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Research Article

Review of Blast Injury and Developing Threshold Values for Human Injury

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Abstract : In today's world, explosions frequently occur in terrorist bombings, industrial and manufacturing sectors, and daily life. The blast waves generated by explosions subject structures and the human body to significant blast loads. These blast loads can cause deadly structural collapses, and serious injuries or fatal outcomes can occur in various parts of the human body, such as the brain, lungs, heart, auditory system, eyes, abdominal region and musculoskeletal system due to the impact of the blast load. This article initially discusses the blast wave and its characteristics (peak pressure and duration) as well as the parameters of the blast wave, which have been related to injuries occurring in the major organs of the human body. Subsequently, the effects of blast loading have been quantitatively documented under the headings of blast injuries, types and mechanisms of blast injuries, and the effects of explosions on the human body, correlating the severity of injuries with nearly all major systems of the human body. As a result, various injury scaling criteria have been carefully compiled to determine thresholds for major organ injuries, and ultimately, limit blast pressure values for different parts of the human body (lung, ear and head) have been proposed.

Keywords : Blast Injury, Blast Wave, Explosion, Injury Criteria, Injury Scaling

1 Introduction

Explosions occur when a liquid or solid substance instantaneously transitions to the gas phase, generating energy in the form of sound, heat, light, and pressure. These explosions can result in blast injuries or fatalities. Such injuries are generally caused by the detonation of high-order or low-order explosives. Examples of high-order explosives include C-4, Semtex, dynamite, ammonium nitrate, and trinitrotoluene, whereas low-order explosives include Molotov cocktails, pipe bombs and gunpowder. High-order explosives generate supersonic explosions that can move at speeds of up to 8000 meters per second and bringing about pressures up to 30000 times the atmospheric pressure [1]. As the name suggests, low-order explosives have less destructive power compared to high-order explosives but can cause severe explosions when combined with secondary agents (such as metal fragments, nails etc.).

The explosion effects data presented in the UFC 3-340-02 [2] guide largely pertain to the blast pressures of open spherical TNT explosives. Those data can be potentially extended to contain other explosive materials by associating the 'effective explosive weight' of these materials to the explosive energy of an equivalent weight of TNT. In addition to energy output, other factors can influence the equivalence of the material compared to TNT. These factors contain the shape of the material (round, flat, square etc.), the quantity of explosive substance, whether the explosion occurs in an open or enclosed space, and the pressure range considered (close, medium, or long distances). For blast-resistant design, the effects of the energy output of an explosive material of a particular shape compared to that of similarly shaped TNT can be indicated as a function of the blast heat of various materials as follows [2]:

$$W_E = \frac{H^d_{EXP}}{H^d_{TNT}} W_{EXP} \tag{1}$$

where H^d_{EXP} : heat of detonation of explosive in question , H^d_{TNT} : heat of detonation of TNT, W_{EXP} : weight of the explosive in question , W_E : effective charge weight . In conclusion, the characteristics of blast waves resulting from condensed high-energy explosives are apparently similar to those produced by TNT, and the blast parameters of other explosives can be determined using explosives that have blast effects similar to those of spherical TNT. This is referred to as the TNT equivalent of explosives. Generally, the equivalent factor is utilized in relative comparisons, and the data is obtained by comparing the air blast data of different high-energy explosives. Table 6 in explosion physics part of the Wang and Jiang's book provides a list of TNT equivalent factors for computing impulse and overpressure for the explosion of various explosives in an infinite air environment [3]:

1.1 Blast Wave

The pressure or blast wave generated by the sudden release of energy into the atmosphere is one of the most crucial aspects in blast-resistant design. The shape and magnitude of the blast wave, propagating outward in all directions from the explosion source at sonic or supersonic speeds, depend on the nature of the energy release and the distance from the epicenter of the explosion (standoff distance). The blast wave has two distinct characteristic types, namely shock waves and pressure waves, and their typical pressure-time curves are shown in Figure 1 below [4]:

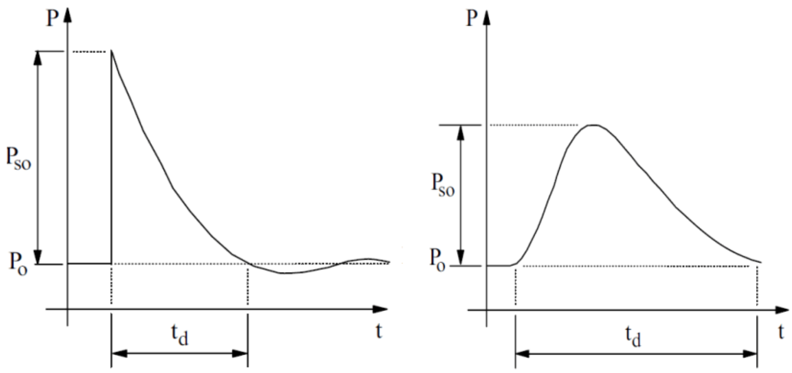


Figure 1: Characteristic types of blast wave: shock wave (left) and pressure wave (right) [4]

Examining the blast pressure-time curve of the shock wave reveals that this wave initially peaks instantaneously at a value above the ambient atmospheric conditions, and then gradually falls to the ambient pressure level with highly damped oscillations. Consequently, it can be stated that the positive phase of the blast wave is followed by a negative phase pressure wave. Looking at the blast pressure-time curve of the pressure wave, it can be observed that the pressure increases over time to reach a peak value, followed by a decrease in pressure over time. It is necessary to define the fundamental parameters of the blast wave as components of the blast load on building elements. These are defined as the maximum pressure for the positive phase, P_{so}, the duration of the positive phase, t_d, and the associated positive impulse, I_o; and for the negative phase; the maximum pressure, P_{so}^{-}, the duration of the negative phase, $t_d{}^{-}$, and the associated negative impulse, $I_o{}^{-}$ [4]. The areas under the pressure-time curves represent the impulse value of the explosion.

$$I_o = \int P(t)dt \tag{2}$$

For a triangular wave : $I_o = 0.50 P_{so} t_d$, For a half-sine wave : $I_o = 0.64 P_{so} t_d$. For an exponentially decaying shock wave : $I_o = c P_{so} t_d$, Here, $P(t)$ represents the function of the variation of overpressure with time, P_{so} : the maximum lateral overpressure value, t_d : the duration of the positive phase, c : value ranging between 0.2 and 0.5 depending on P_{so}. In addition, the blast waves resulting from explosions exhibit very high strain rates in the range of 10^2 to 10^5 s^{-1}. The high and sudden loading rate is critical as it changes the expected damage mechanisms for various structural elements and the dynamic mechanical properties of the target structures, as well as being of paramount importance for human injuries. Figure 2 illustrates the ranges within which strain rates vary for different types of loading conditions [5].

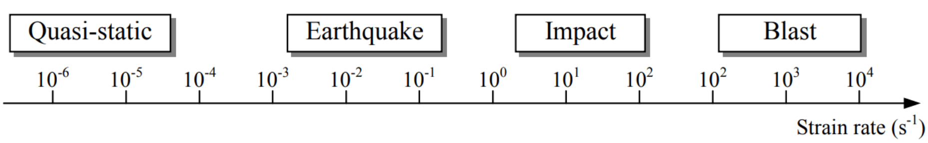


Figure 2: Variation of strain rate for different types of loading [5]

Also, the impulse and peak pressure values on the structure change with the standoff distance, R (distance from the explosive). For a spherical TNT explosions, the positive phase pressures, durations, impulses and other parameters of this shock environment vary with the scaled distance (Figure 3) [2].

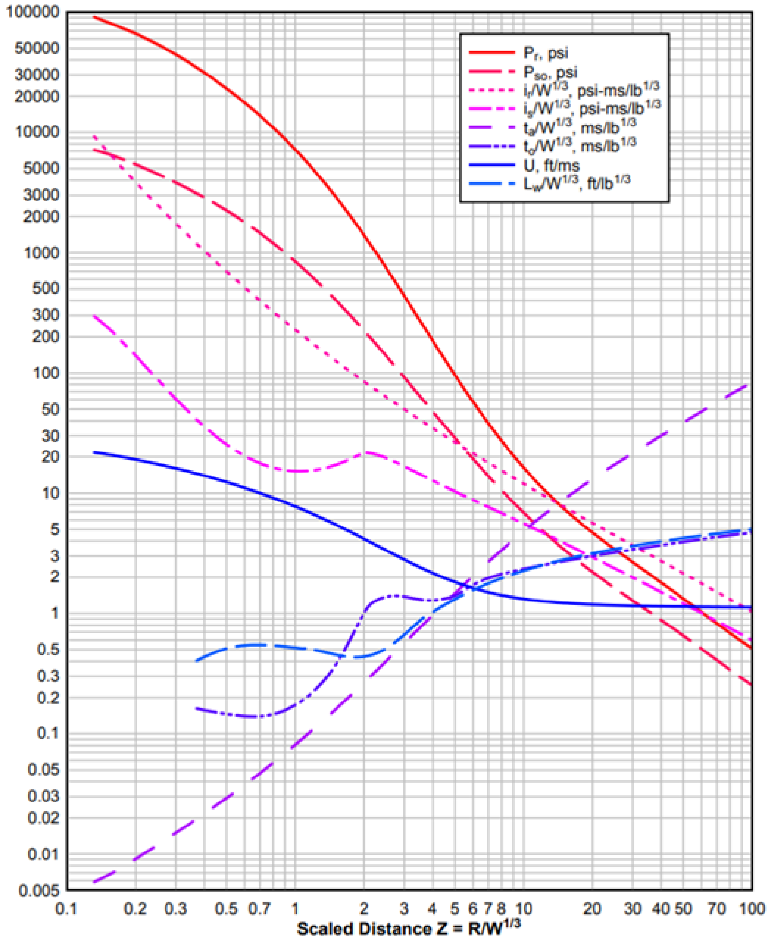


Figure 3: Positive phase shock wave parameters for a spherical TNT explosion in free-air at sea level [2]

1.1.1 Blast Wave Parameters

In addition to the maximum overpressure, impulse and duration, other blast wave parameters that may be involved in determining the blast loads for a structure include [6]:

- Peak reflected pressure, P_r
- Peak dynamic (blast wind) pressure, q_o
- Shock front velocity, U
- Blast wave length, L_w

Typically, these secondary parameters can be computed using the primary blast wave parameters as explained below.

Peak Reflected Pressure, P_r

When a blast wave from an open-air explosion strikes a surface, it reflects. As a result of this reflection, the surface is subjected to a pressure much higher than the incident lateral pressure. The magnitude of the reflected pressure is determined as an amplification of the incident pressure:

$$P_r = C_r \, P_{so} \tag{3}$$

where C_r : coefficient of reflection. The coefficient of reflection bases on the incidence angle of the wave relative to the reflecting surface, the type of the blast wave and the peak overpressure. The curves in Figure 4 and Figure 5 present the coefficient of reflection (C_r) for peak overpressures up to approximately five times the atmospheric pressure and for shock and pressure waves at incidence angles ranging from 0° to 90° [6].

For maximum overpressure values up to 138 kPa (20 psi), which is the range expected in most air explosions, Newmark indicates a simple formulation for the reflection coefficient of a blast wave at normal 0° incidence :

$$C_r = P_r/P_{so} \approx 2 + 0.05P_{so}(P_{so} : [psi]) \tag{4}$$

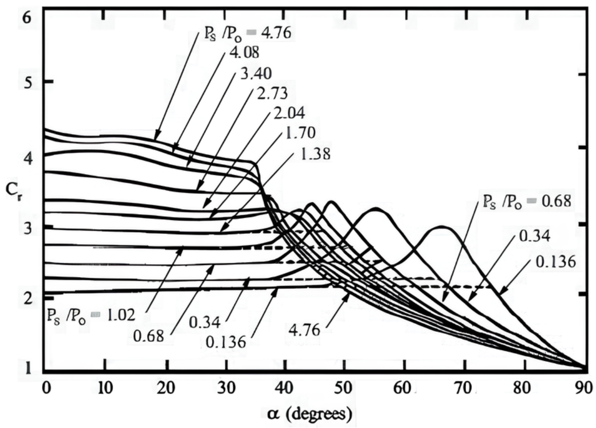


Figure 4: Determination of the reflection coefficient for shock wave [6]

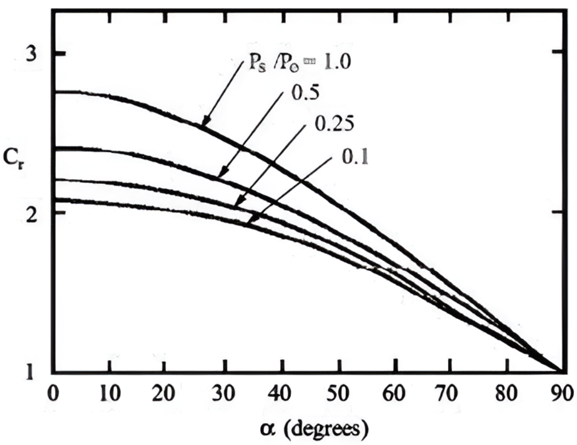


Figure 5: Determination of the reflection coefficient for pressure wave [6]

$$C_r = P_r/P_{so} \approx 2 + 0.0073P_{so}(P_{so} : [kPa]) \tag{5}$$

The dimensions of the reflecting surface can change the duration of the reflected pressure.

Peak Dynamic (Blast Wind) Pressure, q_o.

As the blast wave propagates through the atmosphere, the blast wind pressure, caused by the movement of air due to the blast wave, depends on the velocity of air particles, i.e., the maximum overpressure of the blast wave. To calculate this blast effect, data have been provided by Baker and UFC 3-340-02. Under normal atmospheric conditions, the maximum dynamic pressure can be obtained using Newmark's empirical formulation [6]:

$$q_o = 2.5P_{so}^2/(7P_o + P_{so}) \approx 0.022P_{so}^2[psi] \tag{6}$$

$$q_o = 2.5P_{so}^2/(7P_o + P_{so}) \approx 0.0032P_{so}^2[kPa] \tag{7}$$

where P_o denotes the atmospheric pressure of the environment. The net dynamic pressure on a structure is the product of the dynamic pressure and a drag coefficient, C_d. Depending on the orientation and shape of the obstructing surface, the drag coefficient alters. For a rectangular building, the coefficient of drag can be used as -0.4 for the side and rear walls, as well as roof and $+1.0$ for the front wall [6].

Shock Front Velocity, U

As the blast waves resulting from a free-field explosion propagate through the medium, they travel at or above the speed of sound. For TNT explosives that release high energy, graphs of scaled distance against shock front velocity are provided in UFC 3-340-02 guide. However, similar graphs are not available for the propagation of pressure waves. For design intentions, it may be accepted that a pressure wave moves at the same speed as a shock wave. For standard atmospheric conditions and low-pressure ranges, the pressure / shock front velocities in air can be obtained utilizing the following equations provided by Newmark [6].

$$U \approx 1130(1 + 0.058P_{so})^{0.5}(ft/s) \tag{8}$$

$$U \approx 345(1 + 0.0083P_{so})^{0.5}(m/s) \tag{9}$$

Blast Wavelength, L_w

At any given time, the propagating blast wave extends over a restricted radial distance as the pressure / shock front moves outward. The pressure is greatest at the front and decreases towards the ambient pressure along the length of the blast wave, denoted as L_w. The length of the blast wave in the low-pressure range, can be approximately calculated as follows [6]:

$$L_W \approx Ut_d(m) \tag{10}$$

2 Blast Injury

After discussing the explosion, blast wave, and its characteristics and parameters, this section examines blast injury types and mechanisms, the effects of the blast wave on structures and various parts of the human body, such as the brain, lungs, heart, auditory system, eyes, abdominal region, and musculoskeletal system. Section will end with the injury scaling part.

Typical pressure wave forms for a simple open (free) field explosion and a confined explosion are given in Figure 6. When examining the pressure-time histories, it can be observed that a blast wave in a closed area creates an environment with high pressures for extended periods, allowing more energy transfer to the victim. This increased energy transfer can enhance the lethality of the explosion [7].

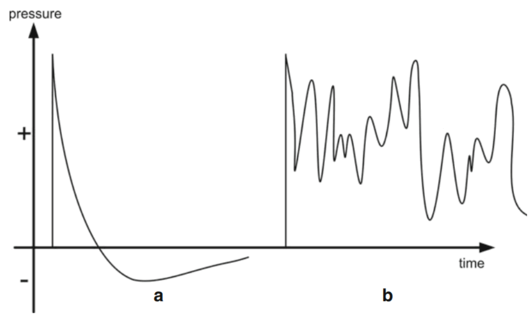


Figure 6: Pressure waveform of a simple open / free field explosion (a) and a closed field explosion (b) [7]

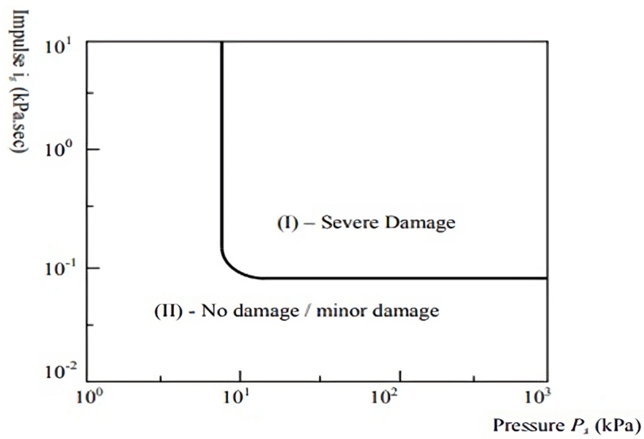


Figure 7: Typical pressure – impulse curve [8]

Also, Figure 7 presents a typical pressure-impulse (P-I) diagram. The pressure-impulse diagram is used to determine specific damage levels by combining the explosion pressures and impulses applied to a specific structural element. As seen in the diagram (Figure 7), Region I indicates severe structural damage, while Region II shows no damage or minor damage [8]. In this context, in recent years, significant efforts have been made to develop blast-resistant reinforced concrete structures for military buildings in regions frequently affected by terrorist attacks and wars [9].

2.1 Blast Injury Types and Mechanisms

Blast injuries alter significantly from other types of injuries in aspects such as injury mechanisms, conditions causing the injury, treatment, and on-site conditions. Therefore, epidemiological features and the injury characteristics of blast injuries are also distinct from those of other injury types.

During a blast injury, both the indirect and direct effects of the blast wave impact the body, making the injured tissues and organs, injury processes and mechanisms quite complex. This complexity is further exacerbated by the varying environment and conditions where the injury occurs. Thus, blast injuries are characterized by features not seen in other types of injuries. Generally, the characteristics of blast injuries can be listed as [3]:

- The dynamic pressure, overpressure and negative pressure of a blast wave can lead to injury either individually or in combination, acting both indirectly and directly. Therefore, complicated injuries are seen in explosions and blast injuries.
- While blast injuries can harm any tissue or part of the body, most blast injuries influence target, specific organs due to the characteristics of the shock wave and the medium of propagation.
- Although minor external injuries may be visible on the human body, serious internal injuries may also occur simultaneously.
- Finally, the rapid worsening of the injury is another characteristic of blast injuries.

Table 1 summarizes common types of blast injuries for different parts of the human body, such as the head, neck-spine, thorax, abdomen, upper extremity, and lower extremity [7].

Table 1: Common types of blast injuries [6]

Parts of the Human body					
Head	Neck - Spine	Thorax	Abdomen	Upper Extremities	Lower Extremities
Fractured skull (brain exposed)	Excessive mobility / fractured spine	Excessive bruising	Penetrating foreign body	Fractured upper / forearm	Fractured Tibia / Fibular / Femur
Fractured maxilla / mandible	Paravertebral haematoma	Penetrating foreign body	Laceration	Disruption at shoulder / elbow / wrist	Foot injury
Disrupted brain tissue	Deep thermal burns	Lacerations	Thermal burns	Hand injury	Disrupted / Fractured Pelvis
İntracranial bleeds	Foreign body-neck	Haemothorax / pneumothorax	Splenic rupture	Penetrating metallic / glass foreign body	Penetrating metallic foreign body
Descalping / Laceration	Laceration	Lung contusions	Renal injury	Traumatic amputation	Traumatic amputation
Tympanic membrane rupture		Fractured / Disrupted ribs		Laceration	Laceration
Deep thermal burns		Deep thermal burns		Degloving	Degloving
Eviscerated eye		Inhalation injury		Deep thermal burns	Deep thermal burns
Orbital injury Bruising					

Table 2 shows that blast injuries are classified as primary, secondary, tertiary, quaternary, and quinary, and the types of injuries with high occurrences for these injury mechanisms can be observed [1].

2.2 Review for the Effects of Explosion on the Human Body

Explosions cause damage to numerous components by their nature. Considering the impact load generated during an explosion, the effects of this impulse on structures and the human body are currently being investigated. Different outcomes can occur depending on the explosive types, the presence of shrapnel, the direction of the blast wave, and the effects of quaternary injuries.

Table 3 summarizes the injury criteria recommended by the NATO HFM-148 task group for different body regions, the injury threshold values according to these criteria, and the corresponding anthropomorphic test devices (crash test dummies) [10]. The anthropomorphic test device (ATD), commonly known as a crash test dummy, is a highly precise testing tool utilized to measure human injury potential in vehicle collisions. Crash test dummies simulate human responses to deflections, impacts, forces, accelerations and moments of inertia during a collision. Here, the relevant crash test dummy types are the Hybrid III 50th Male, the ES-2re and MIL-Lx. The Hybrid III male model is the most commonly utilized crash test dummy. The MIL-Lx, lower leg is attached to a standard Hybrid III ATD. Figure 8 shows the corresponding ATDs with example figures [11]. In addition, in spherical air blasts occurring at various distances, the blast wave parameters showing combinations of positive phase durations and peak overpressure are plotted as a series of curves collected according to the respective explosive masses, and are overlapped with estimated primary blast injury (PBI) criteria in Figure 9 [12]. For 100g and 10kg explosives, the curves are plotted with matching stand-off distances to the explosive at specific intervals. When examining the equivalent TNT explosive masses for the actual blast scenarios, the 10kg and 100g explosive masses approximately serve as explosions of improvised explosive devices

Table 2: Blast Injury Mechanisms [1]

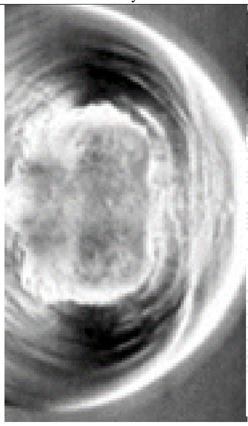
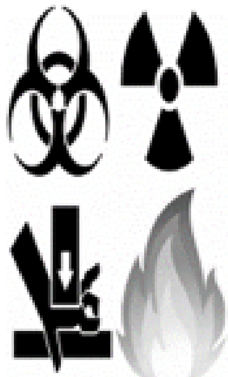
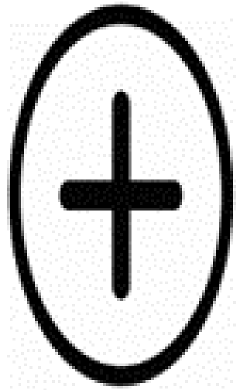
	Primary	Secondary	Tertiary	Quaternary	Quinary
Mechanism					
Definition	High-order explosives : -Impact of over pressurization wave on body surfaces.	High and low order explosives: - Due to flying debris, bomb fragments, other projectiles.	High-order explosions: - Due to individuals being thrown by blast winds or structural collapse	Any explosion-related injury, illness, or disease not due to primary, secondary, or tertiary mechanisms: - Includes exacerbations and complications of pre-existing illnesses.	Hyperinflammatory behavior, unrelated to their injury complex and severity of trauma
High Yield - Injuries	-Blast lung -TM rupture -Globe rupture -Abdominal hemorrhage	-Soft tissue injury -Globe penetration -Wound contamination	"Flying people injury" -Bony fracture -Traumatic amputation -Closed and open brain injuries	-Burns -Crush injury -Inhalation injury	-Prolonged shock and hypotension

Table 3: Injury assessment reference values and associated ATD for evaluating injury risk for different body regions according to NATO [9]

Body Region	Injury Criteria	Metric	Pass / Fail Level	ATD
Head	Head injury criterion	HIC15	250	H3 veya ES-2re + MIL-Lx
Neck	Axial compression force	Fz-	4.0 kN @0 ms / 1.1 kN > 30 ms	ES-2re + MIL-Lx
	Axial tension force	Fz+	3.3 kN @0 ms / 2.8 kN @35 ms / 1.1 kN > 60 ms	ES-2re + MIL-Lx
	Shear force	Fx / Fy	3.1 kN @0 ms / 1.5 kN @25-35 ms / 1.1 kN > 45 ms	ES-2re + MIL-Lx
	Bending moment (flexion)	Mocy+	190 Nm	ES-2re + MIL-Lx
	Bending moment (extension)	Mocy-	96 Nm	ES-2re + MIL-Lx
	Axial tension force	Fz+	1.8 kN	ES-2re + MIL-Lx
Shoulder	Compression force	Fy	1.4 kN	ES-2re + MIL-Lx
Thorax (ribs) (upper/middle/lower)	Rib deflection criterion	RDClateral	28 mm	ES-2re + MIL-Lx
Thorax	Thoracic compression criterion	TCCfrontal	30 mm	H3 + MIL-Lx
Thorax	Viscous criterion	VCfrontal	0.70 m/s	H3 + MIL-Lx
Thorax	Viscous criterion	VClateral	0.58 m/s	ES-2re + MIL-Lx
Abdomen (front/middle/rear)	Abdominal peak force	Ftotal	1.8 kN	ES-2re + MIL-Lx
Spine	Dynamic response index	DRIz	17.7	H3 veya ES-2re + MIL-Lx
Pelvis	Maximum pubic force	Fy	2.6 kN	ES-2re + MIL-Lx
Upper legs	Axial compression force	Fz-	6.9 kN	H3 veya ES-2re + MIL-Lx
Lower legs	Axial compression force	Fz-	2.6 kN	H3 veya ES-2re + MIL-Lx
Internal organs Lungs	Chest wall velocity predictor	CWVP	3.6 m/s	H3 veya ES-2re + MIL-Lx

and anti-personnel landmines, respectively.

As a result, the following sections will provide information about the responses and injuries of different parts of the human body due to explosions.

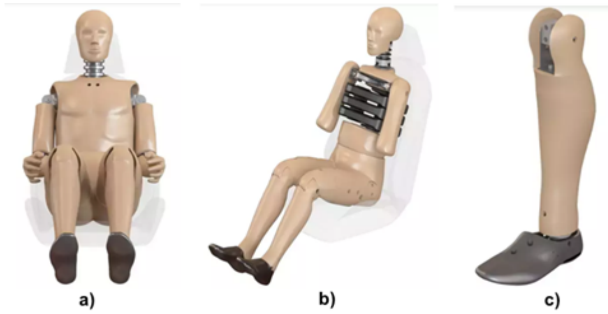


Figure 8: ATD types : a) H3 50th Male, b) ES-2re, c) MIL-Lx legform [11]

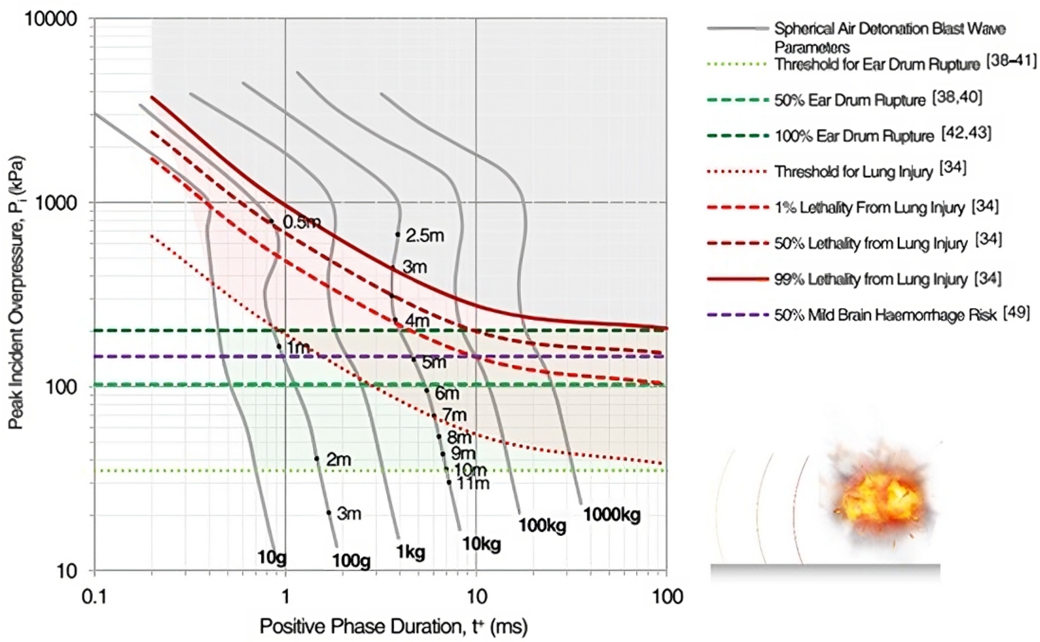


Figure 9: Analysis of PBI criteria based on blast wave parameters resulting from spherical air blasts at different stand-off distances [12]

2.2.1 Head

Traumatic brain injury (TBI) or head trauma is a type of injury resulting from the effect of kinetic energy from the primary blast wave on the brain. Typically, blunt force can complicate the injury in addition to the blast wave. The explosion can further affect the brain through the penetrating effects of secondary injuries or closed head injuries caused by tertiary injuries [13]. Common examples of secondary blast injuries include facial laceration and bodily injuries caused by glass shards. At this point, it is important to note that the properties of the interlayer material in glass significantly affect the structural performance of glass against impact. The full performance of glass is determined by parameters such as the type of glass, its thickness, the type and speed of impact, and boundary conditions [14].

TBIs are generally categorized as primary and secondary injury phases. The primary phase involves direct damage from the transmit of blast load to the intracranial contents while the secondary injury phase involves a series of molecular mechanisms that begin at the moment of impact and continue over hours or days [15]. This phase is multifactorial, involving delayed physiological events in response to the first injury.

The Glasgow Coma Scale (GCS) can be utilized to assess whether a brain injury resulting from a blast is mild, moderate, or severe. Table 4 provides information on the criteria and scoring system of the Glasgow Coma Scale [16]. A score of 13-15 indicates minor brain injury, a score of 9-12 indicates moderate brain injury, and a score of 3-8 indicates severe brain injury.

Dizziness, headache, memory loss, seizures, numbness, weakness, and difficulty concentrating are the additional signs and symptoms of TBI [17].

2.2.2 Auditory System

The auditory system is typically influenced by the primary blast wave. The tympanic membrane (TM) can simply stretch due to the differential pressure and can rupture at pressures (<0.5 atm) much lower than those required to harm other organs [18].

Table 4: Glasgow Coma Scale (GCS) criteria and scoring system [14]

GLASGOW COMA SCALE (GCS)		
Response	Scale	Score
Eye Opening Response	Eyes open spontaneously	4 Points
	Eyes open to verbal command, speech, or shout	3 Points
	Eyes open to pain (not applied to face)	2 Points
	No eye opening	1 Point
Verbal Response	Oriented	5 Points
	Confused conversation, but able to answer questions	4 Points
	Inappropriate responses, words discernible	3 Points
	Incomprehensible sounds or speech	2 Points
	No verbal response	1 Point
Motor Response	Obeys commands for movement	6 Points
	Purposeful movement to painful stimulus	5 Points
	Withdraws from pain	4 Points
	Abnormal (spastic) flexion, decorticate posture	3 Points
	Extensor (rigid) response, decerebrate posture	2 Points
	No motor response	1 Point
Minor Brain Injury = 13 -15 points; Moderate Brain Injury = 9-12 points; Severe Brain Injury = 3-8 points		

All patients subjected to an explosion shall be investigated about tinnitus and hearing loss during the initial trauma assessment. To avoid further auditory damage, reducing noise exposure is crucial for long-term recovery.

Most individuals with eardrum injuries who are hemodynamically stable, have no signs on chest radiography, and are followed up by otolaryngology, and who show no findings of blast injury or additional symptoms after a 4-6 hours observation period, recover without intervention. However, about 30% of these individuals progress some degree of permanent loss of hearing [19], [20].

A diagram showing the threshold levels for eardrum rupture and hearing loss due to different blast pressure values is provided in Figure 10 as specified in UFC 3-340-02 (2008) [2]. The graph indicates that 50% of human eardrums exposed to blast pressure rupture at 15 psi, while the threshold pressure for eardrum rupture is 5 psi. It is also observed that temporary hearing loss occurs at lower pressure levels than those causing eardrum rupture [2].

2.2.3 Lung

The lungs can sustain severe damage and potentially fatal outcomes from the primary blast wave due to the significant differences in density throughout the organ. Primary blast lung injury (PBLI) is more likely to happen in closed environments where high-grade explosives are used, which prolongs the duration of the blast wave, or when the victim is close to the blast. The occurence of PBLI in those who die directly at the blast site may be quite high, ranging from 13% to 47% [21].

Lung injury caused by the primary blast wave contains pulmonary contusions, intrapulmonary hemorrhage, and tearing of the alveolar capillaries. The immediate result of this energy distribution can manifest as respiratory distress, pneumothorax, hypoxia and hemothorax. In addition, there is potential for sudden air embolism from the tearing of alveolar capillaries, which can very quickly result in cardiac arrest or cardiogenic shock. The level of lung damage is related to the degree of absorbed energy from the primary blast wave. Patients can show inadequate oxygenation in the tissues (hypoxia), shortness of breath (dyspnea) and/or increasing cough. Tachycardia (a heart rate over 100 beats per minute), reduced breath sounds and rhonchi may also be present. Also, secondary blast lung damage from debris or flying shrapnel can be more evident during the examination, given the indications of blunt trauma to the thorax or the existence of a penetrating wound.

Depending on available data, survival threshold curves for lung injuries from the response to short-term (3–5 ms) rapidly rising pressures (shock wave) are provided in Figure 11 as specified in UFC 3-340-02 (2008). The graph uses W_h $(1lb = 0.454kg)$ to denote human weight. According to the graph, the threshold pressure for lung hemorrhage is 30–40 psi, severe lung hemorrhage is 80 psi and above, and the fatality threshold for lung damage is approximately 100 to 120 psi [2]. The mentioned pressure values are maximum effective pressures, meaning the incident (incoming) pressure should be considered as the largest of the incoming pressure, incoming pressure plus dynamic pressure, or the reflected pressure. Table 5 summarizes the limit pressure values for different types of injuries. Additionally, since survival probability is mass-dependent, the survival probabilities for infants, children, and adults will differ. The recommended weights are 11 lb ($\approx 5kg$) for infants, 55 lb ($\approx 25kg$) for small children, 121 lb ($\approx 55kg$) for adult women, and 154 lb ($\approx 70kg$) for adult men [2].

2.2.4 Eye

The eye, with its heterogeneous density, is remarkably impressionable to trauma. Consequently, the organ is easily affected by damage from both the primary blast wave and secondary blast injury. These injuries are relatively typical in the patient

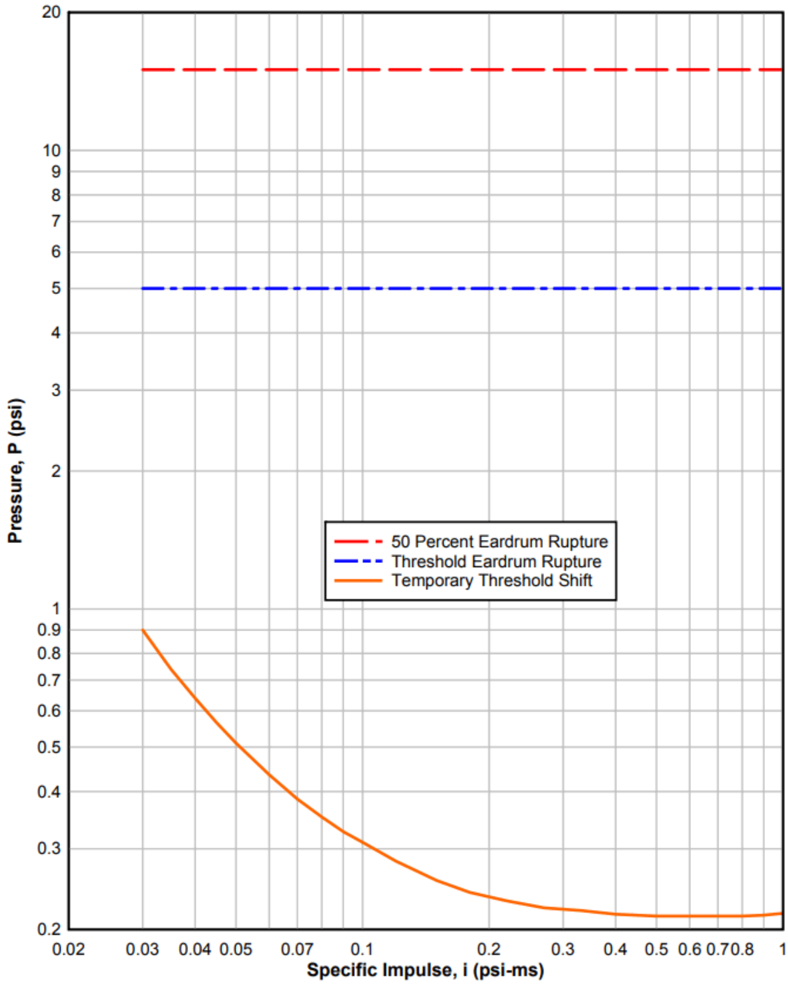


Figure 10: Human ear damage due to blast pressure [2]

Table 5: Effects of short-term (3-5 ms) rapidly rising air blasts on the human body [2]

Critical Organ or Event	Maximum Effective Pressure (psi)
Eardrum Rupture	
Threshold	5
50 percent	15
Lung Damage	
Threshold	30 - 40
50 percent	80 and above
Lethality	
Threshold	100 - 120
50 percent	130 - 180
Near 100 percent	200 - 250

population although they are exceptionally deadly,. The most common blast-related eye injuries contain injuries from both intraocular foreign bodies and superficial, corneal abrasions and eyelid injuries [22]. Secondary blast injuries from flying debris account for the majority of eye injuries in blast patients, including superficial foreign body injuries, conjunctivitis, corneal abrasions and eyelid lacerations. However, the primary blast wave can also cause iris tears, globe rupture, and inflammation-related optic nerve injuries (retrobulbar hematoma) [23].

2.2.5 Cardiac

Although the heart and major blood vessels do not include gas, they can be injured by the kinetic forces and pressure of explosions. Blast-related cardiac injuries present with pathology and content similar to blunt cardiac trauma, containing

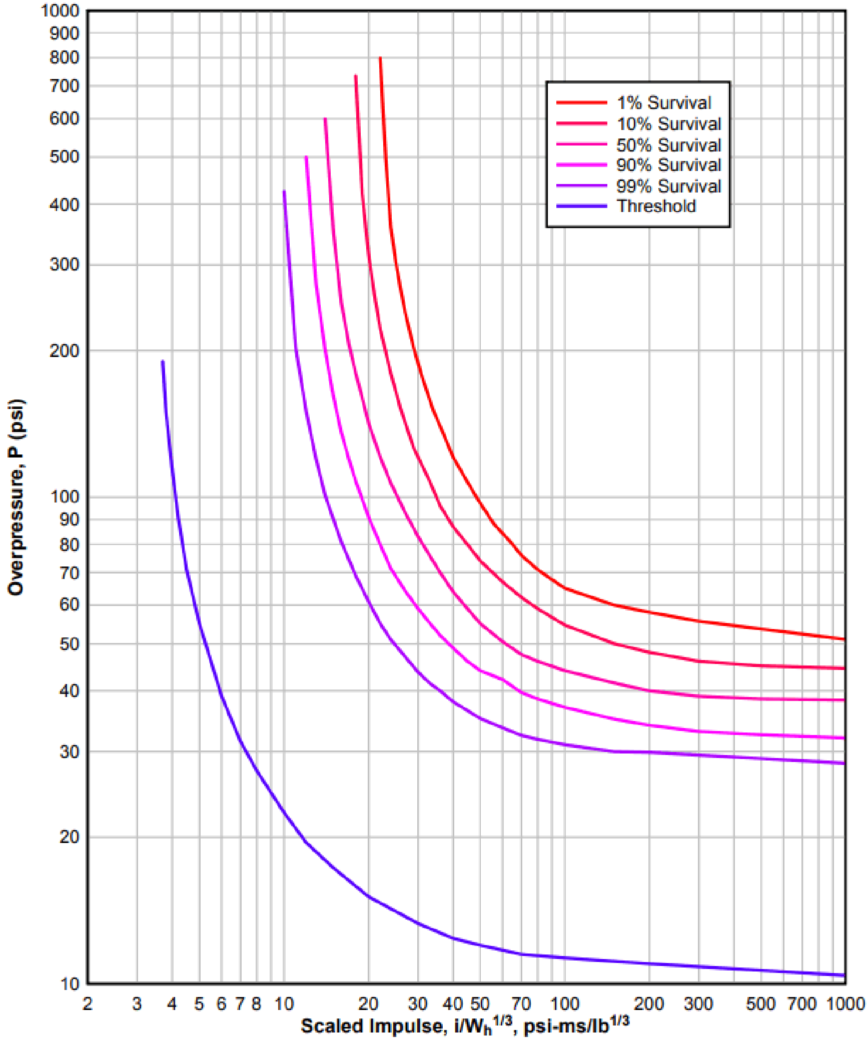


Figure 11: Threshold curves for survival in lung injury, $W_h =$ Weight of human being (lbs) [2]

myocardial contusion, tamponade (fluid accumulation in the pericardial sac), free/septal wall rupture, valve injury, papillary muscle rupture and aortic injuries. When blast-induced cardiac dysfunction is suspected, reducing positive pressure ventilation and providing inotropic support is advised instead of aggressive fluid administration due to the high probability of identical lung injury [24].

2.2.6 Abdomen

The gastrointestinal (GI) system is sensitive to injury from the primary blast wave due to its gas-containing components and heterogeneous density. Although rare among blast survivors, primary blast wave-induced injuries to the intestines can result in perforation, hemorrhage, ischemia and infarction. A huge level of energy transmition from the primary blast wave is needed for these injuries, and they are typically seen in those close to the explosion [24].
Literature indicates that injuries to the GI tract (large intestine, small intestine, stomach) account for 48% of abdominal injuries in blast victims [25]. The gas including sections of the GI tract are the most defenseless to the primary blast effect, but solid organs can also be damaged. GI injury is also more common in underwater explosions due to the medium's capability to transmit pressure and apply higher forces. Damages to solid organs such as the spleen, kidneys and liver are mainly linked with the patient's proximity to the source of the primary blast wave and high-grade primary blast waves [25].
Abdominal symptoms can be developed by patients up to 14 days after exposure to a blast [26]. Therefore, monitoring of symptoms and repeated evaluation are crucial for diagnosing gastrointestinal damage [13].

2.2.7 Musculoskeletal System

Blast injuries usually affect the musculoskeletal system. In a group of 101 blast victims, 57% had extremity injuries. Among these, 75.2% had at least one fracture, and over 90% had open fractures [27]. The closer the blast victim is to the epicenter of the explosion, the more likely they are to have multiple fractures, and more serious open fractures are affiliated with higher mortality [27]. For patients with serious extremity hemorrhage, tourniquet application is essential. For individuals with indication of traumatic injury, plain radiographs of the effected region shall be acquired after initial stabilization. Other injuries of extremity can be splinted after initial stabilization.

2.3 Injury Scaling

An injury scale is a method used to assign severity score or a numerical assessment to traumatic injuries. The most commonly utilized injury scale is the Abbreviated Injury Scale (AIS), developed by the American Association for Automotive Medicine (AAAM) and it first published in 1971.

2.3.1 Abbreviated Injury Score (AIS)

The Abbreviated Injury Scale (AIS) is a method of injury scaling that assigns a severity rating from 1 to 6 to distinct anatomical injuries. Table 6 supplies the AIS definitions and examples for spine and head injuries. An essential restriction of the AIS is that it does not represent the potential outcome for the entire individual and examines each injury in isolation [28].

Table 6: Abbreviated Injury Scale (AIS) scores and example injury types for two body parts [10]

AIS	Severity	Head	Spine
0	None	—	—
1	Minor	Headache or dizziness	Acute strain (No fracture or dislocation)
2	Moderate	Unconsciousness less than 1 hour ; Linear fracture	Minor fracture without any cord involvement
3	Serious	Unconscious 1 to 6 hours ; Depressed fracture	Ruptured disc with nerve root damage
4	Severe	Unconscious 6 to 24 hours ; Open fracture	Incomplete cervical cord syndrome
5	Critical	Unconscious more than 24 hours ; Large hematoma	C4 or below cervical complete cord syndrome
6	Maximum Injury (virtually nonsurvivable)	Crush of skull	C3 or above cervical complete cord syndrome

2.3.2 Injury Severity Score (ISS)

The Injury Severity Score (ISS) that was developed in 1974 is a technique used to characterize trauma patients with multiple injuries and is commonly used in trauma literature due to its connection with the AIS. The ISS depend on the AIS, which explains the severity of injuries in distinct body parts [29].

$$ISS = (A)^2 + (B)^2 + (C)^2 \tag{11}$$

Values A, B, and C in Equation 11 represent the scores of the three most severely injured body parts according to the Abbreviated Injury Scale. A represents the face, neck and head; B represents abdomen and the thorax; and C represents the extremities. Considering that the maximum AIS score for each region is 5, the ISS ranges from 0 to 75. However, if any of the three values is 6, the ISS is automatically set to 75 because an AIS score of 6 represents an injury that is not survivable. Table 7 describes the injury severity levels, definitions, and examples of possible injuries for different value ranges of the Injury Severity Score [30].

2.3.3 Dynamic Response Index (DRI)

The Dynamic Response Index (DRI) indicates the peak dynamic pressure of the spinal column and is computed by modeling the human body as an analog, lumped mass-parametric mechanical system consisting of a mass, damper and spring. The DRI model evaluates the human body response to temporary acceleration-time profiles. Potential spinal injuries for positive z-acceleration environments in ejection seats could be predicted effectively by using the DRI. The threshold acceleration values for DRI are provided in Table 8 [28].

Table 7: Injury based damage level definitions (ISS) [12]

ISS Range	Proposed Hazard Level	Injury Description	Example of Injuries
$ISS \geq 25$	High Injury	Fatal / Severe Injury	Multiple very serious injuries Primarily fatalities
$10 < ISS < 25$	Medium Injury	Serious Life Threatening Injury	Very severe lacerations with significant blood loss Severe open bone fractures Crush injuries Skull fractures
$5 < ISS \leq 10$	Low Injury	Hospitalization Required, Not Immediately Life Threatening	Bone fractures Large numbers of lacerations Artery or tendon lacerations Concussions
$1 < ISS \leq 5$	Very Low Injury	Medical Aid Necessary, But No Hospitalization Required	Lacerations to face and body from glass fragments Cuts or abrasions to eye Contusions and abrasions
$0 \leq ISS \leq 1$	Minimal Injury	No Medical Aid Required	No injury Minor bruises and cuts Small foreign object in eyes Hearing loss

Table 8: Dynamic Response (DR) limits [10]

DR Level	Acceleration Direction (occupant's inertial response)					
	x		y		z	
	DRx < 0	DRx > 0	DRy < 0	DRy > 0	DRz < 0	DRz > 0
Low	-28	35	-14	14	-13.4	15.2
Moderate	-35	40	-17	17	-16.5	18
High risk	-46	46	-22	22	-20.4	22.4

2.3.4 Head Injury Criterion (HIC)

The Head Injury Criterion (HIC) is an evaluation of the possibility of head injury resulting from an impact. This variable is normally obtained from the acceleration-time history at the center of gravity of a dummy's head when exposed to impact forces.

$$HIC = max\left[(t_2 - t_1)\left(\frac{1}{(t_2 - t_1)}\left[\int_{t1}^{t2} a(\tau)d\tau\right]\right)^{2.5}\right] \tag{12}$$

The acceleration-time history, $\alpha(t)$, calculated at the center of mass of the dummy's head, is used analytically to compute the HIC as the square root of the sum of the squares of the acceleration-time histories in the x, y, and z directions over a 15 ms time interval, as given in Equation 13 [31]:

$$a(t) = \sqrt{(a_x{}^2(t)) + (a_y{}^2(t)) + (a_z{}^2(t))} \tag{13}$$

In the HIC formulation, t_1 represents the starting time, and $\Delta t = t_2 – t_1$ represents the maximum time interval over which the acceleration is calculated. With the condition $0 \leq t_1 \leq t_2 \leq T$, it is indicated that t_1 and the maximum time interval, Δt can initially be selected arbitrarily. Additionally, some simplified model assumptions are explained as follows [31]:

- The time interval $t_2 – t_1$ should be $\leq 36ms$. According to experience, larger deceleration times do not boost the risk of injury.
- The highest acceleration values should last 3 ms. This requirement arises from measurement method reasons and is sustained by the acceptance that shorter decelerations don't have any impact on the brain.

The head injury criterion consist of four distinct injury criteria [31]:

- Head Injury Criterion [HIC] : Skull fracture from blunt object impacts and brain injury.
- Blunt Object Skull Fracture Injury Criterion [kN] : Skull fracture resulting from blunt object impacts.
- Facial Injury Criterion [kN/mm] : Injury resulting from blunt object impacts and facial fracture.
- Facial Laceration Criterion : Facial laceration.

The levels related to the head injury criterion, the corresponding Abbreviated Injury Scale (AIS) values, and the associated descriptions of head injury or consciousness level are provided in Table 9 [31].

Table 9: Consciousness levels associated with Head Injury Criteria [31]

Head Injury Criteria	AIS Code	Level of Brain Concussion and Head Injury
135 - 519	1	Headache or dizziness
520 - 899	2	Unconscious less than 1 hour - Linear fracture
900 - 1254	3	Unconscious 1 - 6 hours - Depressed fracture
1255 - 1574	4	Unconscious 6 - 24 hours - Open fracture
1575 - 1859	5	Unconscious greater than 24 hours - Large hematoma
> 1860	6	Non-survivable

Table 10: Head Injury Criterion (HIC) tolerance levels [31]

Injury Criteria		Tolerance Levels				
Criterion	Units	Level 0 No Injury Egress	Level 1 Minor Injury Egress	Level 2 Major Injury Egress Assisted	Level 3 Severe Injury Medical Assistance	Level 4 Potentially Non-survivable
HIC - Brain injury (in all head impacts)	HIC (15 ms)	<150 (No concussion)	<150 (No concussion)	150 - 500 (Mild concussion)	500 - 1800 (Severe concussion)	>1800 (Life threatening coma)
HIC - Skull fracture (flat impacts)	HIC (15 ms)	<500 (No fracture)	<500 (No fracture)	500 - 900 (Minor fracture)	900 - 1800 (Major fracture)	>1800 (Life threatening coma)
Blunt object skull fracture	kN	<0.02 (No fracture)	<2.2 (No fracture)	2.2 - 5.5 (Minor depressed fracture)	>5.5 (Major depressed fracture)	>5.5 (Life threatening)
Facial injury	kN/mm	<0.02 (Very minor injury)	0.02 - 0.045 (Minor facial injury)	0.045 - 0.0825 (Major facial injury)	>0.0825 (Severe facial injury)	>0.0825 (Life threatening)
Facial laceration	Cuts to chamois leather thin layer	0	0	Moderate	Major	N/A

Also, Table 10 provides the tolerance levels and associated descriptions for different types of head injury criteria [31]. Tables 9 and 10 are used to evaluate the injuries sustained by the dummy in numerical analyses.

The probabilities of different severity levels of head injury for a given head injury criterion score are shown in Figure 12. The graph indicates that a HIC score of around 2500 corresponds to a 85% fatality rate and a 95% likelihood of critical head injury [31].

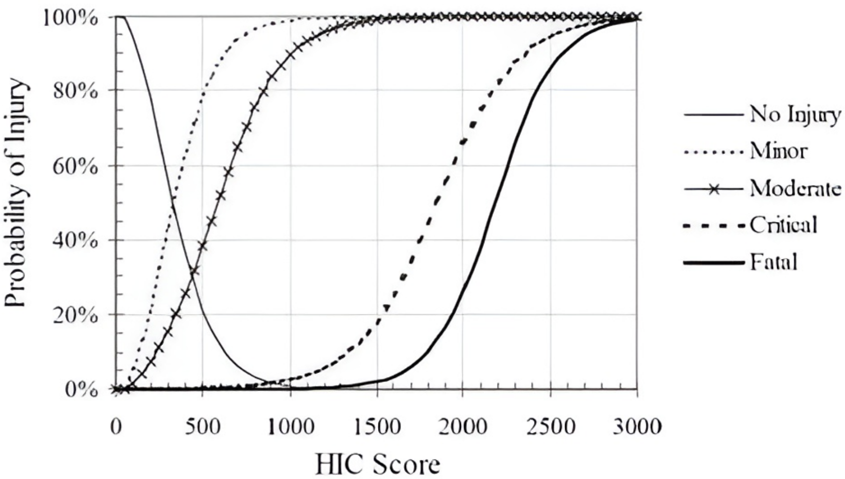


Figure 12: Probabilities of different severity levels of head injury for HIC scores [31]

2.3.5 Neck Injury Criterion

The Neck Injury Criterion (NIC), introduced by the National Highway Traffic Safety Administration (NHTSA), integrates the impacts of moments and forces calculated at the occipital condyle and is a excelling estimator of cranio-cervical injuries. The NIC consider N_{TF} (tension-flexion), N_{TE} (tension-extension), N_{CF} (compression-flexion) and N_{CE} (compression-extension). Federal Motor Vehicle Safety Standard (FMVSS) 208 needs that none of the four N_{ij} values surpass 1.4 at any point. The generalized N_{ij} is given by the following equation [28]:

$$N_{ij} = \frac{F_z}{F_{zc}} + \frac{M_y}{M_{yc}} \tag{14}$$

where F_z is the axial force for the upper neck (N), F_{zc} is the critical axial force (N), M_y is the moment around the occipital condyle (Nm), M_{yc} is the critical moment around the occipital condyle (Nm).

2.3.6 Lumbar Load Criterion

The lumbar load criterion specifies that the highest compressive force calculated between the lumbar spine and pelvis of a test dummy during a crash impact, where the vertical axis of the spine is parallel to the predominant impact vector, should not exceed 6672 N [28]. Additionally, the compressive force should not surpass 3800 N over a 30 ms time interval [28]. This is one of the most commonly utilized criteria in crash tests and vertical impact. Lastly, severe compression or severance of the spinal cord can result in death or paralysis.

2.3.7 Chest Criteria

The Chest Injury Criterion specifies that the maximum resultant acceleration measured by a triaxial accelerometer in the upper thorax should not exceed 60g for more than 3 ms [28]. In addition, chest deflection determined by a chest potentiometer behind the sternum should be less than 7.62 cm for the Hybrid III dummy [28].

2.3.8 Femur Force Criterion

The Femur Force Criterion indicates that the axial compressive force carried along each upper leg shall not be bigger than a certain value. Impulse loads that are larger than this limit may result in the total fracture of the femur bone and cause the severance of main arteries, leading to excessive bleeding. Different studies specify distinct values for the permissible highest axial compressive force. It is indicated by the Wayne State University that the permissible maximum value is 10,000 N [28]. The U.S. Department of the Army declares that the axial compressive force should not exceed 7562 N over a 10 ms time interval and should not exceed 9074 N at any moment [28].
In real dummies, load cells are put in the dummy's leg and are calibrated to measure the compressive force in the femur.

2.4 Proposed Injury Criteria

Based on numerous studies in the existing literature, when threshold values related to blast pressure for human injuries in spherical air blasts are reviewed and compiled [2], [3], [7], [12], [28], [31], the limit blast pressure values for different parts of the human body for various positive phase duration ranges are proposed as shown in Table 11.

Table 11: Limit blast pressure values for different parts of the human body and corresponding blast positive phase duration ranges

Positive Phase Duration td (ms)	Criteria	Lung	Ear	Head-Brain
$td \leq 10$	Peak Pressure (kPa)	55 : Threshold 150 : 1% Lethality 200 : 50% Lethality 300 : 99% Lethality	35 : Threshold 100 : 50% Ear Drum Rupture 200 : 100% Ear Drum Rupture	150 : 50% Mild Brain Hemorrhage Risk 270 : 50% Moderate Brain Hemorrhage Apnea Risk 400 : 50% Primary Blast Brain Fatality
$10 < td \leq 50$	Peak Pressure (kPa)	42 : Threshold 110 : 1% Lethality 160 : 50% Lethality 220 : 99% Lethality	35 : Threshold 100 : 50% Ear Drum Rupture 200 : 100% Ear Drum Rupture	150 : 50% Mild Brain Hemorrhage Risk
$50 < td < 200$	Peak Pressure (kPa)	28 : Threshold 90 : 1% Lethality 125 : 50% Lethality 185 : 99% Lethality	35 : Threshold 100 : 50% Ear Drum Rupture 200 : 100% Ear Drum Rupture	150 : 50% Mild Brain Hemorrhage Risk

3 Conclusion

In this paper, the focus is on the blast wave, blast wave parameters, blast injuries, types and mechanisms of blast injuries, the effects of explosions on the human body, and injury scaling and criteria. It is observed that for a blast with a positive phase duration up to 10 ms, the threshold blast pressure for lung injury is 55 kPa, whereas for the ear it is 35 kPa. At a blast pressure of 150 kPa, the probability of death due to lung injury is 1%, while there is a 50% risk of experiencing a mild brain hemorrhage. At 200 kPa, the probability of death due to lung injury is 50%, and there is a 100% likelihood of eardrum rupture. At a threshold of 300 kPa, there is a 99% likelihood of death due to lung injury. Additionally, the threshold for a 50% chance of moderate brain hemorrhage is 270 kPa, whereas at a threshold of 400 kPa, primary blast-induced brain fatalities are expected. Finally, a blast pressure range of 690-825 kPa is considered the threshold range for blast-induced death, with values between 895-1240 kPa indicating a 50% chance of death, and values in the 1380-1725 kPa range indicating an almost 100% likelihood of blast-induced death [2].

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Authors' Contributions
In this study, authors contributed equally to the study.

Competing Interests
The authors declare that they have no conflict of interest.

References
[1] J. Bukowski, C. D. Nowadly, S. G. Schauer, A. Koyfman, and B. Long, "High risk and low prevalence diseases: Blast injuries," *The American Journal of Emergency Medicine*, vol. 70, pp. 46–56, 2023.
[2] U. DoD, "Unified facilities criteria (ufc) structures to resist the effects of accidental," 2008.
[3] Z. Wang and J. Jiang, *Explosive Blast Injuries: Principles and Practices*. Springer Nature, 2023.
[4] S. Nadyrov, "Pencere camının ve çerçeve sistemlerinin patlamaya karşı davranışı," Master's thesis, Fen Bilimleri Enstitüsü.
[5] M. Chiranjeevi and J. Simon, "Analysis of reinforced concrete 3d frame under blast loading and check for progressive collapse," *Indian Journal of Science and Technology*, vol. 9, no. 30, pp. 1–6, 2016.
[6] T. C. on Blast-Resistant Design of the Petrochemical Committee of the Energy Division of ASCE, "Design of blast-resistant buildings in petrochemical facilities." American Society of Civil Engineers, 2010.
[7] A. M. Bull, J. Clasper, and P. F. Mahoney, "Blast injury science and engineering," *Switzerland: Springer*, 2016.
[8] T. Ngo, P. Mendis, A. Gupta, and J. Ramsay, "Blast loading and blast effects on structures–an overview," *Electronic journal of structural engineering*, no. 1, pp. 76–91, 2007.
[9] M. Şahin, İ. Karagöz, M. Öksüz, and S. Yazıcıoğlu, "Properties of concrete reinforced with m12 monofilament type polypropylene fiber," *El-Cezeri*, vol. 8, no. 1, pp. 481–494, 2021.
[10] F. J. Gallun, A. C. Diedesch, L. R. Kubli, T. C. Walden, R. L. Folmer, M. S. Lewis, D. J. McDermott, S. A. Fausti, and M. R. Leek, "Performance on tests of central auditory processing by individuals exposed to high-intensity blasts," *J Rehabil Res Dev*, vol. 49, no. 7, pp. 1005–25, 2012.
[11] (Accessed 07,01,2024). [Online]. Available: https://www.humaneticsgroup.com/
[12] J. Denny, A. Dickinson, and G. S. Langdon, "Defining blast loading 'zones of relevance'for primary blast injury research: A consensus of injury criteria for idealised explosive scenarios," *Medical Engineering & Physics*, vol. 93, pp. 83–92, 2021.
[13] J. E. Smith and J. Garner, "Pathophysiology of primary blast injury," *BMJ Military Health*, vol. 165, no. 1, pp. 57–62, 2019.
[14] M. Karadağ, U. C. Vural, and B. Karasu, "Otomotiv sektöründe cam," *El-Cezeri*, vol. 6, no. 2, pp. 299–322, 2019.
[15] S. Yamamoto, D. S. DeWitt, and D. S. Prough, "Impact & blast traumatic brain injury: implications for therapy," *Molecules*, vol. 23, no. 2, p. 245, 2018.
[16] B. Jennett, "Development of glasgow coma and outcome scales," *Nepal journal of neuroscience*, vol. 2, no. 1, pp. 24–28, 2005.
[17] M. W. Greve and B. J. Zink, "Pathophysiology of traumatic brain injury," *Mount Sinai Journal of Medicine: A Journal of Translational and Personalized Medicine: A Journal of Translational and Personalized Medicine*, vol. 76, no. 2, pp. 97–104, 2009.
[18] R. G. DePalma, D. G. Burris, H. R. Champion, and M. J. Hodgson, "Blast injuries," *New England Journal of Medicine*, vol. 352, no. 13, pp. 1335–1342, 2005.
[19] S. Goh, "Bomb blast mass casualty incidents: initial triage and management of injuries," *Singapore Med J*, vol. 50, no. 1, pp. 101–106, 2009.
[20] D. D. Yeh and W. P. Schecter, "Primary blast injuries—an updated concise review," *World journal of surgery*, vol. 36, pp. 966–972, 2012.
[21] T. E. Scott, A. M. Johnston, D. D. Keene, M. Rana, and P. F. Mahoney, "Primary blast lung injury: the uk military experience," *Military medicine*, vol. 185, no. 5-6, pp. e568–e572, 2020.
[22] M. G. Morley, J. K. Nguyen, J. S. Heier, B. J. Shingleton, J. F. Pasternak, and K. S. Bower, "Blast eye injuries: a review for first responders," *Disaster medicine and public health preparedness*, vol. 4, no. 2, pp. 154–160, 2010.
[23] Y. Liu, K. Feng, H. Jiang, F. Hu, J. Gao, W. Zhang, W. Zhang, B. Huang, R. Brant, C. Zhang *et al.*, "Characteristics and treatments of ocular blast injury in tianjin explosion in china," *BMC ophthalmology*, vol. 20, pp. 1–8, 2020.
[24] Z. R. Mathews and A. Koyfman, "Blast injuries," *The Journal of emergency medicine*, vol. 49, no. 4, pp. 573–587, 2015.
[25] I. Wani, F. Q. Parray, T. Sheikh, R. A. Wani, A. Amin, I. Gul, and M. Nazir, "Spectrum of abdominal organ injury in a primary blast type," *World journal of emergency surgery*, vol. 4, pp. 1–5, 2009.
[26] C. Owers, J. Morgan, and J. Garner, "Abdominal trauma in primary blast injury," *Journal of British Surgery*, vol. 98, no. 2, pp. 168–179, 2011.
[27] M. Tahtabasi, S. Er, R. Karasu, and E. R. Ucaroglu, "Bomb blast: imaging findings, treatment and clinical course of extremity traumas," *BMC emergency medicine*, vol. 21, pp. 1–10, 2021.
[28] A. Tabiei, C. Lawrence, and E. L. Fasanella, "Validation of finite element crash test dummy models for predicting orion crew member injuries during a simulated vehicle landing," in *10th International LS-DYNA Users Conference*, no. E-16677, 2009.
[29] S. P. Baker, B. o'Neill, W. Haddon Jr, and W. B. Long, "The injury severity score: a method for describing patients with multiple injuries and evaluating emergency care," *Journal of Trauma and Acute Care Surgery*, vol. 14, no. 3, pp. 187–196, 1974.
[30] S. Meyer, L. Little, and E. Conrath, "Injury based glass hazard assessment," *DTIC Document*, 2004.
[31] R. Panowicz, K. Sybilski, and D. Kołodziejczyk, "Numerical analysis of effects of ied side explosion on crew of lightarmoured wheeled vehicle," *Journal of KONES*, vol. 18, pp. 331–339, 2011.