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DEFEAT the DEVICE

An Introduction to the Effects of Explosions and Blast Injuries

The know-how acquired in different Areas of Operation have brought into focus the need for enhanced soldier-based protective systems and other mitigating actions to safeguard our soldiers against improvised explosive devices (IEDs). The employment of IEDs by terrorists, insurgents and criminal organizations also has demanded the need to understand the nature of injuries caused by such devices. This need for understanding includes appreciating the multisystem effects of blasts on different organs and tissues of the body. The wounds from IEDs are complex, and the organization and care will depend on the sort and severity of injuries.

With the augmented rate of global terrorism against noncombatant targets, new consideration has been directed toward injuries in civilian populations. Hence, concerted efforts at understanding the pathophysiology of blast injuries, risk factors, kinds of injury, and means to stimulate recovery from such injuries are of paramount importance.

1. CONCEPTS OF MORTALITY[1]

In contrast to the classic three-phasesdistribution of mortality seen in standard blunt and penetrating trauma, mortality from explosions results in a biphasic distribution; there is a high immediate mortality rate, followed by a low early and late mortality rate. Immediate mortality rates are affected by many factors, including magnitude of the explosion, proximity to potential victims, presence of building collapse, and closed versus open space environment. In a study of 29 mass casualty bombings, Arnold et al. (2004) found that immediate mortality was one in every four persons for bombings with structural collapse, one in every 12 persons in confined space bombings, and one in every 25 persons in open air bombings. Most survivors of explosions have non critical or no injuries. As a result, the low overall mortality rate among the injured is deceiving. A more informative rate is the *critical mortality rate*, which is the mortality rate among the subgroup of critically injured survivors. A *critical injury* may be defined as one in which a casualty presents with an acute airway, breathing, circulatory, or neurological problem that requires

The wounds from IEDs are complex and require a different management and care

immediate surgical intervention, admission to the ICU, and/or endotracheal intubation (Gutierrez de Ceballos et al. 2004). The critical mortality rate is more indicative of the severity of the event and of the results of medical management rendered, and typically ranges from 9 to 22% (Frykberg 2002). In compiling the results of ten terrorist bombing incidents, Frykberg found a linear relationship between the critical mortality rate and the rate of overtriage, which is the percentage of patients with minor injuries but classified as needing immediate treatment. In his study, overtriage ranged from 8 to 80% (averaging 53%) and critical mortality ranged from 0 to 37% (averaging 12.6%); the linear correlation coefficient was an extremely high r = 0.92.

2. EXPLOSION INJURIES[2]

The cause of injury during an explosion is multifaceted (DePalma et al. 2005). When a device detonates, the resulting blast wave interacts with objects in its way. In the human body, the blast wave increases the pressure inside the body and produces stress and shear waves in body tissues. These waves are reinforced and reflected at tissue interfaces, thereby enhancing the injury potential, particularly in gas-filled organs such as the lungs, ears, and bowel. This is referred to as *primary blast injury*. In open spaces, few subjects within the area of the high pressure blast wave survive, as they are literally torn apart by multiple components (fragments, heat, toxic gases, dynamic pressure) of the blast environment. In closed spaces, such as inside buildings or in urban "canyons," primary blast injuries are more common, partially because the reflecting surfaces extend the duration and range of the blast wave, so that lethal overpressures can exist at further standoff distances or around corners, where the other components of the blast environment are basically benign. For example, blast lung injury is a major cause of immediate death at the scene of an explosion in closed space environments, but seldom the cause of death in initial survivors (Gutierrez de Ceballos et al. 2005a, 2005b; Avidan et al. 2005).

Following the shock front, the *blast wind*, which is the dynamic component of the blast wave, propels solid matter such as glass fragments and rocks, penetrating the patient. Penetrating injuries due to an explosion are termed *secondary injuries*, although they are often the primary cause of the injuries. The body may also be thrown into objects, resulting in blunt or crush injuries, referred to as *tertiary injuries*. The resultant heat, flames, and inhalation of hot gases and smoke from an explosion produce *quaternary injuries* such as burns. In spite of the nomenclature characterizing blast injuries as primary, secondary, tertiary, or quaternary, victims of an explosion rarely suffer from just one type of injury. The diverse etiology of injuries from explosions results in a complex and severe pattern of injury not encountered in any other situation. In open space explosions the injury patterns become more distinct as the casualty's initial position from the epicenter is increased.

Types of blast injuries:

- ***Primary due to the blast wave.***
- ***Secondary due to fragments and displaced objects.***
- ***Tertiary due to body's acceleration and deceleration.***
- ***Quaternary due to building collapse or falling parts.***
- ***And thermal injuries related to the ºT rise.***

The following statement in a National Research Council report sums up the availability of data on bombings:

Insufficiency of data on bombings. For technical evaluations, cost-benefit analyses, and formulation of a technically detailed rational response strategy, the data available today on illegal use of explosive materials in the United States do not constitute a suitable basis for a complete scientific analysis (National Research Council 1998).

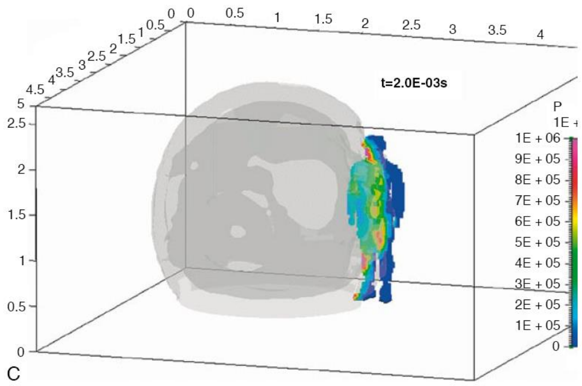

Figure 1. Modeling and Mechanism of Primary Blast Injury. Explosion and blast – Related Injuries. –Navil M. Elsayed, James L. Atkins.

3. BLAST INJURIES[3]

Primary Blast Injuries

Injuries directly inflicted on the human body by a blast wave are referred to as primary blast injuries. When individuals are located in the immediate vicinity of an explosive at the time of detonation, gaping lacerations of the skin and the internal organs and severe mangling of body parts may occur, or the victims' bodies may be even totally disrupted (Hiss & Kahana 1998; Tsokos et al. 2003a, 2003b; Crane 2005).

Traumatic amputation of limbs is a frequent finding, especially in those who were located in the immediate vicinity of the explosive at the time of detonation (Aggrawal & Tsokos 2005; Hiss & Kahana 1998; Tsokos et al. 2003a; Shields et al. 2003; Crane 2005). As a direct effect of the blast wave that creates powerful shearing forces that act in a coaxial direction relative to the bone, comminuted fractures of long bone shafts mayesult. Limb flailing caused by the blast wave then completes the amputation by disrupting the soft tissue (Hull & Cooper 1996).

Apart from whole body disruption and amputation of limbs, direct blast wave exposure almost exclusively affects gas-containing organs. Due to complex phenomena taking place between the blast wave and objects in its path such as the occurrence of marked pressure stresses at air/fluid interfaces, gas-containing organs such as the lungs, middle ear, and gastrointestinal tract are the organs most vulnerable to overpressure brought about by the blast wave. The resulting pathological findings are blast lung injury, tympanic membrane rupture, and bowel contusion and/or bowel perforation in the absence of penetrating abdominal wall wounds (Phillips 1986; Mayorga 1997). Primary blast injuries are estimated to contribute to 47 to 57% of injuries in survivors and to 86% of fatal injuries (Mayorga 1997).

Figure 2. Postmortem lungs from a human blast victim. Explosion and blast Related Injuries. Nabil M. Elsayed, James L. Atkins.

Secondary Blast Injuries

Secondary blast injuries result from blast-energized bomb fragments and other displaced objects at the site of explosion such as fragments of glass, casing, and masonry, causing penetrating trauma (Cooper et al. 1983; Leibovici et al. 1996; Tsokos et al. 2003b; Shields et al. 2003; Aggrawal & Tsokos 2005). The characteristic type of injury due to blast-energized bomb fragments and displaced debris from the scene of explosion is a combination of bruises, puncture abrasions, puncture lacerations, and penetrating wounds (Hiss & Kahana 1998; Crane 2005); this type of injury is referred to as *missile injuries*, *propeller injuries*, or *peppering injuries*.

Tertiary Blast Injuries

Tertiary blast injuries occur when the body is accelerated from the blast wave at first and is then abruptly decelerated on rigid objects, thus resulting in mainly all types of blunt force trauma and, occasionally, in penetrating trauma (Cooper et al. 1983; Leibovici et al. 1996; Shields et al. 2003).

Quaternary Blast Injuries

Quaternary blast injuries are defined as those injuries of victims of explosions that are due to the collapse of a building or falling parts of a building where the explosion took place (Aggrawal and Tsokos 2005). This type of injury is mostly blunt force trauma such as crushing injuries but penetrating trauma and asphyxia of those who are buried under the debris is also frequently observed.

Thermal Injuries

Significant skin burns may be inflicted by explosions. The severity of a burn is directly related to the temperature rise within the skin and the duration of this rise. One has to differentiate between primary and secondary thermal injuries (see Table 3-1).

Primary Thermal Injuries

Although the term *blast wave* refers to the intense over-pressurization impulse created by a detonating explosive, this phenomenon has to be distinguished from the term *blast wind*, a forced super-heated air flow (heat radiation) that is generated by the explosion. It is characteristic of bombings that flash burns inflicted by the blast wind (so-called primary thermal injuries) are usually limited to exposed (undressed) areas of the victim’s body since clothing usually provides good protection from flash burns (Rajs, Moberg & Olsson 1987; Mellor 1992; Tsokos et al. 2003b).

These primary thermal injuries are generally more superficial than those seen as a result of secondary thermal injury.

The pressure tolerance for short duration blast loads is significantly higher than for long-duration blast loads.

Secondary Thermal Injuries

Burns occupying large surface areas and affecting those body areas covered by clothing prior to the explosion imply that either the heat was of such intensity that the victim’s clothing caught fire or that the location where the detonation took place caught fire (Aggrawal & Tsokos 2005). These burns are designated as secondary thermal injuries and are usually more severe than primary thermal injuries.

4. HUMAN TOLERANCE[4].

Blast Pressures.

Human tolerance to the blast output of an explosion is relatively high. However, there are significant factors in determining the amount of injury sustained.

- The orientation of a person (standing, sitting, prone, face-on or side-on to the pressure front),
- Relative to the blast front,
- The shape of the pressure front (fast or slow rise, stepped loading).

Human blast tolerance varies with both the magnitude of the shock pressure as well as the shock duration.

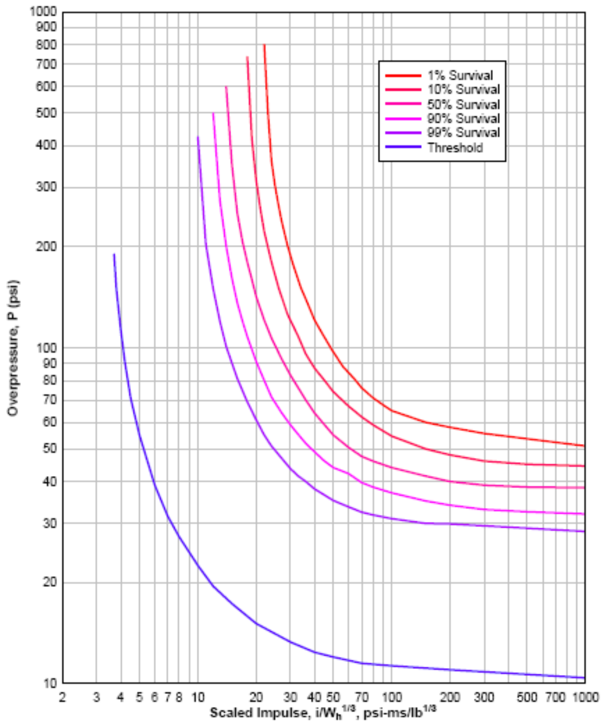

Figure 3. Survival Curves for Lung Damge, Wh = Weight of human being (lbs) UFC 3-340-02

The pressure tolerance for short-duration blast loads is significantly higher than that for long-duration blast loads.

Tests have indicated that the air-containing tissues of the lungs can be considered as the critical target organ in blast pressure injuries. The release of air bubbles from disrupted alveoli of the lungs into the vascular system probably accounts for most deaths. Based on present data, a tentative estimate of man's response to fast rise pressures of short duration (3 to 5 ms) is presented in the Fig.2.

The threshold and severe lung-hemorrhage pressure levels are 30 to 40 psi (2 to 2.75 bar) and above 80 psi (5.5 bar), respectively, while the threshold for lethality due to lung damage is approximately 100 to 120 psi (6.9 to 8.3 bar). Table 1

Critical Organ or Event	Maximum Effective Pressure (psi)/bar*
Eardrum Rupture	
Threshold	5 / 0.345
50 percent	15 / 1.03
Lung Damage	
Threshold 30-40	30-40 / 2.06-2.75
50 percent 80 and above	80 / 5.51 and Above
Lethality	
Threshold	100-120 / 6.89-8.27
50 percent	130-120 / 8.96-9.65
Near 100 percent	200-250 /13.79-17.23

Table 1. Maximum effective pressure is the highest of incident pressure, incident pressure plus dynamic pressure, or reflected pressure. UFC 3-340-02

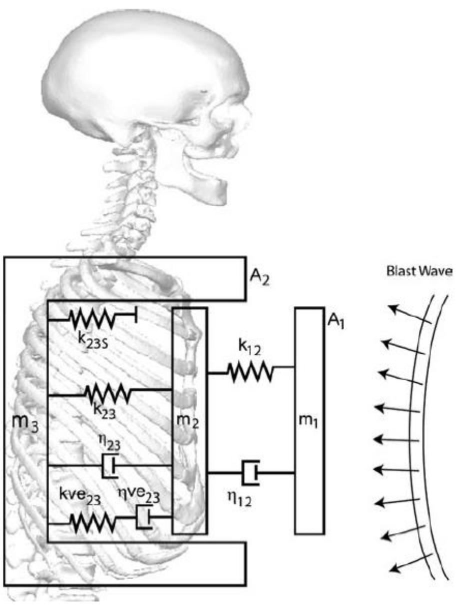

Figure 4. Spring-Mass-Dashpot compact model of thoracic biomechanics and impact injury (based on Lobdell et al. 1973; Viano 1978; Viano & Lau 1988; Stuhmiller et al. 1996).

On the other hand, the threshold pressure level for petechial hemorrhage resulting from long-duration loads may be as low as 10 to 15 psi (0.68 to 1.03 bar), or approximately one-third that for short duration blast loads.

Since survival is dependent on the mass of the human, the survival for babies will be different than the survival for small children which will be different from that for women and men. These differences have been depicted in Figure 2 which indicates that the survival scaled impulse depends on the weight of the human. It is recommended that 11 lb (5 kg) be used for babies, 55 lb (25 kg) for small children, 121 lb (55 kg) for adult women and 154 lb (68 kg) for adult males.

Figure 5. Dummies from "Alava Ingenieros"

A direct relationship has been established between the percentage of ruptured eardrums and maximum pressure, i.e., 50 percent of exposed eardrums rupture at a pressure of 15 psi (1.03 bar) for fast rising pressures while the threshold of eardrums rupture for fast rising pressure is 5 psi (0.34 bar). Temporary hearing loss can occur at pressure levels less than those which will produce onset of eardrum rupture. This temporary hearing loss is a function of the pressure and impulse of a blast wave advancing normally to the eardrum.

Survival depends on the mass of the human.

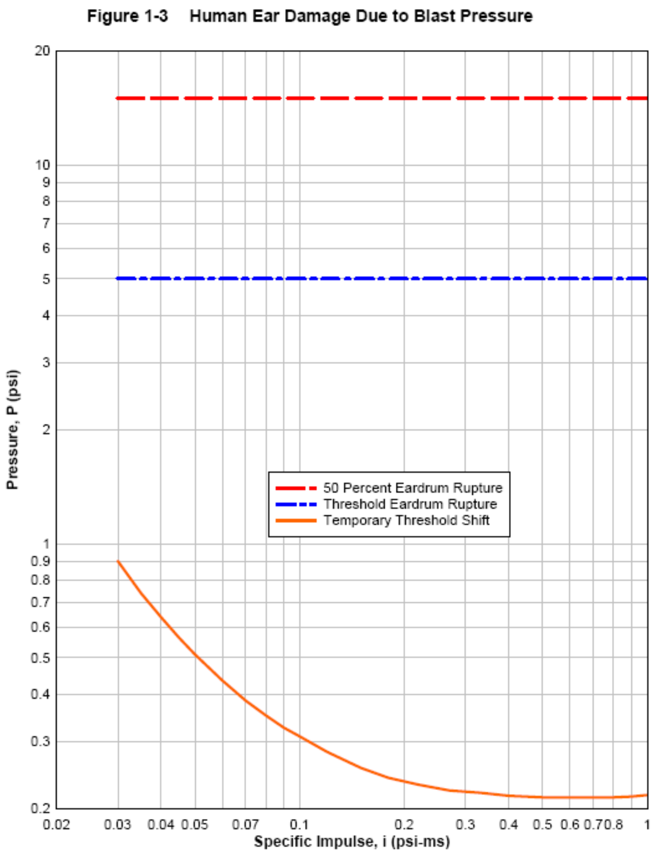

Figure 6. Human Ear Damage Due to Blast Pressure.

The curve which represents the case where 90 percent of those exposed are not likely to suffer an excessive degree of hearing loss, is referred to as the temporary threshold shift. The pressures referred to above are the maximum effective pressures, that is, the highest of either the incident pressure, the incident pressure plus the dynamic pressures, or the reflected pressure. The type of pressure which will be the maximum effective depends upon the orientation of the individual relative to the blast as well as the proximity of reflecting surfaces and the occurrence of jetting effects which will cause pressure amplification as the blast wave passes through openings. As an example, consider the pressure level which will cause the onset of lung injury to personnel in various positions and locations. The threshold would be 30 to 40 psi (2 to 2.75 bar) reflected pressure for personnel against a reflector (any position), 30 to 40 psi (2 to 2.75 bar) incident plus dynamic pressure; 20 to 25 psi (1.37 to 1.72 bar) would be the incident pressure plus 10 to 15 psi (0.68 to 1.03 bar) dynamic pressure for personnel in the open, either standing or prone-side-on, and 30 to 40 psi (2 to 2.75 bar) incident pressure for personnel in the open in a prone-end-on position.

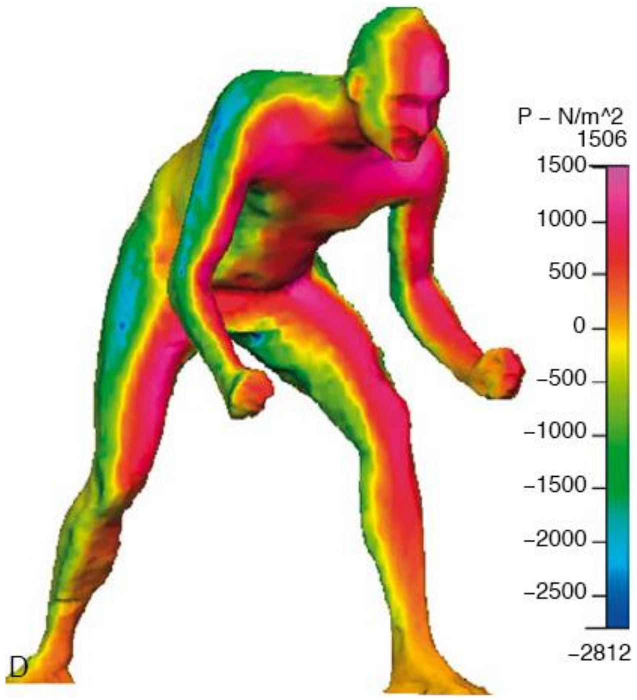

Figure 7. Computational modeling of high speed wind interaction with a human body, pressure loads on the body, and calculation of forces and moments on various body parts for body biomechanics using ATB model (Wilkerson & Przekwas 2005).

However, the above pressure level assumes that an individual is supported and will not be injured due to being thrown off balance and impacting a hard and relatively non-yielding surface. In this case, pressure levels which humans can withstand are generally much lower than those causing eardrum or lung damage. For this case, it is recommended that tolerable pressure level of humans not exceed 2.3 psi (0.16 bar) which is higher than temporary threshold shift of temporary hearing loss (Figure 6) and will probably cause personnel, who are located in the open, to be thrown off balance.

Structures can be designed to control the build-up of internal pressure; however, the jetting effect produced by pressure passing through an opening can result in amplification of the pressures at the interior side of the opening. The magnitude of this increased pressure can be several times as large as the maximum average pressure acting on the interior of the structure during the passage of the shock wave. Therefore, openings where jetting will occur should not be directed into areas where personnel and valuable equipment will be situated.

Structural Motion.

It is necessary that human tolerance to two types of shock exposure be considered:

1. Impacts causing body acceleration/deceleration, and
2. Body vibration as a result of the vibratory motion of the structure.

The more plausible means of impact injury results from subject being thrown off balance.

If a subject is not attached to the structure, he/she may be vulnerable to impact resulting from collision with the floor due to the structure dropping out beneath him/her and/or the structure rebounding upward towards them However, the more plausible means of impact injury results from the subject being thrown off balance because of the horizontal motions of the structure, causing them be thrown bodily against other persons, equipment, walls and other hard surfaces.

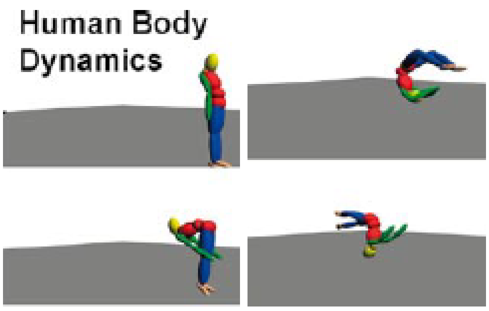

Figure 8. Simulation of the human body dynamics and ground impact resulting from an explosion blast wave load. ATB model used CFD body loads to calculate body biodynamics. Explosion and blast- Related Injuries. Nabil M.Elsayed, James L. Atkins.

Studies have indicated that a probable safe impact tolerance velocity is 10 fps (3.05m/s). At 18 fps (5.5m/s) there is a 50 percent probability of skull fracture and at 23 fps (7m/s), the probability is nearly 100 percent. This applies to impact with hard, flat surfaces in various body postures.

Figure 9. Hanlon, Erin and Cynthia Bir. Validation of a Wireless Head Acceleration Measurement System for Use in Soccer Play. Journal of Applied Biomechanics, 2010, 26, 424-431 © 2010 Human Kinetics, Inc.

However, if the line of thrust for head impact with a hard surface is directly along the longitudinal axis of the body (a subject falling head first), the above velocity tolerance does not apply since the head would receive the total kinetic energy of the entire body mass. Impacts with corners or edges are also extremely critical even at velocities less than 10 fps (3.05m/s). An impact velocity of 10 fps (3.05m/s) is considered to be generally safe for personnel who are in a fairly rigid posture; therefore, greater impact velocities can be tolerated if the body is in a more flexible position or if the area of impact is large.

The effect of horizontal motion on the stability of personnel (throwing them off balance or hurling them laterally) depends on the body stance and position, the acceleration intensity and duration, and the rate of onset of the acceleration. An investigation of data concerning sudden stops in automobiles and passenger trains indicates that personnel can sustain horizontal accelerations less than 0.44*g* without being thrown off balance.

These accelerations have durations of several seconds; hence, the accelerations considered in this paper required to throw personnel off balance are probably greater because of their shorter durations. Therefore, the tolerable horizontal acceleration of 0.50*g* required to provide protection against ground-shock effects resulting from nuclear detonations should be safe for non-restrained personnel (standing, sitting, or reclining).

If the vertical downward acceleration of the structure is greater than 1*g*, relative movement between the subject and the structure is produced. As the structure drops beneath him, the subject begins to fall until such time that the structure slows down and the free falling subject overtakes and impacts with the structure. The impact velocity is equal to the relative velocity between the structure and the subject at the time of impact, and to assure safety, it should not exceed 10 fps (3/05m/s).

Human tolerance to fragment impact is very low.

To illustrate this vertical impact, a body which free falls for a distance equal to 1.5 feet (0.45m) has a terminal or impact velocity of approximately 10 fps (3.05m/s) against another stationary body. If the impacted body has a downward velocity of 2 fps (0.6m/s) at the time of impact, then the impact velocity between the two bodies would be 8 fps (2.4m/s).

Based on the available personnel vibration data, the following vibrational tolerances for restrained personnel are considered acceptable: 2*g* for less than 10 Hz, 5*g* for 10-20 Hz, 7*g* for 20-40 Hz, and 10*g* above 40 Hz.

Fragments.

Overall, human tolerance to fragment impact is very low; however, certain protection can be provided with shelter type structures.
Fragments can be classified based on their size, velocity, material and source:

1. Primary fragments, which are small, high-speed missiles usually formed from casing and/or equipment located immediately adjacent to the explosion.

Figure 10. Open sources. Internet

2. Secondary fragments, which are generated from the breakup of the donor building, equipment contained within the donor structure and/or acceptor buildings which are severely damaged by an explosion.

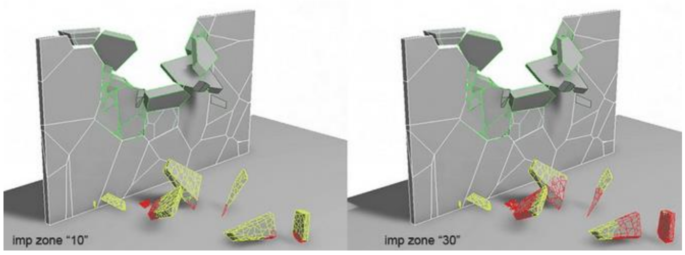

Figure 11. http://www.andvfx.com/demolition-master-manual/#concrete-2nd-break

Discussion of human tolerance of both of these types of fragment overlap, since the basic differences between these fragments are their size and velocity. Impact of primary fragments can be related to an impact by bullets where the fragment is generally small, usually made of metal and traveling at high velocities. A great deal of research has been conducted for the military; however, most of the data from these tests is not available.

Some fragment-velocity penetration data of humans has been developed for fragment weights equal to or less than 0.033 pounds (15gr), and indicates that, as the ratio of the fragment area to weight increases, the velocity which corresponds to a 50 percent probability of penetrating human skin will increase. This trend is illustrated in Table 2 where the increase in velocity coincides with the increase of area of the fragment.

Secondary fragments, because they have a large mass, will cause more serious injuries at velocities significantly less than caused by primary fragments. Table 3 indicates the velocity which corresponds to the threshold of serious human injury. As mentioned above, the impact of a relatively large mass with a velocity less than 10 fps (3.05m/s) against a human can result in serious bodily injury. Also, the impact of smaller masses (Table 3) with higher velocities can result in injuries as severe as those produced by larger masses.

Injures caused by explosives are always much the same but the incidence of theirs changes when we deal with a combat or civil scenario.

Ratio of Fragment area/weight ft²/lb	(m²/Kg)	Fragment Area Based on 0.033 lb. fragment weight ft²	(m²)	Velocity fps	(m/s)	Threshold Energy ft-lb	m-kg
0.03	0.0061	0.00099	9E-05	100	30.48	5	0.69
0.10	0.0205	0.00330	0.0003	165	50.29	14	1.94
0.20	0.0410	0.00660	0.0006	250	76.2	32	4.42
0.30	0.0614	0.00990	0.0009	335	102.1	58	8.02
0.40	0.0819	0.01320	0.0012	425	129.5	93	12.86

Table 2. 50 Percent Probability of Penetrating Human Skin UFC 3-340-02

Critical Organ	Weight (lbs)	Fragment Velocity (fps)	Energy (ft-lb)
Thorax	>2.5	10	4
	0.1	80	10
	0.001	400	2.5
Abdomen and limbs	>6.0	10	9
	0.1	75	9
	0.001	550	5
Head	>8.0	10	12
	0.1	100	16
	0.001	450	3

Table 3. Threshold of Serious Injury to Personnel Due To Fragment Impact UFC 3-340-02

5. CONCLUDING REMARKS

Victims of explosions usually suffer from a combination of blast lung injury, blunt force trauma, penetrating injuries, and burns. The type, distribution, and severity of injuries of bombing victims most often indicate their location in relation to the epicenter of the explosion.

Although the particular environment within which an explosive device detonates significantly influences the pathology of injuries caused by explosives, the pathological features of human blast lung injury, blunt force trauma, penetrating injuries, and burns following explosions are always much the same.

It would appear that among survivors of terrorist bombings against civilian targets, the incidence of burns is relatively infrequent. As shown in the Madrid train bombings, most of the burns tend to be mild flash burns with correspondingly low mortality (Gutierrez de Ceballos et al. 2005) unless the blast is concentrated in a confined space. The incidence and severity of burns will generally increase if the blast results in a fire or is powerful and hot enough to ignite or blow away clothing. Burns, though not as frequent as mechanical trauma in blast mechanisms of injury, can be significant contributors to patient morbidity in both civilian and military populations. The ability to provide adequate burn care from the point of wounding through the burn center and rehabilitation care phases is vital to preparing to deal with the injuries that result from explosions.

Most military patients seen in combat support hospitals have injuries due to explosions. The incidence of primary blast injury is minimal, as the majority of patients have penetrating and/or blunt injuries. Burns account for about 3 to 5% of injuries. Multiple injuries are the norm. The area of the body injured is proportional to the percent of the body surface area at risk. The primary cause of potentially preventable death both before and after admission is hemorrhage. These findings are similar to those seen in previous conflicts and in the civilian population. The majority of patients who die of wounds bleed to death, thus aggressive correction of coagulopathy and control of bleeding is warranted. Victims of explosive injuries have extended stays in intensive care and the hospital as the magnitude and diversity of their injuries is greater than those from gun shots or shrapnel alone.

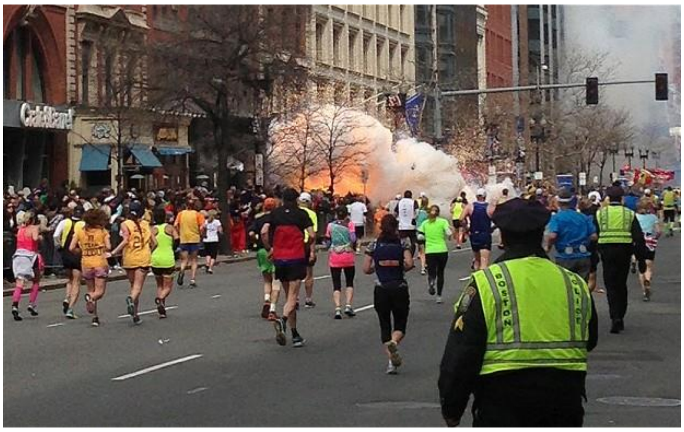

Figure 12. Boston Marathon Explosions. May 2013

References

[1] The Epidemiology and Triage of Blast Injuries. Richard W. Sattin, Scott M. Sasser, Ernest E. Sullivent III, and Victor G. Coronado.

[2] Explosion Injuries Treated at Combat Support Hospitals in the Global War on Terrorism. Charles E. Wade, Amber E. Ritenour, Brian J. Eastridge, Lee Ann Young, Lorne H. Blackbourne, and John B. Holcomb.

[3] Pathology of Human Blast Lung Injury, Michael Tsokos.

[4]UFC 3-340-02 05DEC2008

Disclaimer

Due to the author's Engineering PhD studies, he has had to read several papers that have described the explosion and blast related injuries. He considered them interesting for the C-IED community and thus has presented those parts that could provide the reader a first approach and a general idea about this topic in this document .

All the main points are referred to their original sources and reading of the original paper is a must for those ones who want to learn or know more about this interesting subject

José Ignacio Yenes Gallego

Maj – OF3 ESP (A)
R & D Analyst
Defeat The Device Branch
C-IED Centre of Excellence

Phone: +34 91 856 10 33
E-mail: jyenes@c-iedcoe.es