NEW INSIGHTS INTO THE IMPACT OF BLAST WAVES ON THE HUMAN BODY

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ABSTRACT. Blast damage is a major problem in both military and civilian practice. For effective protection, we need an assessment of the forces and threats that act on a person exposed to an explosion. In general, the victim can be exposed to rapid changes in pressure (shock wave), fragments and debris (pieces) and bodily displacement, resulting in internal injuries and shear effects. The scale, frequency and clinical significance of the different types of injury depends on the nature of the environment (e.g. open or closed), the type of the explosive device, the protection worn by the victim (which can provide greater protection against one aspect of the threat) and the distance from the explosion. This article presents blast wave effects in predicting blast damage through computer modelling of impact. The results obtained are important for improving the explosion protection.

Keywords: shock wave, explosive, blast trauma, detonation

НОВИ ВИЖДАНИЯ ЗА ВЛИЯНИЕТО НА ВЗРИВНАТА ВЪЛНА ВЪРХУ ЧОВЕШКИЯ ОРГАНИЗЪМ

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РЕЗЮМЕ. Взривните поражения са все по-голям проблем, както във военната, така и в гражданската практика. За ефективна защита се нуждаем от оценка на силите и заплахите, които действат върху лице, изложено на експлозия. Най-общо, жертвата може да бъде изложена на резки промени в налягането (ударна вълна), фрагменти и отломки (парчета) и изтласкване на тялото, което води до вътрешни наранявания и ефекти на срязване. Мащабът, честотата и клиничното значение на различните видове наранявания зависят от околната среда (например отворена или затворена), вида на взривното устройство, защитата, носена от жертвата (която може да осигури по-голяма защита срещу един аспект на заплахата) и разстоянието до взрива. Тази статия представя ефектите от взривната вълна при прогнозиране на щети от взрив чрез компютърно моделиране на въздействието. Получените резултати са важни за подобряване на защитата от експлозия.

Ключови думи: ударна вълна, експлозив, взривна травма, детонация

Introduction

In recent years, explosive devices have become the preferred weapon in the majority of terrorist attacks in war zones and other regions of political conflict worldwide. Relative ease of manufacturing and portability of Improvised Explosive Devices (IEDs) make them the weapon of choice in terrorist and insurgent activities.

Injuries that result from a blast are dependent on many factors, including the type of explosive and explosive charge, height of burst, reflecting boundaries or protective barriers, distance between the victim and the blast, the surrounding environment, and the scattering of fragments or other projectiles. The physical environment in which an explosion occurs plays a significant role in the type and degree of injury that may result. Blasts that occur in an enclosed space (e.g. a closed room, a bus, or a subway car) can intensify the effect of the blast wave, resulting in more severe injury patterns than those that occur in open air (e.g. a square, an open market, a train platform). In addition, explosive events associated with building collapse result in higher mortality and morbidity.

Blast Wave Dynamics and Forces

An explosion is caused by the rapid exothermic oxidation of a solid or liquid material into gaseous reaction products resulting in a large energy release in the form of increased pressure and temperature within the explosive compound. Blast waves can be generally classified as simple or complex. The detonation of a typical high explosive in an open space produces a simple, or so-called Friedlander wave, the name comes from the simple equation used to describe the pressure history. The front of the wave, known as the shock front, has a pressure (overpressure) much greater than the region behind it and thus, immediately begins to decay as the shock propagates outward. The pressure may drop to below ambient atmospheric pressure causing suction. A simple blast wave has an overpressure phase called the positive phase and an underpressure phase known as the negative phase with an assumed exponential form as shown in Figure 1.

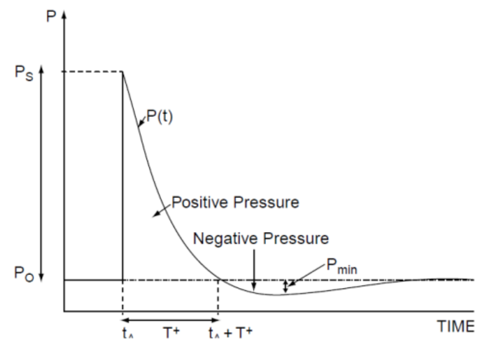

Fig. 1. Simple blast wave showing peak overpressure and the durations of the positive and negative phases

Different authors have recommended the use of various functions to represent the pressure-time history p(t) of the simple blast wave, generally emphasising only the positive phase. A complete function representing the entire positive and negative phase is described by (Dharaneepathy, 1995) by the following:

$$p(t) = p_0 + p_s\left[1 - \frac{(t-t_a)}{T_s}\right].\exp\left[-b\frac{(t-t_a)}{T_s}\right], \quad (1)$$

where:

t is the time measured from the instant the shock wave arrives,
p_0 is the ambient atmospheric pressure,
p_s is the peak overpressure,
T_s is the duration of the positive phase,
t_a is the wave arrival time,
b is a positive constant called the waveform parameter that depends on the peak overpressure.

The most commonly used blast wave scaling is the cube root scaling law, otherwise known as Hopkinson's Law (Baker, 1973). This law states that any pressure generated at a distance R_1 from a reference explosion with weight W_1 will generate the same pressure at a distance R_2 from the same explosive with weight W_2 provided the charges are of similar geometry and in the same atmosphere.

$$\frac{R_2}{R_1} = \left(\frac{W_2}{W_1}\right)^{\frac{1}{3}} = \lambda \quad (2)$$

The parameter λ is referred to as the explosive yield factor. It is customary to use the scaled distance, Z (m/kg1/3), rather than charge distance when dealing with blast waves:

$$Z = \frac{R}{\sqrt[3]{W}} \quad (3)$$

A complex blast wave is typically the result of wave reflections and refractions resulting from interactions with the local environment (e.g. a wall or enclosure). As an explosive charge is detonated the high pressure wave travels outwards from the center of initiation. The high pressure, high speed wave makes contact with everything in its path. The contact between the wave and objects in its path will result in reflections, rarefactions and attenuations of the blast wave. (Katz, 1998). Therefore, the resulting flow field of the blast is not accurately represented by the Friedlander idealised blast wave when an interaction with objects occurs. The exact waveform cannot be determined empirically as it depends on the geometry of the objects in the environment. In order to determine the wave field in a complex environment, a numerical simulation or an experimental simulation is required to obtain the pressure at desired locations.

A charge placed above a flat reflecting surface, such as the ground will produce a complex blast wave. The distance at which the charge is placed above the ground is known as the height of burst (HOB). A diagram of this example is shown in Figure 2.

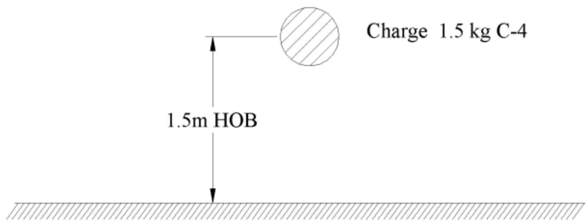

Fig. 2. Bare spherical charge above ground (Cronin, 2004)

In this scenario the explosive is initiated and the blast wave radiates outwards. When the blast wave travels a distance equivalent to the height of burst it makes contact with the ground. As the ground is infinitely rigid, the wave reflects off of the ground and travels back into the initial blast wave. Using a pressure gauge it is possible to measure the interaction between the waves. In this example if a gauge is located directly above the center of the charge, the resulting pressure versus time plot will indicate the initial primary blast wave, followed by the presence of a secondary pressure peak, which represents the reflected blast wave from the ground. The formation of these waves is shown in Figure 3. A characteristic of complex blast wave is the presence of stepped waves, indicating rise and drops in pressure, due to reflections and rarefactions. This is in contrast to the idealised wave, which only includes one peak pressure waveform. The pressure history of the complex waveform shows the initial incident waveform that would be visible in the free field, followed by the waveforms from the reflecting surfaces. In this example there is only one reflecting surface, however, where more reflecting surfaces are present the resulting waveform will depend on the geometry of the reflecting surfaces. The change in geometry will affect both the magnitude and timing of the blast waves.

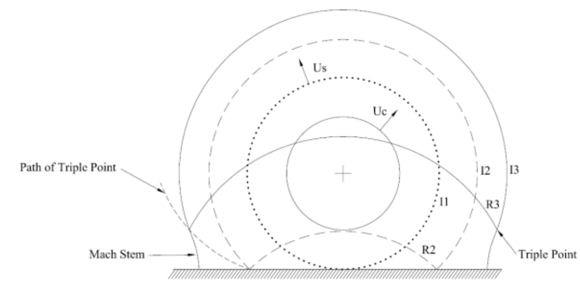

Fig. 3. Complex blast wave formed from ground interaction (Cronin, 2004)

Blast waves can be reflected off a variety of surfaces, including walls, floors and ceilings. As the blast wave impacts the surface the reflected waves' strength is related to the angle of contact with the surface; low angles produce lower strength reflection pressures, whereas perpendicular angles produce very high reflected pressures. The strongest reflected wave occurs when the high pressure wave impacts perpendicular to the surface. At this point the blast wave is further compressed on impact and a reflecting wave begins to travel towards the incident wave. The region where this occurs is known as the reflected region. It contains a very high pressurised zone as compared to a region where no reflection has occurred. The shock wave in this single reflected region can end up being 2 to 20 times greater than the incident shock. (Wightman, 2001) Stronger and more complicated shocks are produced in enclosed spaces or when the shock makes contact with multiple reflecting surfaces. In enclosed spaces the blast wave may undergo repeated reflections from the interior walls and any objects in the space.

A complex blast wave in an enclosure will lead to a longer pressure-time history as compared to a blast in the free field. The longer pressure time histories enable the gases to heat and expand, filling the enclosure and then eventually venting through any openings. One of the simplest scenarios that produces complex blast waves is the detonation of an explosive in an enclosed room. Even with the simple geometry and a charge placed in the centre of the room the resulting blast waves are complex and require CFD simulations to predict the blast flow field (Stuhmiller, 1997).

Figure 4 displays a plot of three pressure signatures. In Figure 4a, an idealised Friedlander curve is shown. Figure 4b shows the pressure time history record from an actual gauge in an experimental trial. This results show similarity to the Friedlander curve, as can be seen by the near instantaneous rise in pressure, the decay to ambient and the negative duration phase. Noise and other artifacts are clearly visible as the plot is not smooth. These slight variations in the plot can be due to vibrations or the effect of placing a physical gauge in the flow field. Figure 4c shows a plot from an actual complex blast wave. This plot consists of an initial pressure and decay wave followed by a number of secondary peaks and decays. The secondary waves are a result of the interactions between the initial wave and its surroundings. Reflections, rarefactions, coalescing and attenuation of waves are all factors in the pressure signature of the complex wave; the signature shown is from a blast wave inside a military bunker (Josey, 2010).

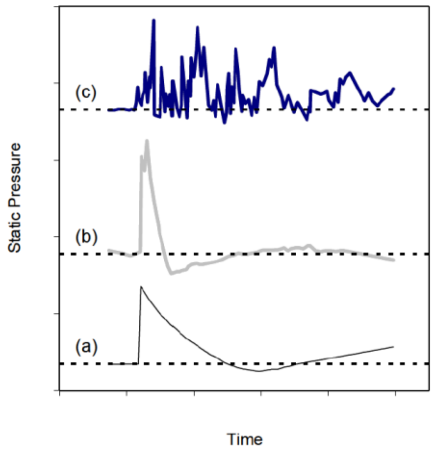

Fig. 4. Blast wave comparisons: (a) idealised blast wave; (b) actual blast wave recorded via a pressure transducer; (c) complex blast wave (Mayorga, 1997)

Enclosed spaces allow the generation of complex blast waves. The reflection of waves from walls, ceilings and floors in enclosed environments enables the development of complex waves with long durations. In terms of blast injury, this allows for a greater transfer of energy to the body. This greater transfer of energy as compared to an idealised blast wave leads to increased bodily injury (Chaloner, 2005).

Blast Wave Interaction with Objects and the Human Body

When a blast wave encounters an object of higher density, such as ground or a human body, it will both reflect off the object and diffract around it. The reflected wave travels back toward the origin and the overpressure of the reflected wave may exceed the overpressure of the incident wave. The magnitude of the reflected pressure is related to both the angle of incidence of the blast wave and to the incident shock strength. The incident wave will also penetrate the object and generate compression and shear stress waves within the object. The exact behaviour depends upon the geometry of the object, the angle of incidence, and the power of the wave. When explosions occur indoors or in street canyons, standing waves and enhanced differences in pressure occur because of the additive effects of reflections from walls and rigid objects (Liang et al., 2002). Figure 5 presents a scheme of an incident shock wave interacting with a body, illustrating the propagating shock wave, shock reflection and diffraction, and stress wave transmitted through the body.

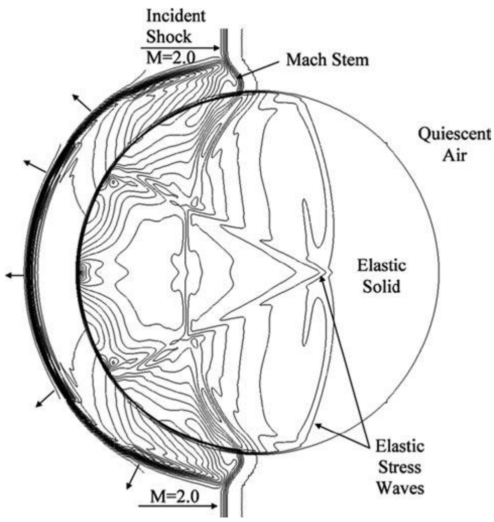

Fig. 5. An example CFD simulations of a planar shock wave diffracting over an elastic cylinder showing pressure contours at a time instant when shock has just passed over the body

In this case, the sound speed in the elastic solid is larger than the shock wave speed in the air and the elastic stress waves inside the body, shown in Figure 5, propagate ahead of the shock wave. The pressure field and the shock wave pattern are shown, including the incident wave, reflected wave, and diffracted waves (Mach stem) around the body, at a time instant when the shock wave passes across the centre of the body.

Shock wave reflections from objects can be either normal, when the wall-shock normal are at a zero angle, or oblique, when the angle of incidence is small, less than about 40° in air. When a blast wave strikes an object it will generate a pressure on the surface of the object that is greater than the peak static pressure of the wave. Intuitively this can be explained by the fact that the forward moving air molecules are stopped at the wall while the molecules behind will still compress the ones on the stopped wave front. Mathematically it can be expressed that, for the normal reflection of an ideal gas from a rigid wall, the total pressure on the object wall (the peak reflected pressure, p_r) is the sum of the static pressure, p_s and the dynamic pressure $q = pv^2/2$:

$$p_r = 2\,p_s + (\gamma - 1)q, \qquad (4)$$

where γ is the ratio of specific heats (γ =1.4 for ideal gas). Using Rankine-Hugoniot relations (Baker, 1974; Smith, Hetherington, 1994) relating mass, momentum, and energy of the incoming wave before the impact and at the wave reflection instant one can eliminate q and relate the reflected pressure to the peak overpressure and the ambient pressure:

$$p_r = 2\, p_s((7p_0 + 4p_s)\ (7p_0 + p_s)) \quad (5)$$

For an object such as a human body, the blast wave reflected pressure (p_r) load on the front (proximal) side for a short period of time will be much larger than the peak overpressure, p_S. The side walls, parallel to the shock propagation direction, will be loaded as the wave passes over them with the p_S. Therefore, the time for loading can be calculated from the blast wave velocity. The rear side loading begins after the blast wave passes the object and after the diffractive waves meet at the centre back side. In addition to the pressure loading, the object will also experience friction drag forces, F_D, induced by the blast wind:

$$F_D = C_D\,.\,q(t).\,A, \quad (6)$$

where q(t) is the dynamic pressure ($q = pv\ (t)^2/2$) of the wind, A is the friction wall area loaded, and C_D is the drag coefficient of the object, which depends on its shape. The drag force will appear after the pressure force and its duration will be longer. Therefore, the total transverse force on an object is a sum of the forces caused by the reflected pressure and drag force.

This cursory analysis of shock wave patterns and the reflected pressure levels, p_r, indicate that blast waves are far more lethal near reflecting surfaces. A person next to a solid wall will be exposed to not only the forward shock wave but also to even stronger reflected waves. Blast injuries in a confined space are particularly severe as the person is exposed to multiple reflected waves coming from various directions. Blast loads on large rigid objects will create strong crushing forces but cause little or no object translocation. Smaller objects, such as explosive casing, debris, and even human beings, will be propelled in the air by pressure and blast wind loading. The translational force will last for a brief time but the drag loading will have a longer duration and can lead to significant body translocation in addition to the overpressure damage.

When a shock wave impacts a living body, a series of instantaneous physical events take place. The body is affected by the primary incident wave, by the wave reflected at the body surface and by the diffracted waves on the side and at the back of the body. From the human injury viewpoint, the most important part of the wave energy is the one that is transmitted into the body in the form of both positive (compression) and negative (tension) stress waves as well as shear stress waves. Normal stress can be defined as the perpendicular force per unit area applied to an object, in a way that compresses (compressive stress) or stretches (tensile stress) the object. Shear stress, or simply shear, is similar to stress, except that the force applied is such that the material is sheared or twisted. It should be noted that the pressure entering the tissue may be higher than in the primary wave, due to a damming up of pressure against the body surface. In air, high frequency acoustic waves and shock waves are decaying due to viscous dissipation, producing heat. In tissues, the steep gradient pressure waves will also be absorbed by viscoelastic damping and tissue plastic deformation (tearing, breaking), resulting in mechanical injury. When the pressure wave crosses material interfaces with different densities, large perturbations in stress and deformation take place. A wave impacting denser material will compress it, creating larger stress (pressure), and when it emerges from denser to lighter material it will create large deformations. Therefore, in the human body organs and tissues of different densities are accelerated at different relative rates, resulting in displacement, stretching, and shearing forces. For those reasons the most vulnerable parts of the body are the air- and gas-containing organs, such as the ear drums, lungs, and intestines. In spite of the relatively uniform density and protective barriers, including the scalp, skull, meninges, and subarachnid cerebrospinal fluid, the brain is also susceptible to blast wave injuries. Highly anisotropic material properties in the brain and immense vascular perfusion will result in nonuniform absorption of the wave energy, stretching and breaking neural axons and the capillary blood brain barrier. Other homogeneous solid viscera transmit the pressure wave to the distal side of the body and are much less susceptible to blast wave injury. In general, the risk of injury is related to the blast energy delivered to the body and the absorption by various tissues.

Free-standing objects exposed to the blast wave (shock wave and the blast wind) will also be displaced. The time integral of the total pressure (p + ½ v^2) and the viscous drag loads integrated over the entire surface of the object will result in a net force and moment causing object translation and rotation in space. The extent of the movement depends on the object mass (inertia), and the magnitude of the total force and moment according to Newton's law. Typically, solid objects such as shrapnel, debris, and human bodies will experience translational motion after the shock has already passed. The time delay depends on the inertia of the body. Current explosive devices are often loaded with metallic objects, which are accelerated by the detonation and blast waves, to inflict penetrating injuries in addition to the blast wave (Elsayed, Atkins, 2008).

Based on this physical description of the blast wave events, explosions have the potential to inflict three injury types: *primary blast injury (PBI)* due to the shock wave, *secondary* injuries due to blast-propelled debris fragments causing blunt or penetrating ballistic trauma, and *tertiary* injuries due to human body translocation by blast loads and the resulting impact on rigid objects, thus resulting in blunt force trauma. *Quaternary* injury often refers to all other types of injury including burns, environmental wound contamination, among others. For ease of reference, a summary of the possible injuries is given in Figure 6.

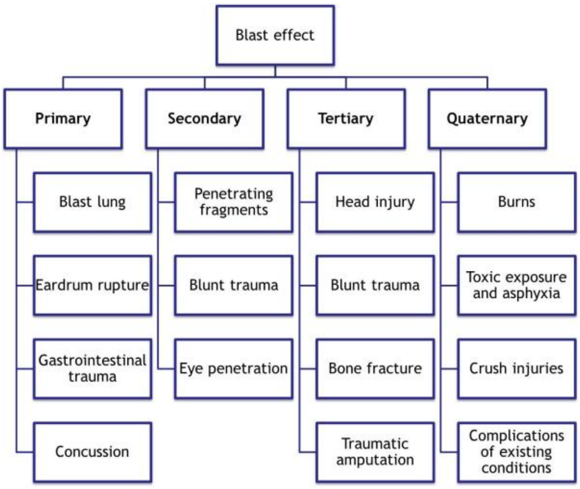

Fig. 6. Blast injury categories (Stewart, 2006)

Primary blast injuries are caused when the blast wave compresses the tissues of the internal organs containing air, such as the lung, ear and gastrointestinal tract. Of these three organ systems, the ear is the most easily damaged. Primary injuries are also commonly referred to as the direct effects of the blast on a human being, opposed to the indirect effects where not the blast wave itself but another phenomenon related to the explosion causes harm.

Secondary blast injuries are much more common than primary blast injuries. They are caused by flying objects that strike people. These can produce both penetrating and blunt trauma, depending on their size and travelling speed. The penetrating injuries occur most often in the exposed areas, such as the head, neck, and extremities, but thoracic and abdominal injuries may occur as well. As distance from the blast centre increases, the effect of the blast itself is reduced, and the effect of fragments and debris propelled by the explosion becomes more important.

Tertiary blast injuries are caused when the victim's body is propelled into another object by the blast winds. This effect is formally known as whole body displacement. If vulnerable body parts such as the skull, the torso or extremities hit a rigid structure, this can obviously cause considerable trauma.

Quaternary blast injuries encompass all other injuries caused by the explosion, including burns from fire or radiation, poisoning from carbon monoxide or other toxic products and inhalation of dust. Crush injuries associated with structural collapse also fall under the quaternary or miscellaneous injuries. Although the loss of structural integrity is observed at rather low overpressure, it is often fatal for the occupants. (Debroey, 2015).

Conclusions

Injuries from explosive materials due to terrorism or other causes are a constant threat that happen worldwide, and they present unique triage, diagnostic, and management challenges. The causes of fatality and injury due to an explosion may range from impacts of fragments and debris, to thermal effects and blast loading of the human body. Blast related injuries include ear drum rupture, traumatic brain injury, acceleration of the body followed by blunt impact, and injury to the air filled organs like the lungs and the gastrointestinal tract. Understanding the mechanisms behind such blast-induced injuries is of great importance considering the recent trend towards the use of explosives in modern warfare and terrorist-related incidents. This article describes the mechanism of propagation of the blast wave and its interaction with objects and the human body. Understanding these phenomena is essential to define appropriate safety distances and to minimise the risk of handling explosives. The knowledge is also important to design protection measures for civilians and military against deliberate explosive attacks.

References

Baker, W. E. 1973. *Explosions in Air.* University of Texas Press, 268 p.

Chaloner, E. 2005. Blast injury in enclosed spaces. − BMJ, 119-120.

Debroey, J. 2015. *Probit function analysis of blast effects on human beings.* MASc Thesis, KU Leuven, Belgium, 137 p.

Dharaneepathy, M. V., K. Rao, A. R. Santhakumar. 1995 Critical distance for blast-resistant design. − *Computers and Structures, 54*, 4, 587−595.

Elsayed, N. M. 1997. Toxicology of blast overpressure. − *Toxicology, 121*, 1−15.

Elsayed, A., J. Atkins. 2008. *Explosion and Blast-Related Injuries: Effects of Explosion and Blast from Military Operations and Acts of Terrorism.* Academic Press, 397 p.

Greer, A. D. 2006. *Numerical modeling for the prediction of primary blast injury to the lung*. MSc Thesis, University of Waterloo, Waterloo, Canada, 184 p.

Josephson, L., P. Tomlinson. 1988. Predicted thoraco-abdominal response to complex blast waves. − *The Journal of Trauma, 28*, 1, S116−S124

Josey, T. 2010. *Investigation of blast load characteristics on lung injury.* University of Waterloo, 219 p.

Katz, E., B. Ofek, J. Adler, H. B. Abramowitz, M. M. Krausz.1989. Primary blast injury after a bomb explosion in a civilian bus. − *Annals of Surgery,* 484−488.

Liang, S. M., J. S. Wang, H. Chen. 2002. Numerical study of spherical blast-wave propagation and reflection. − *Shock Waves, 12*, 59–68.

Mayorga, M. A. 1997. The pathology of primary blast overpressure injury. − *Toxicology*, 17−28.

Smith, P. D., J. G. Hetherington. 1994. *Blast and Ballistic Loading of Structures.* Butterworth-Heinemann, Oxford, 336 p.

Stuhmiller, J. H. 1997. Biological response to blast overpressure: a summary of modelling. − *Toxicology,* 91−103.

Wightman, J. M., S. L. Gladish. 2001. Explosions and blast injuries. − *Annals of Emergency Medicine*, 664−678.