to result in blast injuries. Take for example an equivalent to a 5-megaton nuclear weapon, the shock wave could injure personnel exposed on the ground surface within an area of over 800 km. This is only the direct kill zone, and if the indirect impacts of shock wave are taken into account, the area of effect would enlarge by one to two folds. Shock wave is one of the primary destructive elements that cause injury and damage in the use of a nuclear weapon. In August 1945, some 70% of injuries in the atomic bombings of Japan resulted from shock wave. At Hiroshima, among the deaths early on, 60% were attributed to blast injury. Among victims of moderate and severe injuries that survived after the first day of detonation, those afflicted by blast injuries accounted for 36.6%. In conventional warfare, shock wave is one of the primary destructive elements essential to the different types of explosive weapons. For instance, among the 1303 cases of patients severely wounded by explosion treated at the former Yugoslav Academy of Military Medical Sciences, 51.0% resulted from blast injuries. In skirmishes along the border in southwestern China, among a group of 166 persons injured by artillery and mines, 22.3% resulted from blast injuries.

Outside of the battlefield, many have been injured or killed from explosions in weapon factories, munition depots, chemical plants, mines, or other areas, not to mention victims of terrorist attacks. Bombings account for approximately 75% of terrorist attacks, and blast injury is one of the most common types of injuries caused by such attacks.

With advancements in explosive production and technology, explosives become increasingly diverse and powerful. Some common types of explosives include black powder, ammonium nitrate, nitroglycerine gelignite, TNT, RDX, Composition C and other plastic explosives, emulsion explosives and liquid explosives, to name but a few. In recent years, Composition C plastic explosive has risen as the weapon of choice for terrorist bombing. For example, Composition C plastic explosives were used in two series of bombings in Indonesia, respectively at tourist district on the island of Bali in 2002 and at upscale hotels in the business district of capital Jakarta in 2009.

Explosive devices are becoming smaller and smarter, and less metals are being used. Some explosives are made to look like toys, toothpaste, and other daily items, while others convert cameras, radios, and other objects into small bombs. Methods of detonation have also diversified from safety fuse to electrical, mechanical and chemical means, and even methods like remote control, temperature control, light control, or sound control. On July 9th, 2007, a bombing in Jinan

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shocked the nation, as perpetrator used remote control to detonate an explosive device planted inside a car.

Thus, it can be seen that blast injury is not only a matter crucial to military medicine, but also a type of injury and emergency commonly seen in hospitals.

In addition, it should also be pointed out that most vulnerable to the typical blast injury (as in what is frequently referred to as "explosive blast injury") are auditory apparatus and organs, in particular the lungs because of its high content of air. Many victims meanwhile do not exhibit obvious signs of injury on the surface. In the early phase of injury, the vital signs (e.g., breathing, circulation) of the injured might appear normal because of the body's natural tendency to compensate, but soon after the situation would quickly deteriorate. At the same time, blast injuries might be accompanied by other injuries (i.e., burns or other mechanical injuries), or bodily damage might manifest as multiple trauma. Prompt diagnosis and corresponding treatments are mandatory so as not to miss the best opportunity for medical intervention, otherwise the consequence could be dire or might even result in death.

2 Physical Parameters and Biomechanical Mechanisms of Injury from Blast Wave

2.1 Physical Parameters of Injury from Blast Wave

Main physical parameters of injury from blast wave include: peak value of shock wave pressure, duration of positive pressure, impulse, duration of pressure increase, etc.

1. Peak value of shock wave pressure. Peak value of shock wave pressure refers to the highest value of pressure in a blast wave and may be categorized as overpressure peak, negative pressure peak, and dynamic pressure peak. It is measured in kilopascal (kPa). A blast wave's pressure peak is the main parameter that causes blast injury, and it positively correlates with severity of injury. In other words, the higher the peak value of the shock wave at the site of explosion, the more severe the injury.
2. Duration of positive pressure. Duration of positive pressure refers to the length of time of positive pressure caused by shock wave in the pressure zone. It is measured in millisecond (ms) or seconds (s). Within a certain length of time and under the same peak pressure, the longer the duration of positive pressure, the more severe the injury.
3. Impulse. Impulse refers to the sum of the value of instantaneous pressure within the duration of pressure, or in other words, the integral of the force of pressure with respect to time. It is measured in kPa/s or kPa/ms. Impulse consists of two parameters, i.e., pressure peak and positive pressure duration, and it is more accurate and suitable in describing the relationship between a blast wave and the severity of injuries caused. In particular, for blast injuries that happen underwater, pressure peak is high but positive pressure duration is short; or for composite blast injuries that occur inside enclosed spaces such as that of a tank or armored vehicle, impulse can better explain the relationship between the shock wave's physical parameters and the resulting blast injuries.
4. Duration of pressure increase. Duration of pressure increase refers to the length of time starting when pressure acts on a certain point on the body until reaching its peak value. It is measured in millisecond (ms) or second (s). Duration of pressure increase reflects the rate at which pressure rises on a point affected by the shock wave, and when other conditions are constant, the shorter the duration of pressure increase, the faster the rate of pressure increase, the more severe the blast injury.

2.2 Biomechanical Mechanisms of Injury from Blast Wave

Blast wave injuries mainly result from the direct effect of blast wave, the indirect effect from the displacement of objects caused by the blast, and being thrown and collided against other objects due to dynamic pressure. Injury mechanism behind shock wave can be simplified as either a direct or indirect result of the shock wave. The biomechanical mechanisms, however, are not completely understood, particularly with regard to the effects of the overpressure and negative pressure from a blast wave.

1. Direct effects of blast wave refers to injury arising from the pressure of a blast wave (overpressure and negative pressure). Such injuries are called primary blast injury or pure blast injury, and are chiefly manifested in injuries to air-filled organs such as lungs, gastrointestinal tracts, and auditory apparatus, in addition to possible bleeding in some more solid organs. Strong overpressure on the human body could cause rupture in organs and fractures in bones such as ribs and ossicles, but usually does not cause direct injury on the surface. At present, there is general agreement that direct shock wave injury mechanisms mainly include:
   (a) Implosion: When a shock wave propagates through a liquid medium that contains bubbles or air pockets, the overpressure of shock wave would cause the compressible air to compress drastically, while liquids and solids would not be compressed nearly as much. The shock wave's overpressure is followed by negative pressure, which would cause the compressed

air bodies to expand immensely, much like many mini explosions that release energy in all directions and injure tissues in their surroundings. Implosion-induced injuries usually occur in tissues of air-filled organs such as the lungs and gastrointestinal tract.

(b) Pressure differential: When pressure on two sides of a tissue differ, such pressure differential could directly injure said tissue. Therefore, when a shock wave propagates and as it reaches a certain tissue or organ, the tremendous difference in pressure at a local area within a split instance caused by the high pressure on one side and ambient pressure on the other side could directly injure said tissue or organ. For instance, eardrum rupture caused by overpressure is the outcome of pressure differential. Another example happens in the lungs, when shock wave hits a body, pressures rise in both the liquid (blood inside vessels) and gas (air in pulmonary alveoli), but pressure rises more in liquid, and the massive pressure difference between liquid and gas would rip apart the capillaries, resulting in blood flowing into pulmonary alveoli and pulmonary hemorrhage.

(c) Overtension: When air-filled organs in the body are hit by a blast wave, during the pressure-decreasing and negative pressure phases, these air-filled organs could change from being under pressure to being expanded, as in tissues changing from being compressed to being inflated and extended, and these tissues have to bear tensile strain and tension stress arising from such inflation. In most cases, tissues can withstand much more compression than extension, and when tensile strain reaches a certain point, microvascular endothelial cells and alveolar epithelial cells would become more permeable, which would result in edema and bleeding. Worst, when tensile strain exceeds the limits of the tissue's capacity, more serious edema and bleeding would occur as the tissues and blood vessels rupture. During the course of pressure decrease, the higher the pressure peak and the shorter the duration of pressure decrease (i.e., faster rate of pressure decrease), the more obvious the overtension and the more serious the injury.

(d) Spalling (fragmentation): When a blast wave propagates through the body from a compact tissue into loose tissue, reflections take place at the interface between compact tissue and loose tissue. This type of reflected wave could cause a sudden rise in local pressure in the compact tissue, leading to injuries such as alveolar laceration and bleeding, subendocardial bleeding, and bladder mucosal bleeding.

(e) Inertia: When the same shock wave acts on two tissues with different densities, the two tissues accelerate and decelerate at markedly different rates, and this difference causes tremendous shear stress on the interface between the two tissues, resulting in laceration where the two connect. For examples, rib and intercostal tissue lacerations and bleeding, intestinal and mesenteric tissues lacerations and bleeding are both attributed to shock wave inertia.

(f) Negative pressure: Immediately following the overpressure of a blast wave is negative pressure. The speed at which pressure drops, the duration of negative pressure and peak value of negative pressure are the chief parameters in injury, of which, negative pressure peak value plays the biggest role. Negative pressure could result in severe injuries to the lungs, such as widespread pulmonary hemorrhage and edema. Worth noting is that the negative pressure peak value needed to cause such severe injury is much less than overpressure peak value.

(g) Hemodynamics: After a blast wave's overpressure acts on the body, the pressure pushes against the soft abdominal wall, causing pressure inside the abdominal cavity to rise rapidly, in turn pressing the diaphragm upward, causing blood in the superior vena cava to abruptly rush into the heart and lungs, sharply increasing blood volume in these organs. At the same time, the shock wave's overpressure also presses against the chest cavity, decreasing the volume of the space behind the chest, and since the thoracic cage is relatively harder than the abdomens, the pressure increase in the chest cavity is relatively delayed, resulting in subsequent rush of blood toward the head and sharp increase in blood volume inside the head. Right after overpressure is negative pressure, and the retraction due to pressure decrease would cause the abdominal cavity and thoracic cage to enlarge. This kind of rapid compression and expansion generates huge hemodynamic changes, resulting in injuries to the heart, lungs, and distant vascular tissues (such as that of the brain).

2. Indirect effects of blast wave: Indirect and secondary injuries caused by projectiles and other elements resulting from the dynamic pressure of a blast wave are collectively known as indirect blast wave injuries. Indirect injury effects of blast wave mainly include:

(a) Secondary projectiles: Not only does the dynamic pressure of a blast wave turn fragments and shrapnel of a shell into projectiles that could injure the human body, but also imbues other objects (e.g., glass, stone) with kinetic energy and turns them into damaging projectiles. Bombing investigations and statistical data acquired after the atomic bombings of Japan show that the majority of different kinds of open wounds were caused by these secondary projectiles. In cities, industrial sites, and residential areas, most secondary projectiles are glass shards from windows, in open spaces meanwhile rocks and even dust or dirt could be "weaponized" as projectiles.

(b) Throw and displacement: When dynamic pressure is strong enough, it could manifest as an impact force or projection force. When the dynamic pressure of a blast wave hits a human body, the person could be displaced or thrown high in the air, and then land from a high altitude or impacted against another solid object, resulting in injury. Injuries due to being thrown or displaced are similar to traumas from falling or traffic accident, such as skin abrasion, contusion of subcutaneous tissue, internal organ bleeding and rupture, and bone fracture.

(c) Crush and collision from the collapse of structure: Blast wave often causes a portion or an entirety of structures or fortifications on the ground surface to collapse, crushing or burying people within, leading to surface soft tissue and internal organ injuries alongside bone fractures, with crush injuries and crush syndrome appearing in the more severe cases. When fortifications covered in dirt collapse, people within might be buried and even die from suffocation.

(d) Other concurrent injuries: During the course of an explosion, often times there are other injury causes such as flash, fire, poisonous gas, dust, drowning, radioactive substance, virus, and other pathogens, which could lead to corresponding injuries to the human body.

3 Types of Blast Injuries

Due to the varying metrics systems and standards, blast injuries could be classified using different methods. For instance, methods could be based on blast injury cause, shock wave propagation medium, or body part and organ injured, etc.

3.1 Classification of Blast Injury Cause

Classification based on the biomechanics behind blast injury is a method based on the dynamics of how people are injured by a blast wave. In this regard, most classification methods used in China and abroad are based on the method developed by Zuckerman during World War II. This method classifies blast injury into four types: primary blast injury, type II blast injury, type III blast injury, and type IV blast injury, of which, the last three blast injuries are also known as secondary blast injuries.

1. Primary blast injury refers to injury directly caused by physical factors such as a shock wave's overpressure, dynamic pressure, or negative pressure, and may be called a pure blast injury. Since air is easily compressed and expanded, primary blast injuries are often seen in the lungs, middle ear, gastrointestinal tracts, and other air-filled organs.
2. Type II blast injury refers to bodily injuries caused by projectiles like shrapnel, fragment, broken glass and rock launched by the force of a blast wave. Such injuries are mostly penetration or laceration wounds, and could be seen on any part of the body from the surface and internal organ to the limbs.
3. Type III blast injury refers to collision injuries when people are being thrown by the force of a blast wave, or being struck or crushed by the collapse of structure and fortification. These could result in penetration wound, blunt trauma, bone fracture, traumatic disjunction, crush injury, and crush syndrome on any part of the body.
4. Type IV blast injury refers to any other injuries or diseases related to an explosion but not classified as either primary, secondary, or tertiary blast injury. This miscellaneous group includes bodily harms from flash, fire, toxic gas, dust, drowning, psychological factor, and other issues caused by an explosion, and may afflict any part or organ of the human body.

3.2 Classification of Shock Wave Propagation Medium

Since any blast wave-induced injury to the human body may only occur through some sort of medium, how an explosion causes injury is closely associated with shock waves in different media, including characteristics of propagation, features of injury causes, exposure–response relationship and outcomes. Therefore, classifying blast injury based on the shock wave propagation medium has many merits. Generally speaking, shock wave propagation medium are classified as either air blast injury, underwater blast injury, or solid blast injury.

1. Air blast injury refers to injuries to the body from blast wave propagated through the air. The term "blast injury" predominantly refers to air blast injury. Air blast injury is not only associated with the shock wave parameters discussed before, but also the wavelength and frequency of shock wave in the air. When shock waves in the air have relatively short wavelength and generate high-frequency "cracking" sounds, the number of shock waves that hit the human body is higher per unit of time, which translates into higher probability of injuring the human body. On the contrary, when shock waves in the air have

relatively long wavelength and emit low-frequency "boom" or "thud," usually only a single wave would strike the human body, which in turn means that the probability of harms to the human body is much lower.

At high altitudes, where the air is thin and atmospheric pressure is low, the same shock wave with the same force would cause more severe blast injury than at a lower altitude.

The author's laboratory conducted an experiment using BST-II bio-shock tube to study how rats would be injured by blast waves under different atmospheric pressures (53.99 kPa, 61.33 kPa, and 96.60 kPa). Results show that when overpressure peak value (190.40 kPa) and positive pressure duration (10 ms) remain constant, lower atmospheric pressure leads to significant increase in fatality rate and significant rise in lung injury severity. After 6 h, the fatality rate of the three groups of rats were respectively 36.8%, 25.0%, and 0%, area of pulmonary hemorrhage were respectively (653.21 ± 652.25)mm^2, (313.50 ± 357.25)mm^2, and (63.75 ± 69.01)mm^2, and lung volume indices were respectively 1.51% ± 0.77%, 1.31% ± 0.65%, and 0.93% ± 0.21%, indicating that lower atmospheric pressure raises fatality rate and exacerbates lung injuries.

In addition, BST-I bio-shock tube and decompression chamber were used to replicate and model the rats' high-altitude blast injuries so as to observe morphological and hemorheological changes. Results indicate that pulmonary hemorrhage and edema were more severe compared with low-altitude injuries, blood viscosity elevated significantly and remained heightened even 6 h after injury.

2. Underwater blast injury refers to injury to people in water due to blast wave generated in the subsurface explosion of bombs, missiles, or other explosive devices and propagated through water. Naval warfare is one of the major battlespaces in the future, which is why underwater blast injury has become one of the focal points of modern blast injury research, which take into full account the characteristics of shock wave propagation and injury causes in water.

The physical properties of underwater shock wave vary markedly from shock waves in the air, and therefore, injuries also differ vastly. Some of the main differences include: (1) Increased speed of propagation (usually three to four times faster than in the air); (2) propagated relatively farther, and area of effect of blast wave in water is almost ten times larger than that in the air; (3) no compression zones or rarefaction zones, and water molecules also do not move as much as air molecules as a shock wave propagates through them; (4) when underwater shock waves reach the interface between the water surface and the air, reflection occurs and creates unique reflected waves, or tensile waves. The tensile waves propagate in directions different from the incident waves, and serve to reduce the incident waves (Fig. 1). The closer the point of action to the water surface, the more the incident wave is reduced (Fig. 2). In other words, when there is an underwater explosion, people closer to the water surface would be less severely injured.

Clinical features of underwater blast injury are as follows: (1) There are extremely few injuries to the surface of the body. In an underwater explosion, usually there won't be a large amount of secondary projectiles, and seldom would people be thrown against some sort of hard, solid object. Thus injuries to the surface of the body are rare. (2) Injuries to air-filled organs are severe while injuries to liquid-containing organs are light. The former may be explained by implosion, while the latter is caused by similar density between liquid and soft tissues. Such an experiment has been performed previously: Isotonic saline-filled animal intestine was subjected to an underwater explosion, and no damage to the intestine was observed, even if the intestine was placed near the explosive. However, when there was even a tiny amount of air left inside the intestine, holes could be seen on the intestinal wall right after an explo-

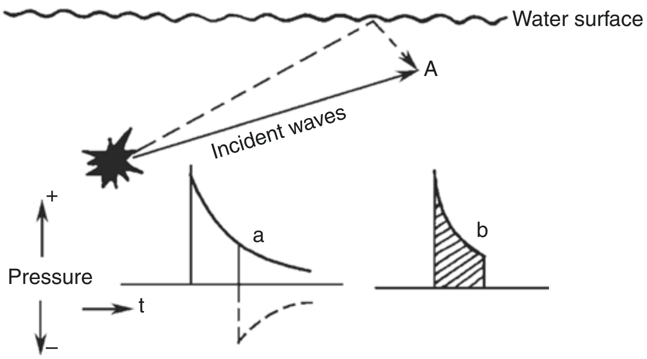

Fig. 1 Formation and action of tensile waves. (**a**) Incident waves before reaching point A; (**b**) reduced incident waves when reaching point A; *A* action point, *t* time

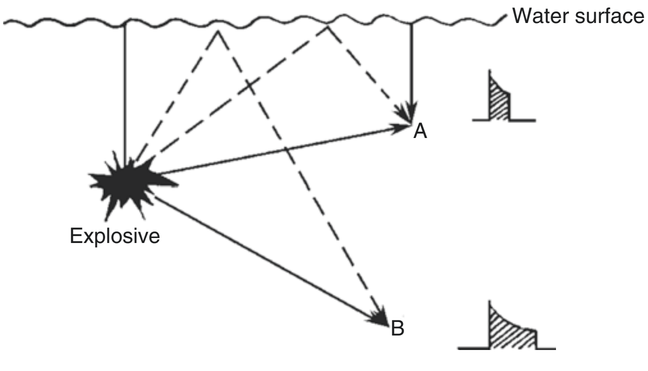

Fig. 2 Different effects of various tensile waves. *A* Action point, *B* Action point

sion. (3) Most head injuries are light. This is because during an underwater explosion, the majority of victims are near the surface and their heads are above water. (4) Most abdominal injuries are severe. For people underwater or floating on the surface, the abdomen is in direct contact with water, and the abdominal wall is relatively soft, which is why when an underwater explosion occurs, organs in the abdomen (gastrointestinal tract for the most part) are more prone to severe injuries compared with an air explosion. (5) The fatality rate is relatively higher. One report indicates that 47 victims out of 118 in an underwater blast died, a fatality rate of 39.8%. Another document reports that 9 victims out of 13 in an underwater blast died, a fatality rate of 69.2%. Meanwhile, in general 90% of air blast injury victims are not severely injured.

In order to understand the characteristics of underwater blast injury and the exposure–response relationship between shock wave strength and injury severity, the author's laboratory carried out the following experiment: 37 mixed-breed dogs anesthetized, floatation devices were attached to their necks so that their heads would stay above water while the bodies and limbs would be underwater perpendicularly to the surface. The dogs were placed on either side of the 3.5 m and 17.5 m in a distance from explosion center (Figs. 1, 2, and 3), TNT explosives ranging from 0.2 to 1.0 kg in quantity were placed 3 m underwater, high-pressure instantaneous detonator was used for detonation, and the survival conditions and pathological changes in the animals were observed on-site and 6 h thereafter. Result shows that (1) the features of physical parameters of underwater shock wave are: high peak pressure value but short duration, as in several hundred microseconds, far shorter than the several or tens of milliseconds in the duration of shock wave in air generated by an explosion. In addition, the duration of pressure increase is measured in microseconds, which is extremely short particularly when compared with the 1 ms-range of explosions in the air. Therefore, cause of injury by underwater shock wave can't be determined simply with using overpressure peak value, and in this regard impulse is more suitable. Preliminary exposure–response relationship analysis indicates that impulse ranges respectively for light, moderate, severe, and extremely severe injuries are 121.1–14.0 kPa/ms, 142.0–214.3 kPa/ms, 247.8–322.6 kPa/ms, and 322.6–579.8 kPa/ms. (2) The lethal radii for 0.2 kg, 0.5 kg, and 1.0 kg TNT explosions are respectively 5 m, 8.75 m, and 12.5 m from the blast center, much farther than the lethal range of mid-air explosions with the same amount of explosives. The lethal radius of 0.5 kg TNT underwater explosion (8 m) is approximate to 40.0 kg of TNT explosion in mid-air. (3) The fatality rate is high. Of the 37 dogs, ten died on-site (two had collapsed lung and pneumonia before injury, and thus were not counted), and no death was recorded 6 h after injury, registering the final fatality rate of 27%. This result may be attributed to the fact that explosions from the same quantity of explosives at different ranges underwater generate much stronger shock waves when compared to explosions in the air. (4) Lung injury is the most common (83.7%) and most serious, with the majority of on-site deaths associated with severe pulmonary hemorrhage and edema, coronary artery air embolism arising from ruptured lung and pulmonary injury were even observed in some animals. (5) There is a high rate of injury to the intestine, with 29.73% afflicted by small intestine injury and 51.35% afflicted by colon injury, far higher than those caused by mid-air explosions. Colon injury was more common because it contains more air. (6) The rate of injury to solid organs is low. Other than three cases of slight bleeding in the pancreas and one case of ruptured liver, no injuries were found in spleens, kidneys, and filled bladders. (7) There are no injuries on the surface of bodies.

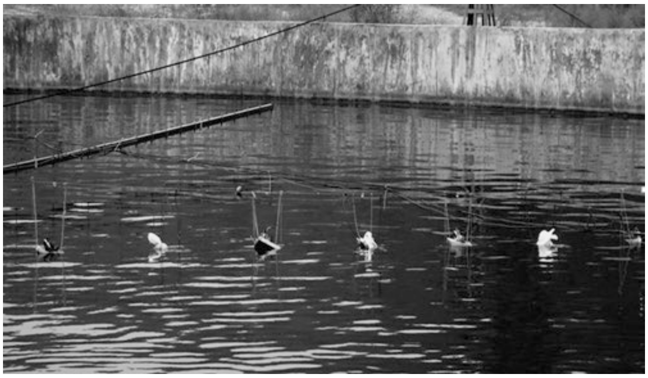

Fig. 3 Placement of test animals for underwater blast injury experiment

3. Solid blast injury refers to injuries to the body from blast wave propagated through solids. The propagation of blast wave in solid is vastly different from propagation in air or water, specifically, the relatively smaller amplitude and shorter time of the shock wave's action (usually within a few milliseconds), but also an immensely faster acceleration. Solid blast injuries are often seen when battleships, tanks, or armored vehicles are hit by an explosive, and the blast wave and secondary shock wave thereafter act on the structure, deck and armor of the struck vessel/vehicle, then propagate in the form of flexion wave. This results in two types of motion: First is the slight displacement and acceleration of solid, and second is the subsequent bending, vibration, and other obvious macroscopic motions. The first type of motion would injure body parts that are in contact with the solid, usu-

ally injuries to the lower limb, especially damage to the ankles. This is considered primary injury of and the general definition of solid blast injury. The second type of motion might cause victims to be thrown against other objects and injured, which would be deemed secondary solid blast injury.

Main characteristics of solid blast injury include: Mostly injuries to bones and joints in the lower extremities, and this kind of bottom-up impact might result in closed fracture and injury to the heel bone, phalanges, shinbone and lower part of calf bone and ankle joint, with heel bone fracture being relatively frequent. Analysis of information about 50 victims of solid blast injuries shows that 18 suffered from bone fractures in the ankles, with the majority being multiple, comminuted fractures, including 11 victims with heel bone fractures affecting 15 limbs. Body part injured is clearly associated with body position, and the majority of injuries occur on one side of the body. For example, a particularly lower extremity is more easily injured when standing, while the spine is more likely to take damage when sitting. Injuries to solid organs in the abdominal cavity are also quite common, and one possible reason is that the acceleration of the shock wave induces deformation and displacement of internal organs, leading to crushing, collision, retraction, and other injuries when organs interact with bones, muscles, and ligaments. Injuries to the liver and spleen are the most frequent. Indirect injuries happen often, mostly manifested as damages such as soft tissue injury, bone fracture, cerebral concussion arising from sudden acceleration and movement of brain matter caused when a person is thrown or horizontally displaced then struck against something. Of the 50 hospitalized cases, 32 showed loss of consciousness, which resulted from head injuries when they were thrown or displaced.

3.3 Classification of Body Part and Organ Injured

Classification based on body part and organ injured is a method that focuses on the specific body part and organ injured by a blast wave. Some common categories are brain blast injury, thoracic blast injury, abdominal blast injury, blast injury of the spinal cord, and blast injury of the extremities. Moreover, blast injuries may also be categorized as injury to the lungs, heart, brain, gastrointestinal tract, liver, auditory apparatus, and other body parts. Among them, blast injuries to the lungs, gastrointestinal tract, and auditory apparatus occur on a more frequent basis.

Through body part and organ-based classification, diagnosis can quickly pinpoint the area(s) injured by blast wave, and carry out corresponding diagnosis, prevention and research methods based on injury mechanisms and characteristics.

3.4 Classification of Injury Severity

1. Pathological classification: Yelverton, an American scientist, recently introduced an injury scoring system that may be used as basis for judging severity of injury. The main points include: (a) First of all, calculate the overall score of an individual injury including its scope, severity, type, depth, or wound condition; (b) divide the score of said injury by the worst case scenario-score for that type of injury to obtain the ratio score of said injury; (c) add the ratio scores of all individual injuries to find their sum; (d) add scores of pathogenic factors (e.g., pneumothorax, hemothorax, hemoperitoneum, coronary artery air embolism or cerebral vascular air embolism); (e) multiply the score by two if the victim dies; and (f) to determine the level of non-auditory apparatus injury, subtract the ratio score for auditory apparatus injury from the Severity of Injury Index (SII) to obtain the Adjusted Severity of Injury Index (ASII). This methodology is detailed and relatively accurate, but also somewhat complex.
2. Clinical classification
    (a) Light: General injuries to auditory apparatus, light internal organ contusions (intraplaque hemorrhage), scratches on the surface of the body, etc.
    (b) Moderate: Relatively large-scale internal organ contusions (patchy hemorrhage or hematoma), relatively light pulmonary edema, large swaths of soft tissue injury, dislocation, rib fracture with no obvious dislocation, cerebral concussion, etc.
    (c) Severe: Ruptured internal organ, fractured bone (thigh bone, spine, cranial base, and multiple fractured ribs), relatively severe pulmonary edema, pulmonary hemorrhage, etc.
    (d) Extremely severe: Extremely serious or fatal injuries such as severe cerebral and spinal cord injury, ruptured chest cavity or abdominal cavity, widespread and serious pulmonary hemorrhage or pulmonary edema, ruptured artery, amputation with severe bleeding, etc.

4 Epidemiological Features of Blast Injury

Blast injuries differ quite markedly from other kinds of injuries in terms of aspects such as injury causing condition, injury mechanism, on-site environment and treatment. Therefore, the injury characteristics and epidemiological features of blast injury are also quite different from other types of injuries.

4.1 General Features of Blast Injury

Since both the direct and indirect effects of a blast wave act on the body during the course of a blast injury, things can get very complicated when injured tissues and organs, injury mechanisms and processes are all taken into consideration. The situation is further compounded due to the varying environments and conditions where injury occurred. Therefore, blast injuries are characterized by features unlike those seen in other types of injuries. In general, the features of blast injury include:

1. Complicated injury: The overpressure, negative pressure, and dynamic pressure of a blast wave all could cause injury on their own or when acting together, both directly and indirectly. This diversity in injury causes and methods means that blast injury types and conditions are complicated. Blast injuries are complicated for the following reasons: Most blast injuries are multiple injuries or injuries to multiple body parts, and external and internal injuries to numerous organs and body parts could all happen at the same time. Most blast injuries are combined injuries such as blast-fragment combined injury, burn-blast combined injury, and radiation-blast combined injury. Blast injuries often include different kinds of injuries such as blunt trauma and penetration wound, or contusion and rupture on the same body, or edema and hemorrhage simultaneously. In particular, external injuries caused by explosion are often accompanied by relatively serious infections due to contact of open wounds with disease-causing agents. Thus, many medical professionals naturally associate blast injury victims with substantial infection.
2. Blast injuries mostly affect specific, target organs. Although blast injuries could damage any part or tissue of the body, because of the features of the shock wave itself and of its propagation medium, most blast injuries affect specific organs. Air-containing tissues and organs are the primary victims of air blast injury or underwater blast injury, which is why injuries to the eardrum in the middle ear, the lungs, and gastrointestinal tract are almost unavoidable. Solid blast injury meanwhile almost always affects body parts in direct contact with the solid medium of shock wave propagation, or body parts that the propagated shock wave act on longitudinally. Thus, identifying the target organ damaged in blast injury is of utmost importance.
3. Light external injury and severe internal injury. This characteristic is the result of the blast wave's mechanisms and modes of action. When a shock wave acts on the body, injury on the surface often appear light, especially injuries caused only by overpressure or negative pressure, whereby the body surface might not even have any obvious sign of damage. However, the target organs inside, such as the lungs or gastrointestinal tract, might have already sustained heavy damage, or in other words, light external injury and severe internal injury.

   At the site of major bomb explosion experiment, when an animal is closer to the center of explosion (distance varies with respect to explosion equivalent), there might be visible signs of external injuries to the body surface and limbs, but injuries to the internal organs are always more severe, and most of the times the primary cause of death. For animals within the range of injury but farther from the center of explosion, there are relatively fewer and lighter injuries to the body surface and extremities, but internal injuries could still be dire and are even the main cause of fatality.
4. Rapid deterioration of injury. For severe or worst blast injuries, there is a relatively stable compensatory period within a short span right after the injury, but if treatment is not administered promptly, the situation would rapidly worsen. In particular, brain injury, pulmonary hemorrhage, pulmonary edema, or other organ injury would further speed up the deterioration.

   During the atomic bombings of Japan in the Second World War, there were a relatively few number of victims recorded as severe or worse blast injuries, which might be because the condition exacerbated rapidly for many such badly injured victims, resulting in casualty. At the site of explosion experiment, it has been observed that some animals initially showed decent conditions and normal movement in a short span after the explosion, but soon they would exhibit difficulty in breathing, shock, and then death. Dissection shows that these animals were mostly afflicted by serious pulmonary hemorrhage, pulmonary edema, or ruptured organs liver, spleen and other internal organs.

4.2 Incidence Rate and Fatality Rate of Blast Injury

With advancements in modern, hi-tech and high-explosive weaponry, and changes in the mode and method of armed conflict, modern warfare has seen an increasingly abundant use of various kinds of hi-speed and high-explosive weapons (including improvised explosive devices), and the ratios of injuries and casualties from blasts and explosions have continued to rise.

Take military actions for instance. Between 2001 and 2014, more than 6700 American soldiers in Afghanistan and Iraq have been killed by explosions, and over 50,000 wounded. For the US forces in Iraq between March 2003 and October 2011, improvised explosive device (IED) alone killed around 2200 American soldiers and injuring another 22,000. During the two military campaigns in Iraq, the number of deaths and casualties among the Iraqi troops and normal citizens are even more difficult to count or even estimate.

In the past several decades, there have been many acts of violence perpetrated through explosives around the world, with terrorist bombings being especially devastating. In Israel alone, nearly 20,000 terrorist attacks were perpetrated between September 2000 and December 2003, resulting in approximately 900 casualties, of which suicide bombings have killed 412, accounting for 45.78% of total. Report from the UNESCO Center for Peace shows that between September 11th, 1993 and September 10th, 2009, across the globe there were 624 terrorist bombings that resulted in multiple injuries and deaths, with casualties amounting to a total of 26,073 victims (an average of 42 killed in each attack). The September 11th attacks in 2001 were a watershed moment, with 68 major terrorist bombings (including 9/11 itself) having been committed in the previous 8 years, resulting in the deaths of 3921 persons; meanwhile 556 major terrorist bombings took place in the next 8 years, killing a total of 22,152 persons, with the number of occurrences and casualties being respectively 8.2 times and 5.7 times more than the first 8 years. Clearly, terrorist attacks around the world have been on the rise, and their destructiveness to the worldwide community is only getting worse.

At present, there is not yet a relatively uniform database about bombing-related injuries anywhere in the world. In addition, due to the difficulty in gathering data about explosion-related injuries in warfare, there is still no report or analysis, at least with a relatively comprehensive scope, on worldwide data about the epidemiology of blast injuries. Most blast injury data available originate from the analysis of data of individual explosions, or data from regional databases or research centers such as the US-based Terrorism Research Center and the Global Terrorism Database. Therefore, no one has an accurate idea about the overall incidence rate and fatality rate of explosion-related blast injuries, and we can only make estimates through investigations and data analysis.

1. Blast injury incidence rate: At present, the atomic bombings of Hiroshima and Nagasaki in 1945 by the USA remain the only use of nuclear weapons in warfare, and some of the earliest statistics and data for analysis of relatively detailed extent also came from these atomic bombings. Post-war info on injury and casualty shows that among the moderately and severely wounded, 36.6% were blast injuries, 60% of early casualties in Hiroshima died from injuries due to blast wave, nearly 70% of the wounded (70% for Hiroshima, 64.3% for Nagasaki) that have survived after 20 days of the bombing were afflicted with combined injury that included blast injury. These wounded obviously suffered from blast injuries coupled with some other injuries (e.g., burns, radiation). Due to the limited understanding about and diagnostic capacity for blast injury at the time, it is possible that some others wounded by blast injuries were not tallied. Thus, conservative estimate of blast injury incidence rate for the atomic bombings should be above 70%.

In the modernization of weaponry, development in explosive weapon is one of the fastest and most obvious. From simple artillery shells, bombs, mines and cluster bombs, to high-explosive squash head (HESH) projectiles, shaped charges and weapons based on augmented shock waves (e.g., fuel-air explosives), even large atomic bombs and hydrogen bombs, the destruction to equipment and structures and fatality to personnel caused by the blast wave of these weapons are increasingly terrifying. In other words, shock wave is destined to be one of the most important and dangerous cause of injury and death in armed conflicts in the future, whether nuclear or conventional.

The USA deployed thermobaric weapon (fuel-air explosives) for the first time during the Vietnam War, and report of data analysis about 101 cases of wounded personnel shows that blast injury incidence rate was 50.4%. Another report indicates that blast injury incidence rate during the First Chechen War in Russia was 30%. When tallying the 1303 cases of patients severely wounded by explosion treated at the former Yugoslav Academy of Military Medical Sciences, it was discovered that blast injury incidence rate was 51.0%. In skirmishes along the border in southwestern China in the 1980s, among a group of 166 persons injured by artillery and mines, blast injury incidence rate was 22.3%. In a research about a certain model of fuel-air explosive carried out by the author's organization, it was discovered that of the animal deaths caused by said model of fuel-air explosive, the incidence rate of blast injury was a whopping 100%, while that for severely injured animals exceeded 90%.

Various types of bombs and improvised explosive devices have become the weapon of choice in terrorist attacks, and blast injuries from these explosives constitute the main cause of injury and death in victims. Analysis of statistics of 647 wounded terrorist attack victims tallied after their arrival at hospital shows that blast injury incidence rate was 29.8%. Analysis of a group of 3357 victims in another terrorist bombing points out that of those that died on-site, blast lung injury alone accounted for 47.0%.

In terms of distribution of body parts injured by blast wave, figures from different reports vary. In general, among blast wave survivors, about 10% have injured eyes, 9–47% have damaged auditory apparatus, 3–14% have obvious blast injury to the lungs, while only 0.3–0.6% suffered from blast injury in the gastrointestinal tract.

Clinically speaking, although incidence rate of abdominal injury from blast wave is not very high, the fatality rate from such injury is relatively high. Analysis of 61 articles and papers between 1966 and 2009 shows that average incidence rate of abdominal blast injury was 3.0% (lowest was 1.3%, highest was 33.0%). Primary blast injury incidence rates in open space and enclosed space are respectively 5.6% and 6.7%.

2. Blast injury fatality rate: Compared with other types of injury, blast injuries are characterized by more complications and more severe injuries, as well as a higher fatality rate. In most cases, death rates of blunt trauma or penetration wound exhibit a classic three-phase distribution, while that of blast injury is characterized by a two-phase distribution, namely a relatively higher rate of instantaneous death, and relatively lower fatality rate later on.

   Instantaneous death rate is contingent on a myriad of influential factors such as intensity of explosion equivalent, distance from center of explosion, potential number of victims, structural collapse of buildings, and whether environment is open or enclosed. When other conditions are the same, structural collapse of buildings and fortifications, and whether environment is open or enclosed, are relatively more influential on blast injury severity and fatality rate.

   When buildings and fortifications collapse due to an explosion, death rate of blast injury significantly rises. For example, analysis of blast injury data about 29 groups of explosion victims shows that instantaneous death rate is as high as 25% when there is structural collapse. In addition, explosions in enclosed spaces would lead to a larger number of and more severe primary blast injuries, along with a significant increase in instantaneous death rate. Research report shows that in explosions that occurred in enclosed spaces, death rate fluctuates between 8.3% and 15.8%, whereas fatality rate in open space explosions is merely 2.8–4%. Other experiment and research outcomes also demonstrate that with the same explosion equivalent and same density of animal distribution, primary blast injury incidence rate would reach as high as 78% and death rate 49% in enclosed space. Meanwhile, in open space, primary blast injury incidence rate drops to 34% and death rate merely 7.8%.

   At the explosion site, victims with light or moderate primary blast injuries usually appear similar to those unwounded persons due to the absence of external injuries, but it is extremely difficult to diagnose and identify any damage to internal organs on-site. In addition, the fatality rate among victims with light or moderate primary blast injuries is very low, which drags down the death rate of blast injuries and can't truly reflect the severity of blast injuries. Therefore, some researchers use death rate from critical injury to reflect the seriousness of blast injury of an explosion and rescue performance level. In most cases, critical blast injury may be categorized as requiring immediate surgery, ICU care, or endotracheal intubation due to acute problems in windpipe, breathing, circulatory system, or nervous system. Death rates of critical blast injury as seen in documents and reports range from 9% to 22%.

5 Principles for Treatment of Blast Injury

In order to promptly and effectively perform emergency rescue, diagnosis, evacuation and transportation to hospital, and treatment, first and foremost it is necessary to determine injury severity before carrying out corresponding measures.

5.1 Light Blast Injury

Such injuries are mainly light cerebral concussion, light pulmonary hemorrhage, general auditory apparatus injury, cuts and scratches on the surface of the body, among others. Usually this category of victims are the most numerous, accounting for roughly half of all blast injury victims. Due to the lack of obvious internal organ damage or body-wide symptoms, this class of injury does not seriously affect victim's capacity and does not mandate special treatment.

5.2 Moderate Blast Injury

Such injuries are mainly relatively serious cerebral concussion, light pulmonary edema, serious auditory apparatus injury, internal organ intraplaque hemorrhage or patchy hemorrhage or hematoma, and large swaths of soft tissue injury, among others. Clinical symptoms are relatively obvious, usually accompanied by body-wide symptoms. Hemoptysis is common 1–3 days after moderate lung injury, auscultation might discover occasional rale and crepitus, and similar symptoms to other injuries for soft tissue injury and single dislocations. Situations for some victims might worsen because of combination of other injuries or inadequate protection during the evacuation process, but in general there won't be shocks or life-threatening risks. Most victims would eventually recover rather well, and only a small percentage would experience worsened situation due to other injuries.

5.3 Severe Blast Injury

Such injuries are mainly cerebral contusion, relatively serious pulmonary edema or hemorrhage, ruptured or perforated internal organs (i.e., liver, spleen, stomach, intestine, and bladder) and bone fracture (i.e., thigh bone, spine, cranial base and multiple fractured ribs), among others. Cerebral contusion might result in unconsciousness and increase in intracranial pressure. Lung injury might lead to dyspnea and hemoptysis, percussion of the chest may produce dull sounds, and auscultation might discover wide areas of moist rale. Ruptured abdominal organs might result in abdominal pain, abdominal wall tension, pain, pressing pain, rebound tenderness, and other peritoneal irritations. Ruptured liver or spleen might result in serious internal bleeding or shock, while gastrointestinal rupture or perforation might lead to diffuse peritonitis. Bone fractures have similar symptoms as other injuries and should be treated as per other injuries.

5.4 Extremely Severe Blast Injury

Such injuries are mainly multiple severe injuries like severe cerebral and spinal cord injury, chest, abdominal and spine injury, ruptured organ, serious pulmonary edema or hemorrhage, ruptured artery, serious crushing injury to soft tissue and amputation, among others. In addition, such victims might also suffer from serious burns or radiation injury. Victims in this category are mostly located near ground zero, and often die within a short period due to excessive injury. Most deaths early on result from serious cerebral and spinal injuries, ruptured organs resulting from serious hemorrhage (hemorrhagic shock) and multiple fractures (fat embolism). Deaths later on are chiefly attributed to perforation peritonitis, bronchopneumonia, septicemia, and other secondary infections. Serious cerebral injuries and multiple internal organ ruptures have clinical symptoms similar to other injuries and should be treated as general injuries. Most of the extremely severely wounded victims die within a day.