Chapter 7

THE PHYSICS AND MECHANISMS OF PRIMARY BLAST INJURY

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INTRODUCTION

An explosive is a substance that can be made to undergo a rapid chemical reaction that will transform a liquid or solid into gas, liberating a large amount of energy.[1] The products of the detonation (or *explosion)* of a conventional explosive are *(a)* a region of highly compressed gas (the *blast)* that rapidly expands to occupy a volume at least 10^5 times greater than that of the original explosive and *(b)* various solid residues from the explosive or its casing. In addition, nuclear detonations release radioactive particles when fission or fusion occur.

An explosion that occurs in the earths atmosphere is called an *air blast;* a blast that occurs in water is called an *underwater blast.* Conventional military explosives range from a few ounces up to thousands of pounds of trinitrotoluene (TNT) equivalent. Nuclear weapons produce blast waves that are equivalent to thousands or millions of tons of conventional explosives.[2]

The rapid expansion of gas after detonation almost instantaneously compresses the surrounding air into a *shock wave* that propagates supersonically and in all directions from the explosion (Figure 7-1). The shock wave that is generated by the rapid release of gas from an explosive is called the *blast wave.* The rush of air caused by the net motion of the gas is called the *blast wind.*

Blast injury is a general term that refers to the biophysical and pathophysiological events and the clinical syndromes that occur when a living body is exposed to blast of any origin. Blast-wave physical properties, the complexity of the waveform, and the number of blast repetitions determine the potential for *primary blast injury* (PBI).

PBI occurs when the blast wave strikes and compresses the body. Energy is transferred directly from the transmitting medium (air or water) to the body surface. Damage is almost totally limited to the auditory system and the gas-containing structures of the respiratory and gastrointestinal tracts.

Secondary blast injury occurs when flying debris, collapsed buildings, or other environmental material energized by the explosion strike the body. A high incidence of casualties with secondary injuries from broken glass can be expected when blasts occur in urban areas.

Tertiary blast injury occurs when a casualty's body is thrown against the ground, equipment, structures, trees, or other stationary objects by pressure differentials or blast winds. *Mutilating blast injury* (that is, traumatic amputation) occurs as a combination of secondary and tertiary blast effects.

Blast waves that come from an explosion used to propel a soldier's own munitions are called *weapon noise.* Their principal hazard is to the soldier's hearing.

FUNDAMENTALS OF BLAST AND BLAST WAVES

The defining characteristic of a *blast wave* at any point in space is the variation in ambient pressure over time (its *pressure-time history).* The increased pressure (above normal from a blast is termed the *blast overpressure.* The level of overpressure depends upon *(a)* the energy of the explosion, *(b)* the distance from the point of detonation, *(c)* the elapsed time since the explosion, and *(d)* the measurement technique. Blast *strength* is defined as the ratio of overpressure to ambient pressure. Some exotic explosives, such as fuel-air mixtures, can produce large overpressures with long *positive durations* (that is, the time over which the pressure is greater than the ambient undisturbed pressure). Blast waves that arise from weapon noise have small positive durations (usually less than 5 msec) and modest peak overpressures (less than 1 atm) and are accompanied by negligible blast winds. Nuclear weapons can generate blast waves that have overpressures of several atmospheres, positive durations lasting several seconds, and blast winds of hundreds of miles per hour.

The molecules of gas in the atmosphere around us are in constant thermal motion.[3] On average, at sea level, there are 30 million billion molecules in every cubic millimeter of air, moving at speeds on the order of 300 m/s and bumping into one another 100 million times each second, after traveling only 0.001 mm. This continual bombardment of gas molecules against any solid surface exerts a force on every part of that surface and is most appropriately expressed as a force per unit area, or a *pressure.*

The average energy of motion of individual molecules is measured by the temperature of the gas, while the mass of molecules in a given volume is measured by the density of the gas. Pressure, temperature, and density are measures of the *state* of the gas. Because all

Fig. 7-1. **A** large conventional explosion is shown from a distance. Beyond the fireball, the blast wave appears as a sharp line, which is caused by refraction of light by the higher-density gas at the shock front.
Source: D. R. Richmond

three quantities are manifestations of the underlying motion of the molecules, they are related to one another by *equations of state.*

Physical Characteristics of Wave Propagation

When the state of a gas is disturbed, for example by opening a door into a closed room, the molecules near the door are momentarily compressed. Because the molecules move so much faster than the door, however, this local aggregation of molecules is quickly dispersed. These small compression disturbances travel at the speed of sound. The room quickly reaches a state of slightly higher but uniform pressure. Similarly, when passengers force their way onto an already crowded train, a new arrangement (in which the distance between people has evened out) takes place throughout the car without much motion of any one individual. The propagation of state changes, without the need for much motion of the individual elements, is called *waue propagation.* The speed at which such a disturbance propagates is called the ***ware** speed,* while the net speed at which individual elements move is called the *material speed.*

There are many examples in ordinary life of wave propagation. Sound is propagation of local concentrations of pressure through any gas, liquid, or solid. Water waves are the propagation along the surface of local variations in the water level. Electrical signals along a telephone line are the propagation of local variations in the electric and magnetic fields within the wire. In each of these examples, the material speed of the individual elements is quite small compared to the wave speed. The air that is moved in the act of speaking barely leaves the region of the vocal cords by the time the sound is heard across a room. The water molecules move at only a small fraction of the speed of the water wave. Even more dramatically, in the time the electrical signal passes from Los Angeles to New York, the electrons in the telephone wire responsible for starting the signal have moved less than 1 cm.

A different situation exists if the material speed approaches or exceeds the wave speed. When the material speed exceeds the wave speed, the individual

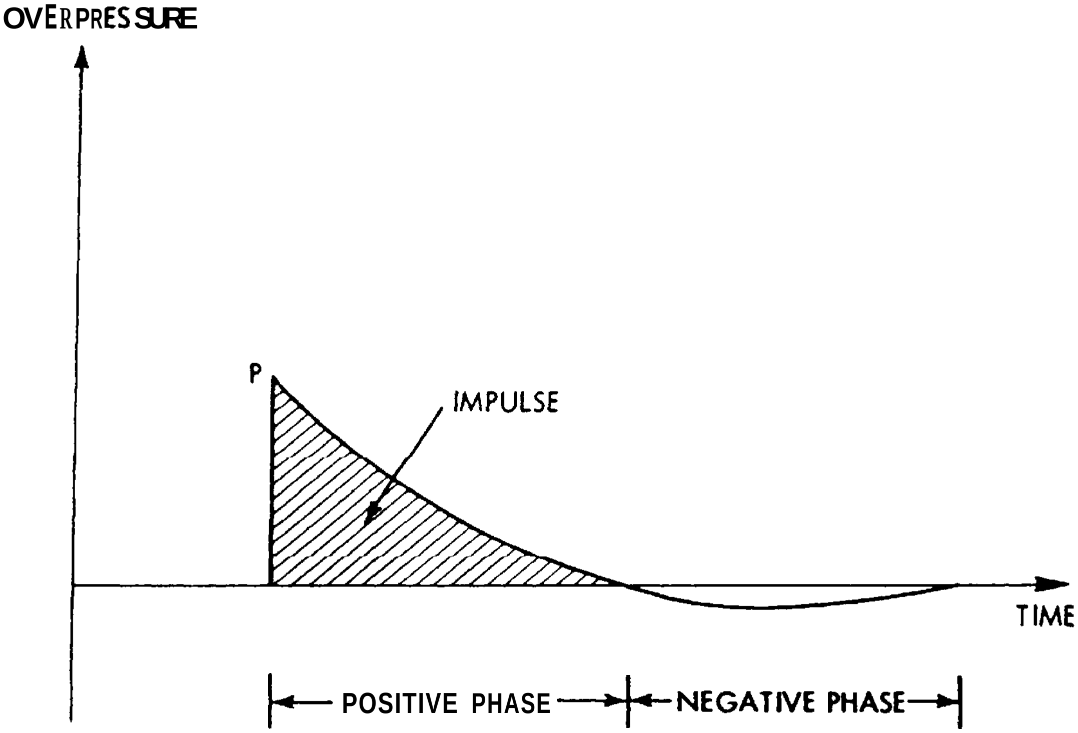


Fig. 7-2. This graph illustrates the ideal pressure-time history of an air blast in an undisturbed, free-field environment (a Friedlander waveform). The impulse is the integral of pressure over time. P is the peak overpressure.
Source: Walter Reed Army Institute of Research

elements are pushed together faster than the disturbances can be relieved by the thermal motion. Consequently, the molecules pile up and the densities, pressures, and temperatures increase rapidly. Eventually, because the wave-propagation speed also increases as these quantities increase, a state is reached in which the piling up that is caused by the material motion is just balanced by the dispersion of the thermal motion. This local high pressure, temperature, and density—the shock wave—advances faster than the speed of sound through the undisturbed medium.

The Blast Wave

The term *blast front* is often used to describe the leading edge of the blast wave as it moves into undisturbed ambient air. This front increases the density of the air through which it passes, raising its temperature and accelerating the air molecules. In the denser air at the blast front, the pressure wave travels faster than it would through ambient-pressure air.

The gases from an explosion push out circumferentially and rapidly into undisturbed air. As the blast front passes, they create both a high-pressure region (the *positive phase,* shown in Figure 7-2), and a blast wind. Because the gas is rushing away from the explosion, it not only decompresses the original high-pressure region that the explosion caused, but it also continues to expand. This creates a region of below-atmospheric pressure (the *negative phase)* that also propagates away from the explosion. Since the speed of propagation increases with pressure, the negative phase of the blast wave moves more slowly than the blast front does, and becomes separated from the front by greater and greater distances as the blast wave progresses.

In the positive phase, the air is compressed almost instantly to a peak value that decays exponentially back to and then below the ambient (baseline)pressure, into a negative phase. During the positive phase, the flow of gas, or blast wind, is away from the explosion. The direction of flow reverses in the negative phase, with a net movement of gas back towards the relative vacuum at the detonation point. The negative phase is thought not to contribute to blast injury, although definitive data do not exist.

The Pressure Waveform

A blast wave occupies a particular place at any given time, and a pressure-measuring device placed at a fixed location for a defined period of time can quantitatively describe a blast. As a result, the spatial variation of the wave is translated into a time variation, its pressure-time history or *pressure waveform.* Simple measurements of the blast wave are meaningful only when the pressure waveform has a very simple shape (Figure 7-2). Characterization of such waves, called *ideal blast waves,* includes making the following observations:

- The ambient atmospheric pressure is noted before the wave arrives
- The pressure rises almost instantaneously to the peak overpressure when the blast front arrives
- The pressure remains above ambient while the positive phase of the blast wave passes the measuring point
- The positive-phase duration is the interval between the arrival of the blast front and the first return to ambient pressure
- A lower-than-ambient pressure that slowly returns to ambient marks the passage of the negative phase

Many mathematical forms have been suggested to capture the time variation of these ideal blast waves. One equation, *the Friedlander waveform,* describes the theoretical variation of the positive pressure behind the shock front:[4]

$$P(t) = P_s \, (1-$$

where $P(t)$ is the pressure at any given time (t), P_s is the peak overpressure (an instantaneous static pressure quantity), t_o is the positive duration (the time duration of the positive pressure), and b is a decay constant, a parameter that describes the rate at which the overpressure decreases after the peak.

Blast waves are typically measured by piezoelectric or piezo-resistive pressure transducers.[4] Less-common photographic methods include *(a)* high-speed cameras, *(b)* shadowgraphs, and *(c)* Schlieren and streak films.[4,5] Figure 7-2 illustrates an ideal pressure-time pattern measured by a gauge that was oriented ***side-un*** (that is, the sensing surface is oriented parallel to the direction of wave propagation) to the blast in the *free field* (that is, away from any complicating surfaces that would disturb the blast wave). Major environmental features, such as buildings and vehicles, can reflect the *incident* wave (that is, the original blast wave) and lead to very complex overpressures, where measurements are suspect and the potential for injury is difficult to predict.

The pressure-time history of the ideal blast wave is characteristic of many blast waves, especially those far from the explosion. However, if the chemical reactions are slow, or if the point of observation is close to the explosion, non-ideal effects are seen. The most common deviation from the ideal waveform is a second, smaller peak that appears when the negative phase begins. This peak corresponds to a recompression of gas at the detonation site. Distortions of the ideal waveform can also occur when the combustion of slow-burning munitions continues after the blast wave has formed.

Conventional Explosives

Conventional explosives contain compounds of hydrogen, oxygen, nitrogen, and carbon. The explosive material may be a solid, slurry, liquid, or gas. *Primary explosives,* such as mercury fulminate, lead azide, and lead stefinite, are very sensitive and may be induced to explode by heat or pressure. *Secondary explosives* are less sensitive and may be either single compounds, such as TNT and pentaethyltrinitride (PETN), or mixtures. For example, Composition C4, a common plastic military explosive, contains 91% cyclotrimethylenetrinitramine (RDX), rubber, oil, and a plasticizer.[4] *Insensitive explosives* have been developed that require the impact of a high-velocity metal flyer plate to initiate a detonation. They will not detonate even when they are in contact with another explosive and are insensitive to high temperatures. Their inherent stability makes them safe to store and transport. Tables 7-1 and 7-2 give some characteristics of common single- and mixed-composition explosives.

General-purpose explosive munitions usually consist of *(a)* a detonator or a fuse containing a sensitive primary explosive, *(b)* a booster of relatively sensitive secondary explosive, and *(c)* a main charge of an insensitive explosive. The weight of the explosive charge generally increases proportionately to the total weight of the munition. The ratio of charge weight to weapon weight ranges from 0.15 for howitzer shells, 0.25–0.33 for hand grenades, 0.51 for 500-pound bombs, to 0.86 for 10,000-pound bombs. In conventional munitions such as grenades and artillery shells, an appre-

TABLE 7-1

BASIC PROPERTIES OF COMMON SINGLE-COMPOUND HIGH EXPLOSIVES

Explosive	Equivalent Weight Relative to TNT*	Density (g/cm^3)	Detonation Velocity (km/s)	Consistency
Ammonium Nitrate, AN	—	1.73	7.00	Solid
Nitroglycerin, NG	—	1.60	7.58	Liquid
Trinitrotoluene, TNT	1.00	1.65	6.90	Solid
Pentaerythritol Tetranitrate, PETN	1.27	1.70	7.98	Solid
Cyclotrimethylene trinitramine, RDX	1.19	1.80	8.75	Solid
Cyclotetramethylene tetranitramine, HMX	–1.30	1.90	9.10	Solid
Nitrocellulose, NC	—	1.2–1.7	7.30	Solid

***Based on the peak pressure produced compared to TNT**

ciable fraction of the explosive energy is dissipated in bursting the casing and accelerating the case fragments. Such weapons do most of their damage as a secondary blast effect because the fragments are able to cause injuries far beyond the effective range of the blast wave.

The Scaling Laws

For any type of explosive, every combination of weight and distance from the explosion produces a particular pressure-time history. It has long been noted that if a particular peak overpressure occurs at one distance for one weight of explosive, then that same peak overpressure will occur at a smaller distance for a smaller weight and at a larger distance for a larger weight. Mathematical relationships that allow the results of one set of conditions to be determined from the results of another set are called *scaling laws.* Compilation of a wide range of experimental results produced the *cube* root or *Hopkinson's Rule:* The peak overpressure depends on the *scaled distance,* defined as the physical distance from the explosive divided by the cube root of the weight of the explosive charge. For example, 1 pound of TNT produces a peak overpressure of 0.5 atm at a distance of 10 feet. The scaled distance is $10 \div 1^{0.33} = 10$. At twice the physical distance (20 feet), 8 pounds of TNT will produce the same peak overpressure. The scaled distance is $20 \div 8^{0.33} = 10$.

Hopkinson's Rule has simplified the calculation of the peak overpressure from relying on distance and explosive weight independently to relying on a single combination of the two quantities. By measuring the peak overpressure at various distances from a single **weight of explosive, the variation with the scaled** distance can be determined. The peak overpressure due to any other amount of that explosive at any distance can be estimated without conducting further experiments.

Useful as Hopkinson's Rule is, it has significant limitations. New experiments would have to be conducted if another type of explosive were used or if the blast occurred at other altitudes where atmospheric conditions differed. It would be useful to have a more general scaling law.

The laws of physics governing blast waves are described by certain mathematical equations? The solution of those equations provide the pressure-time history of the blast wave. To find the solution, a particular choice of explosive energy, atmospheric conditions, and distance from the charge must be made. With certain simplifications, it is possible to

TABLE 7-2

BASIC PROPERTIES OF COMMMON MIXED-COMPOUND EXPLOSIVES

Explosive*	Equivalent Weight Relative to TNT**	Density g/cm^3	Detonation Velocity km/s	Consistency
ANFO 94 AN/6 FG	0.82	–0.8	–4.7	Powder
Composition B 40 TNT/60 RDX	1.11	1.70	7.9	Solid
Octol 25 TNT/75 HMX	1.06	1.82	8.4	Solid
Pentolite 50 TNT/50 PETN	1.42	1.67	7.4	Solid
Dynamite 50 NG/0.2 NC/34 SN/15.8 C	0.90	1.40	–5.8	Solid
Bonded Mixtures				
Composition C4 91 RDX/ 2.1 rubber/ 1.6 oil/ 5.3 plasticizer	1.37	1.0–1.60	8.0	Plastic
Sheet Explosive 60–85 PETN/0–8 NC rubber and plasticizer	–1.27	–1.50	–7.0	Rubberlike sheets

*FO: Fuel oil; SN: Sodium Nitrate; C: Combustibles and chalk

**Equivalent to weights based on peak overpressure produced compared to TNT

rearrange those equations so that only dimensionless combinations of parameters appear. Solving these dimensionless equations would allow the scaling laws to be derived from basic physical principles. Unfortunately, the mathematics of the blast-dynamics equations are extremely difficult and a general solution is not known.

Blast parameters scaled to distance at sea level are given in Figure 7-3. In general, the peak pressure decreases with distance while the positive duration increases and the *positive phase impulse* (that is, the integral of the overpressure over the positive duration) falls. For a 1-pound sphere of TNT detonated in unconfined (free) air, this graph may be read directly. To use larger explosive weights, the actual distance must be scaled by dividing by the cube root of the weight of the explosive charge. The peak pressure is read directly and the scaled blast parameters are then read from the graph and converted to the actual parameters by multiplying by the cube root of the charge. To use Figure 7-3 for explosives other than TNT, the actual charge weight must be multiplied by the compound's TNT equivalency, some of which are given in Tables 7-1 and 7-2.

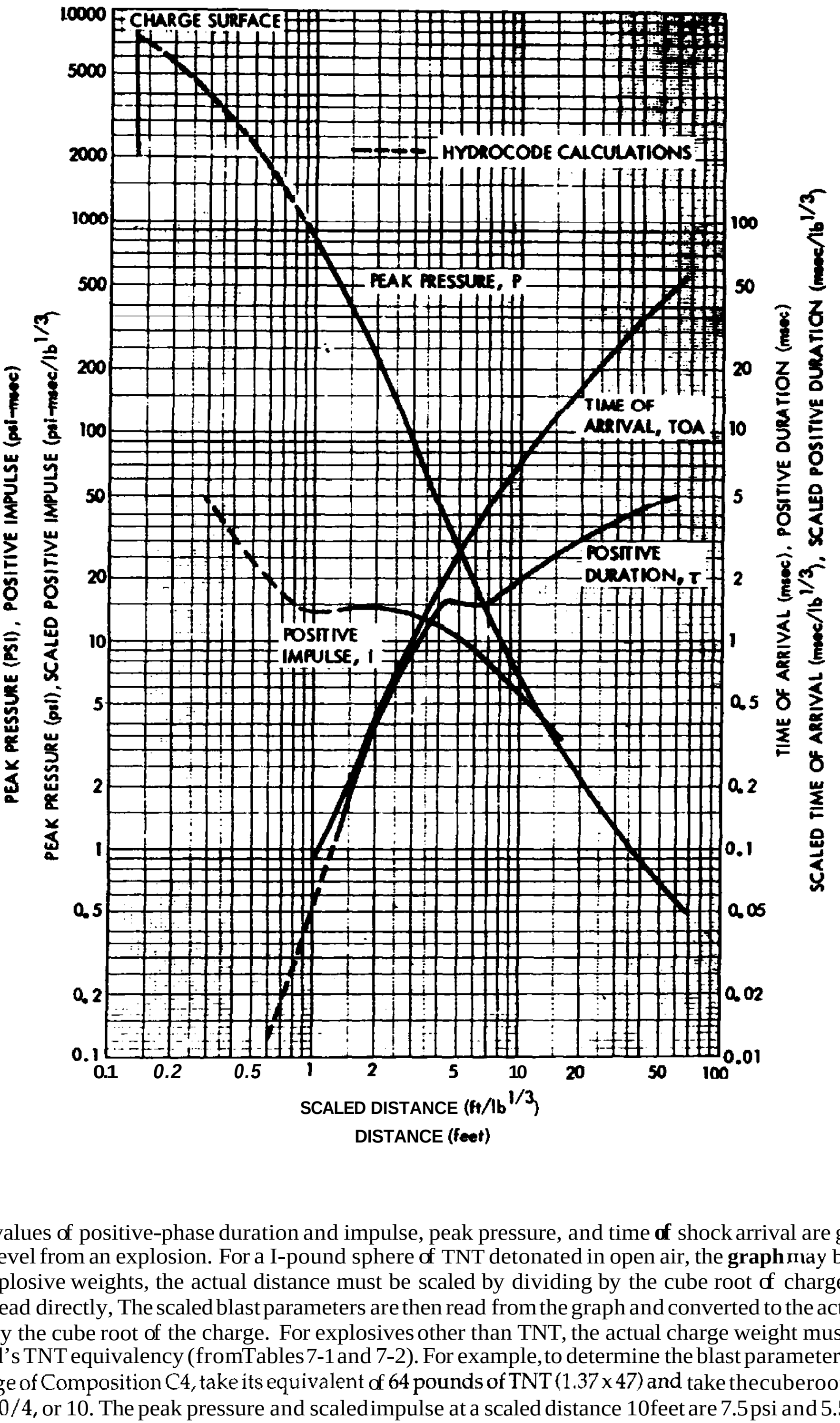


Fig. 7-3. Scaled values of positive-phase duration and impulse, peak pressure, and time of shock arrival are given for scaled distances at sea level from an explosion. For a I-pound sphere of TNT detonated in open air, the **graph** may be read **directly. To** use larger explosive weights, the actual distance must be scaled by dividing by the cube root of charge weight. Peak pressure is then read directly, The scaled blast parameters are then read from the graph and converted to the actual parameters by multiplying by the cube root of the charge. For explosives other than TNT, the actual charge weight must be multiplied by the compound's TNT equivalency (from Tables 7-1 and 7-2). For example, to determine the blast parameters at 40 feet from a 47-pound charge of Composition C4, take its equivalent of 64 pounds of TNT (1.37 x 47) and take the cube root (4). The scaled distance is then 40/4, or 10. The peak pressure and scaled impulse at a scaled distance 10 feet are 7.5 psi and 5.5 psi-msec. The impulse is multiplied by 4 *to give* an actual peak pressure of 30 psi and an impulse of **22** psi-msec.

Source: Reference 7

Nuclear Blast Waves

Nuclear blast waves differ from those of conventional munitions principally in their positive-phase durations, which may last as long as several seconds, compared to milliseconds with TNT. A nuclear explosion may also produce a *precursor shock wave* under certain conditions of burst height and terrain.’ The intense radiant thermal pulse heats the ground and adjacent air layer. The shock front near the ground travels faster in this layer of heated air and runs ahead of the main pressure wave. Because the velocity of the air flow in the precursor shock wave is greatly increased, its blast wind is several times greater than that found in an ideal wave having the same peak pressure. *Drag-sensitive equipment* (which is less massive or has a greater exposed surface) and personnel may be displaced great distances by the precursor wave, which is a tertiary blast effect.

BLAST MEASUREMENTS AND EFFECTS

Intense blasts are necessary to produce manifestations of PBI other than ear lesions. Because the intensity of the blast (the peak overpressure) decreases rapidly with distance from the detonation, personnel must be very close to an explosion to sustain PBI. At these short ranges, fragment injuries and thermal burns may mask the blast injury. In fact, fragments of conventional munitions travel in air far beyond the distance that the blast will cause injury.

The destructive aspect of a blast is due to the force it exerts. This force, called the *blast loading,* must be described as a force per unit area, or pressure, and is usually not the same on all parts of a building or a person. The blast loading on a structure depends upon its geometry and its orientation to the incident blast wave. Structural damage would be determined by the inter-relationships between material strength and local stresses produced by the external blast loading.

Blast-Pressure Measurement

Blast pressures are defined as either *static, dynamic,* or *reflected.* Pressure-measuring devices record the force exerted on a small sensing surface. The *static* (or side-on) *pressure* is measured by a sensing surface that is oriented parallel to the direction of propagation of the wave (gauge *e* in Figure 7-4). It is unaffected by any kinetic energy in the traveling wave front and measures the air compression that is active in all directions due to the thermal motion of the gas.

If that sensing surface is oriented so that the net motion of the wave front strikes the surface, then the *total pressure* is recorded (gauged in Figure 7-4). The total pressure includes both the static pressure, due to the thermal motion, and the *dynamic pressure,* due to stopping the net air motion at the sensor surface. Dynamic pressure is the force that is associated with the blast wind (that is, the movement of air particles at the leading edge of the shock wave). It is measured as the difference in the reading between two sensors oriented at right angles, side-on and facing the blast wave (Figure 7-4).

The standard practice in blast measurement is to record the static component of the pressure and to present that measurement in terms of the peak overpressure and positive-phase duration. However, readers should not ignore the fact that the blast wind generated by nuclear and large conventional munitions may add substantially to the destructive potential of the static overpressure alone.

Structural Blast Loading and Wave Reflection

When a blast wave encounters a large, solid barrier, like the wall of a building or the ground itself, the motion of the gas molecules is impeded. If the barrier is perpendicular *(normal)* to the direction of propagation of the blast wave, the wave is said to undergo a *normal reflection.* At the barrier, the blast wave can no longer propagate forward into undisturbed gas. Consequently, the molecules are compressed even more by those following until they are so tightly packed that they push back in the direction of the incident wave. This even greater concentration of gas molecules that builds up on the surface facing the incident wave is called the *reflected region.*

If there is a negligible amount of blast wind associated with the incident wave, then the reflected region will have an overpressure about twice that of the incident wave. As the blast winds become stronger, the overpressure in the reflected region grows proportionally and can be tenfold greater than the peak pressure in the incident wave.

The reflected region will continue to increase as long as it is supplied by the incident wave. If the

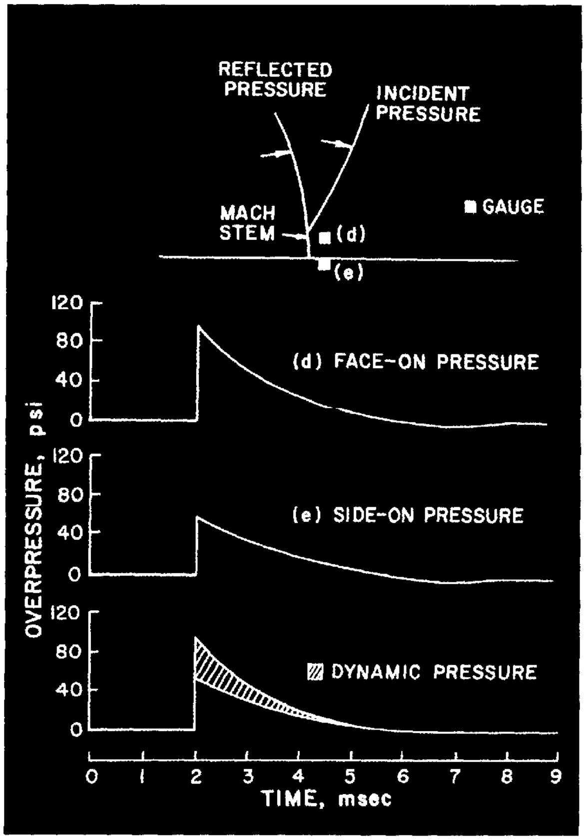


Fig. 7-4. Static and dynamic pressure measurements are depicted for an explosion occurring near the ground. The incident wave reflects from the ground. The reflected and incident waves interact near the surface to produce a strengthened wave called the Mach stem. Gauge e is oriented with its sensing surface parallel to the direction of propagation of the wave and measures the static (or side-on) pressure in the Mach stem. Gauge d is oriented face-on to the shock and measures both the static and dynamic components of the blast wave. The dynamic pressure is the difference between the two measurements.
Source: D. R. Richmond

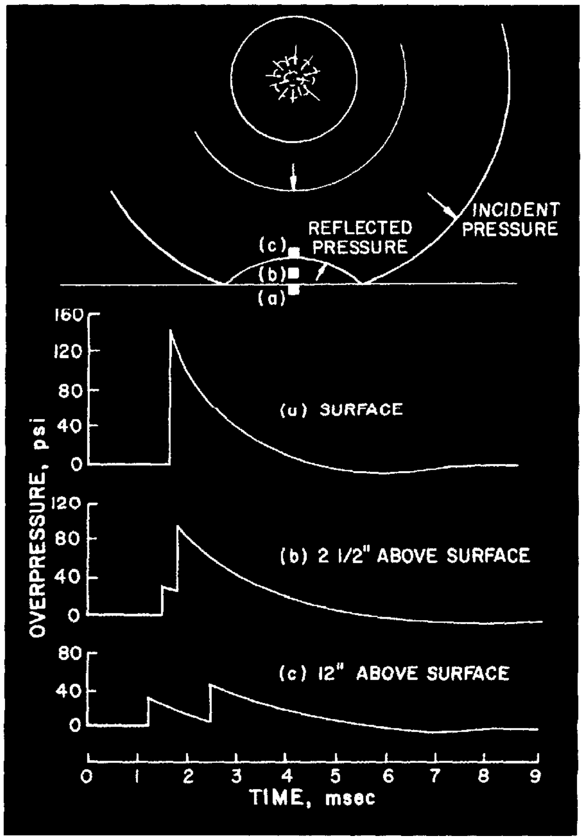


Fig. 7-5. Pressure measurements are depicted near a reflecting surface. Gauge *a* is at the surface and shows the interaction of the incident and reflected waves as a single wave with peak pressure much greater than that in the incident wave. Gauge *b* is slightly above the surface and shows the incident wave and an overlapping reflecting wave. Gauge c is farther from the surface and shows less interaction of incident and reflected waves.
Source: D. R. Richmond

incident wave is of finite duration, then the region of high reflected pressure will extend only a finite distance from the wall and only for an amount of time approximately equal to the duration of the incident wave (Figure 7-5). The reflection process results in a reflected wave, which moves in the opposite direction of the incident wave with a nearly identical wave form.

When the blast wave strikes a surface obliquely, the reflection process is more complex. The angle between the direction of propagation of the incident wave and the reflecting surface is called the angle of incidence, whereas the corresponding angle for the reflected wave is called the *angle of reflection*. If the blast is weak (that is, the overpressure is not much greater than the ambient pressure) then the angle of reflection is equal to the angle of incidence. This regular *reflection* is geometrically the same as light reflecting off a flat mirror. As the blast strength increases, the incident and reflected waves interfere with one another with the result that the angle of reflection is smaller than the angle of incidence. When the blast strength reaches a critical value, the waves combine to produce a Mach *stem,* which propagates as a single front along a reflecting surface.' (The Mach stem, first described by Dr. Ernst Mach in 1877, is not related to Mach numbers, although both are named for Dr. Mach.) Away from the surface, separate incident and reflected waves occur (Figure 7-4). The point at which the three waves join is called the *triple point*. In most large explosions, a person on the ground will only be affected by the Mach stem as it moves along the ground, where the peak pressure will be greater than that in the incident wave. For a surface burst, in order to account for the Mach stem, the actual charge weight in Figure 7-3 must be increased by a factor of 1.7.

When a blast wave strikes a structure, it can exert a tremendous force that can damage or demolish it. Imagine a building with one side normal to the blast. That side will **be** subjected to the reflected pressure for the duration of the wave, while the opposite side will be subjected to only the ambient pressure until the blast has propagated around to the back. Then the back of the building will be subjected to a pressure comparable to the static overpressure. Even modest pressure differences over the large surface area of most buildings can create enough motion to cause critical structural elements to collapse.

Quantitative values of reflected pressure, dynamic pressure, and blast-wind speed (particle velocity) at the shock front can be plotted as functions of incident static overpressure (Figure 7-6). Table 7-3 gives several examples that illustrate the nonlinear increase in both reflected and dynamic pressures with increasing static shock strengths.

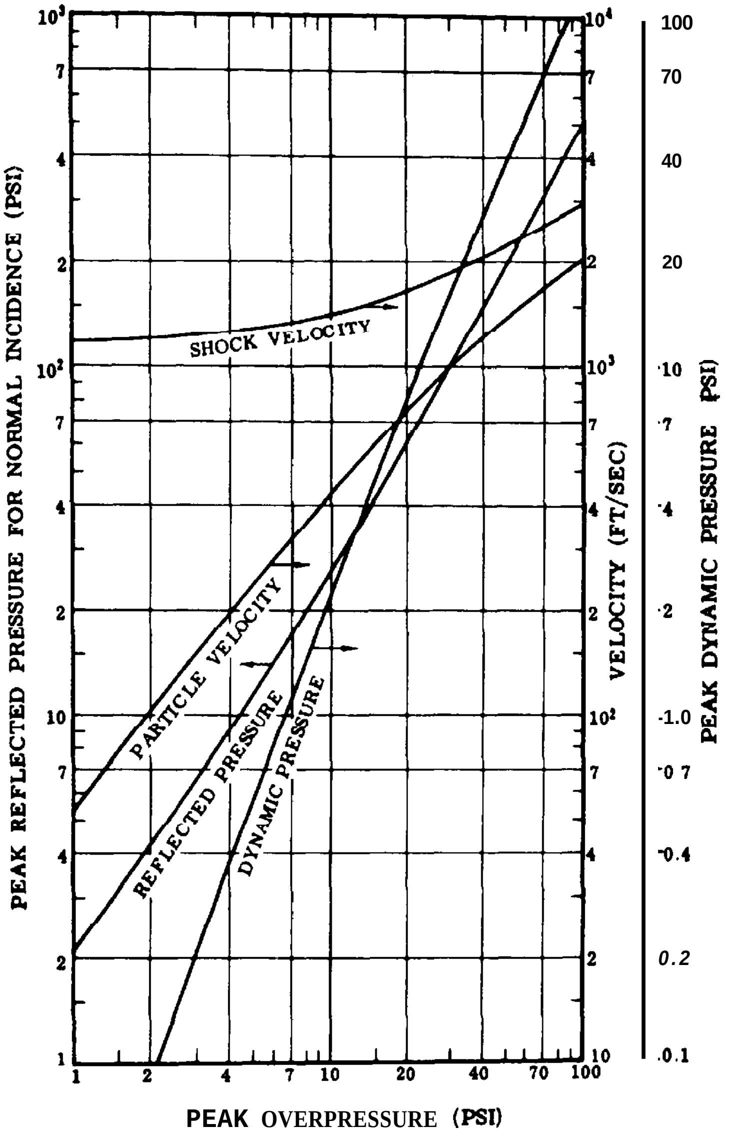


Fig. 7-6. Shock-wave parameters for dynamic pressure, reflected pressure, particle velocity (blast wind), and shock-wave velocity are plotted as a function of incident shock strength as measured by static peak overpressure. Source: Reference 2

TABLE 7-3

WIND VELOCITY RELATED TO BLAST PARAMETERS

Wind Velocity (Mph)	Maximum Pressure in Psi*		
	Incident Static	Reflected	Dynamic
40	1	2	0.02
70	2	4	0.1
160	5	11	0.6
290	10	25	2
470	20	60	8
670	30	90	16
940	50	200	40
1500	100	500	125

*Illustrative values of peak reflected and dynamic pressures demonstrating the nonlinear increase in both with increase shock strength measured *as* peak static overpressure. By way of comparison, a hurricane wind of 120 mph exerts a dynamic pressure of about 0.25 psi.

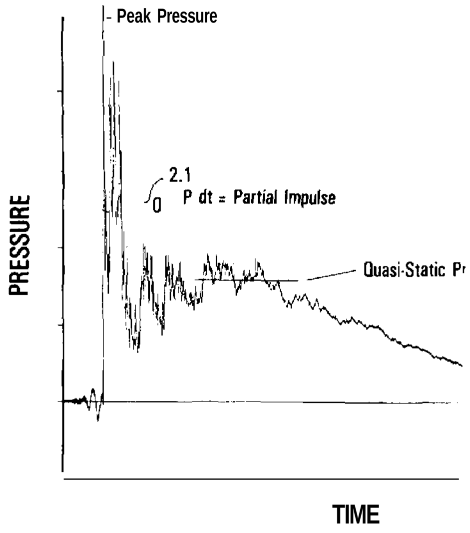


Fig. 7-7. This graph represents a complex blast wave that was recorded inside an armored vehicle that had been penetrated by a shaped-charge munition. Note the many distinct peaks of interacting reflections. After approximately 10 msecs, the ambient compartment pressure is increased by the bulk expansion of gas (quasi-static pressure).
Source: U.S. Army Ballistics Research Laboratory

Complex Blast Waves

Blast waves inside an enclosure undergo repeated reflection from the interior surfaces and create a pressure environment called a *complex blast wave.* Not only is the pressure-time history in such an environment very irregular and long lasting, but because the reflected waves will strike the sensing surface at many different angles, a measuring device does not record only the static component. As a result, even interpreting the pressure wave form is difficult.

Complex blast waveforms in an enclosure have three characteristics: *(a)* the incident blast waves, *(b)* a jumble of reflected waves, and *(c)* the static pressurization of the enclosure (Figure 7-7).

If an explosive is detonated within an enclosure, the first blast wave to arrive at a given location depends only on the explosive energy and the distance from the measuring point—the same as if the blast had occurred in a free field. After reflections begin to occur, however, the pressure-time history becomes a jumble of separate waveforms. The magnitude and timing of these waves depends on the structure of the enclosure and the orientation of the sensor. Finally, the gases liberated by the explosion heat and expand to fill the enclosure, both of which raise the ambient pressure. This static pressurization will eventually subside as the gases vent through openings in the enclosure.

On the battlefield, simple foxholes offer the potential for one of the most common occurrences of complex blast waves. Even though the blast wave propagates across the top of the foxhole and does not directly impinge upon it, the static overpressure causes a wave to propagate into the foxhole and to reverberate inside. Depending on the size and shape of the foxhole and the location of the soldier within it, the effective overpressure loading (and hence the hazard of injury) can be greater than that of the incident blast wave itself.

Blast waves can enter buildings through openings in much the same way that they enter foxholes. Structures hardened against ionizing and thermal radiation may be vulnerable to the blast effects of nuclear weapons. Radiation propagates in a straight line and can be effectively blocked by a barrier such as an earthen berm. A blast wave will propagate around or over the impediment. A useful analogy might be that light cannot be seen from behind a hill, but noise can be heard.

Complex blast waves can also be created when weapons are fired inside a structure. The exhaust gases cause weapon noise, which, in a free field, would cause only auditory injury. Inside a small enclosure, however, the reverberation of the waves and the pressurization of the enclosure lead to much greater loading and the potential for nonauditory blast damage.

Armored vehicles are also subject to complex blast effects on the battlefield. While blast waves can enter armored vehicles through openings like they do in buildings, it is more likely that blasts will be associated with enemy weapons designed to penetrate the vehicle. The penetration of the armored walls leads to both continued ignition of the original munition and secondary explosions from the fuel or other interior combustibles. Penetrating wounds from fragments remain the dominant threat, but as antispall materials are improved, blast becomes a greater potential casualty generator.

TOLERANCE TO AIR BLAST

Blast load on a person is similar to that on a building, except that the time it takes for the blast wave to engulf the body is much shorter than the time necessary for the body to respond. A person is more affected than a building by the crushing effects of the overpressure and the effects of the blast wind. Since the reflected pressure can be considerably greater than the static component, the body's orientation with respect to both the blast itself and any rigid surfaces from which the wave will reflect can affect the body's response.

Small-caliber weapons such as rifles produce blast waves of very short duration and modest overpressure that primarily threaten the auditory system. Larger-caliber weapons such as howitzers produce blast waves of many milliseconds' duration, and with overpressures of as much as 5 psi in crew locations. The principal hazard to soldiers firing these heavy weapons, however, is still to the auditory system. Shoulder-fired weapons and mortars produce high peak overpressures at the position of the soldier, precisely because the soldier is so close to the weapon at the time of firing. Fortunately, the durations are very short, and hearing loss remains the principal hazard.

Curves estimating human tolerance to free-field air blast as functions of the maximum incident overpressure and positive duration at sea level appear in Figures 7-8, 7-9, and 7-10.[8] They are based on results from studies that determined the dose-response of thirteen species subject to blast waves of various durations generated by high explosives in the open and inside shock tubes? At short durations there is an

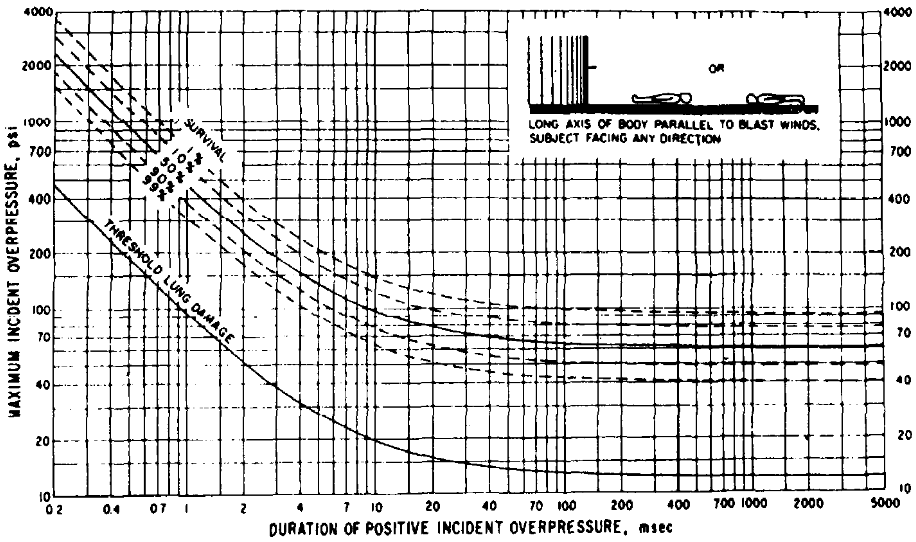


Fig. 7-8. The estimated tolerance for a single air blast at sea level is given for a 70-kg human oriented end-on to the shock wave.
Source: Reference 8

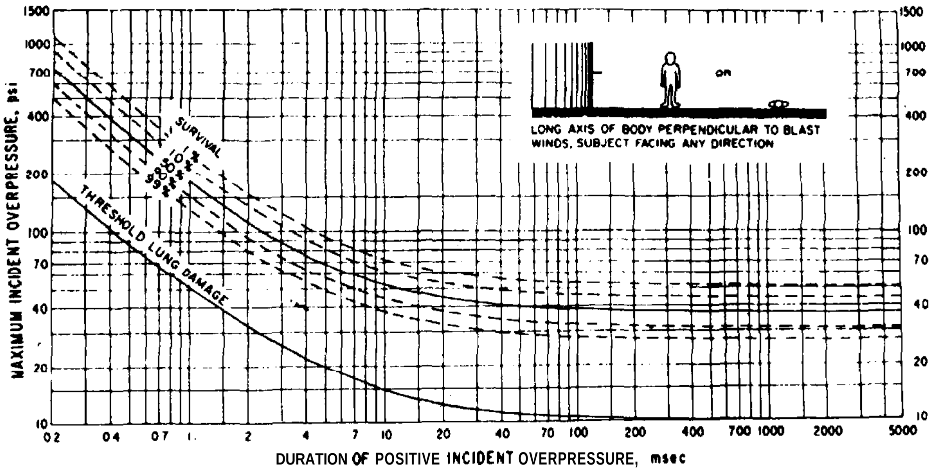


Fig. 7-9. The estimated tolerance for a single air blast at sea level is given for a **70-kg** human oriented side-on to the shock wave.
Source: Reference 8

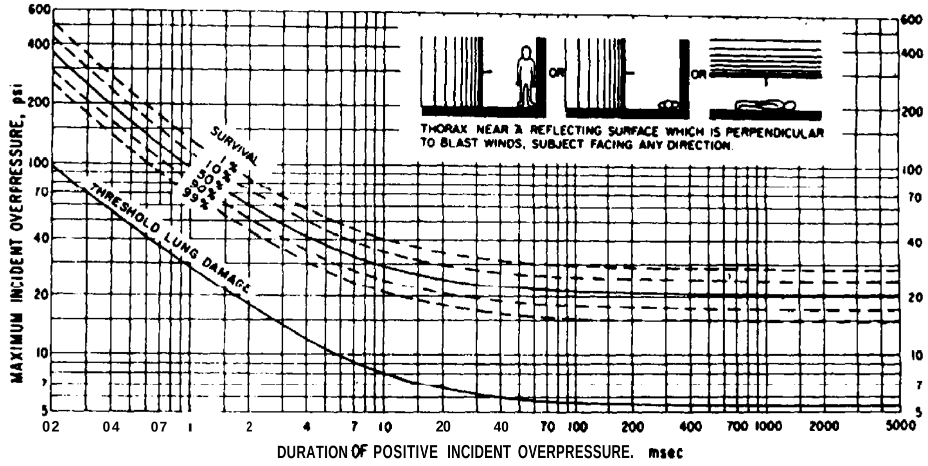


Fig. 7-10. The estimated tolerance for a single air blast at sea level is given for a 70-kg human oriented against a reflecting surface that is perpendicular to the shock wave.
Source: Reference 8

interaction between peak pressure and duration, which are the determinants of impulse. At durations longer than 20-30 msec (the range of nuclear or very large conventional explosives), the injurious effect varies directly with the overpressure level alone.

Effects of Body Positioning

Personnel oriented *end-on* to the blast wave (that is, lying down with either their head or feet pointed toward the blast) offer little resistance to the dynamic pressure component of the wave, and the incident shock (or side-on pressure) constitutes their air blast dose (Figure 7-8). The end-on orientation also gives the best protection against being displaced by the blast wind.

For persons side-on to the approaching blast wave, the dynamic pressure and incident pressure are additive (Figure 7-9). In the region of short-duration blast waves (a positive phase of 3 msec or less), there is a twofold difference in magnitude between the curves for the end-on and side-on orientations.

Individuals positioned against a large reflecting surface and normal to the incident shock would have the peak reflected pressure as their effective blast dose (Figure 7-10).

For example, the *threshold* (that is, the lowest overpressure at which trivial lesions are first detected) for lung injury is about 12 psi for blast waves of greater than 20–30 msec duration; scattered pleural petechiae are the threshold injury. Subjects end-on to the blast would require an incident shock of 12 psi static pressure to cause this lesion. If the subjects are oriented side-on, an incident shock of 10 psi (with an associated dynamic pressure of 2 psi) would cause equal damage. If the subject is against a reflector, an incident shock of just over 5 psi (reflecting to 12 psi) would cause the same injury. Although all three examples have different incident blast waves, the biologically effective blast loading is the same.

Effects of Repeated Exposure to Air Blasts

Injury from blast is a function of intensity (pressure and impulse for short-duration waves, and pressure alone for long-duration waves) and the number of shock waves.[10,11] Figures 7-11, 7-12, and 7-13 present curves relating the estimated incident static pressures and positive-phase durations producing both threshold and severe injuries in the lungs, the gastrointesti-

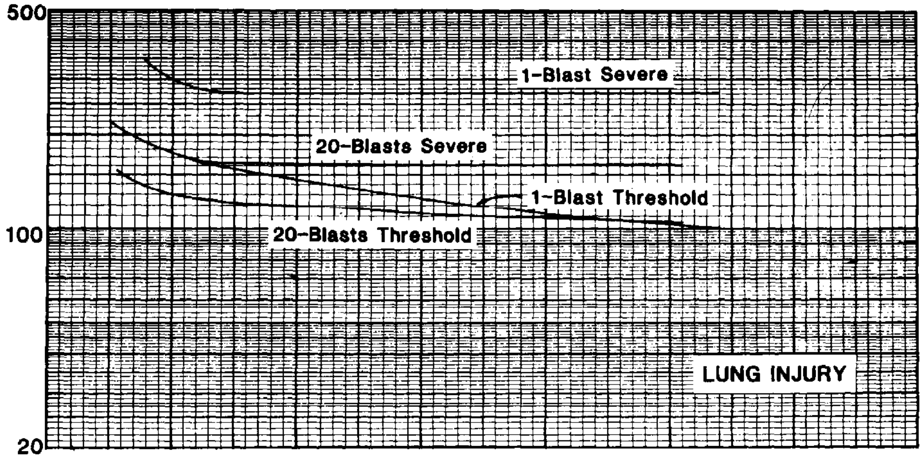


Fig. 7-11. The estimated free-field air blast conditions for one and twenty blasts are depicted for threshold and severe injury to the lungs. Threshold injury is the presence of scattered pleural petechiae, and severe injury is confluent hemorrhage covering a significant portion of the lung's surface.
Source: Walter Reed Army Institute of Research

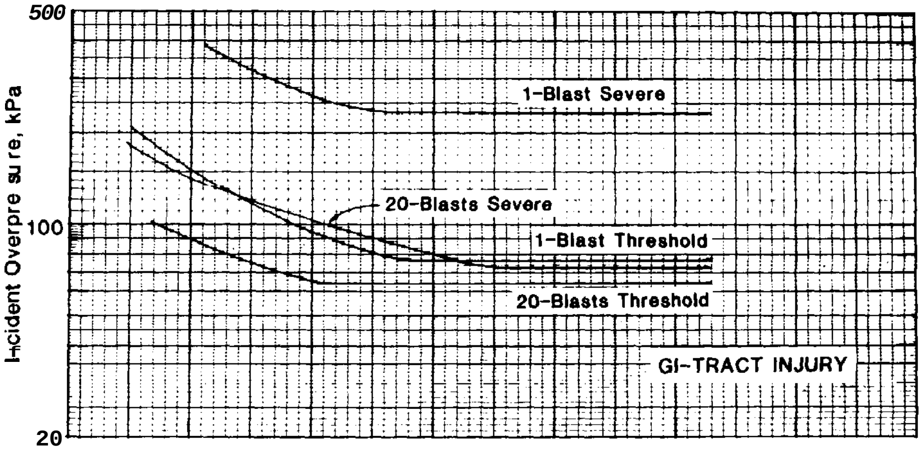


Fig. 7-12. The estimated free-field air blast conditions for one and twenty blasts are depicted for threshold and severe injury to the gastrointestinal tract. Threshold injury is the presence of scattered petechiae on the serosal or mucosal surface, and severe injury is extensive transmural hemorrhage or visceral rupture.
Source: Walter Reed Army Institute of Research

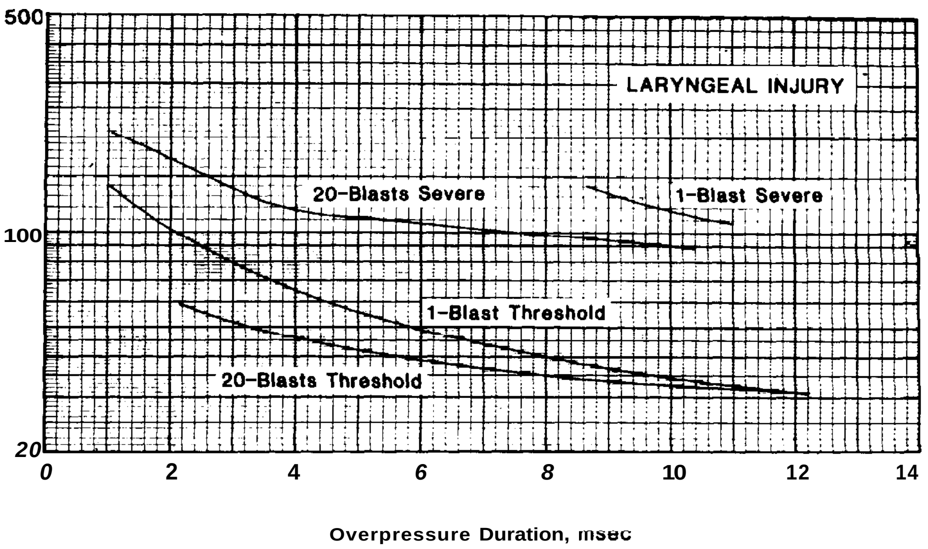


Fig. 7-13. The estimated free-field air blast conditions for one and twenty blasts are depicted for threshold and severe injury to the larynx. Threshold injury is the presence of scattered petechiae in the larynx, and severe injury is confluent hemorrhage. Source: Walter Reed Army Institute of Research

nal tract, and the upper respiratory tract of humans exposed to either one or twenty air blasts at sea level. These estimates are based on information obtained from sheep and swine that were exposed to repeated blasts from explosive charges ranging in weight from 0.5 to 64 pounds.

The larynx is the most sensitive nonauditory structure to repeated blasts, followed by the gastro-intestinal tract and the lungs. Once the threshold overpressure for injury for a single blast is exceeded, the injury worsens with repeated exposures, especially in the gastrointestinal tract and lungs. However, tolerance is high for subthreshold exposures. The effect of daily exposure to multiple blasts was tested with sheep exposed to subthreshold blasts of about 10 msec duration and 7 psi peak pressure. One group received fifty blasts at a rate of one blast per minute. Postmortem examinations at 1 hour after the fiftieth blast revealed only light contusions and ecchymoses in the lining of the upper respiratory tract. There were no lung hemorrhages or gastrointestinal tract lesions. Specimens given fifty blasts daily (one per minute) for 4 days and examined at 1 hour after the blasts ended on day 4 showed the same minor upper respiratory lesions; the lungs and gastrointestinal tract were without significant injury.[12]

In a study demonstrating the significance of repeated exposure, sheep and swine were subjected to repeated blasts at a rate of one per minute.[13] A remarkable increase in pulmonary hemorrhage and lethality was found for multiple blasts that were greater than threshold levels. A blast that resulted in 1% mortality when delivered only once produced 20% mortality when given twice, and 100% mortality when given three times. At suprathreshold levels, multiple low-dose blasts interact synergistically to enhance injury and mortality.

To evaluate the effect of varying the interval between blasts, groups of rats were subjected to long-duration overpressures of about 26 psi.[13] One exposure resulted in 5% mortality at 24 hours. Three blasts administered at 15-minute intervals produced 87% mortality. At 30 minutes between blasts, the lethality dropped to 36%; at 4-hour intervals, to 27%; and with 24 hours between exposures, to 7%. Therefore, increasing the time between individual events can ameliorate the blast-injury enhancement from multiple exposures.

Military personnel are repeatedly subjected to relatively low-intensity blasts during training and combat operations. Soldiers who fire artillery, mortars, recoilless rifles, and shoulder-launched antiarmor weapons

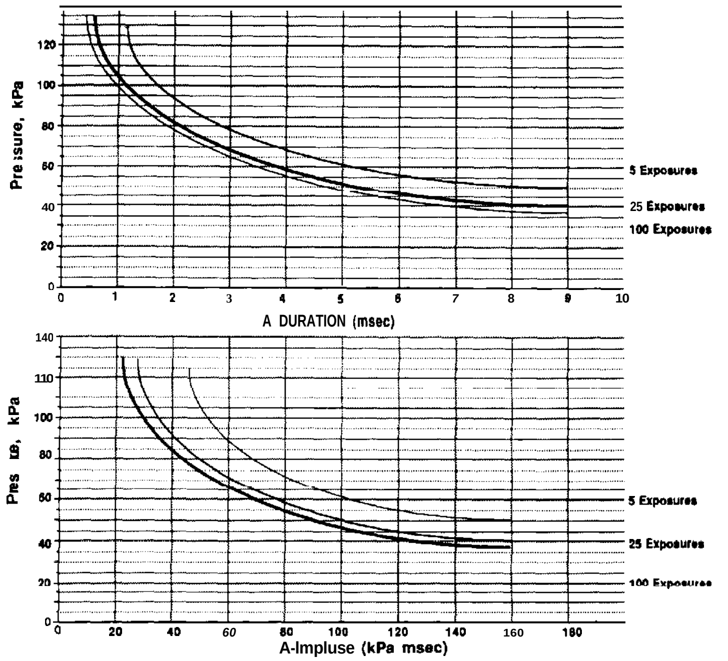


Fig. 7-14. The estimated threshold for trivial laryngeal injury in humans at sea level is given as a function of the blast wave's static peak pressure, the number of exposures, and either impulse or positive-phase duration. These data have been used to define limits for exposure to intense weapon-muzzle blast for soldiers in training.
Source: Reference 11

are in the position to receive muzzle or breech blasts from their own weapons. Although damage-risk criteria for hearing loss from repeated impulse noise have existed since the late 1960s, attempts have been made only recently to compile criteria for nonauditory blast effects at these levels." Threshold injuries to the upper respiratory tract of sheep and swine produced by 5, 25, and 100 repeated blasts in relation to the incident overpressure, duration and impulse are plotted in Figure 7-14. Such estimates of threshold injury have been applied to human tolerance limits for blast from the firing of heavy weapons.

UNDERWATER BLAST

An explosive charge that is detonated underwater will produce a large volume of gaseous by-products in the form of an underwater bubble! This expanding bubble sends out a compressive shock wave into the surrounding water at a speed of about 5,000 fps. As the bubble rises to the surface, it oscillates—collapses and re-expands—and sends out a series of weaker pressure waves called *bubble pulses.* As the primary shock wave reaches the surface, it is reflected as a tension wave, which spalls the surface of the water. Tiny water droplets (the spall) form a characteristic dome around the gas bubble (Figure 7-15), which soon vents, forming a spray plume (Figure 7-16).

A typical underwater blast-wave pattern for a gauge located near the surface shows the initial peak pressure and the pressure decay that is rapidly truncated by the tension wave arriving from the surface reflection (Figure 7-17).[14] In effect, the tension wave (also called the cut-off wave) reflecting from the surface cancels out a portion of the compressive shock wave. However, if the shock wave is reflected from a rigid underwater surface such as a rock bottom, the pressure in the primary shock wave will be increased by a reflecting compressive wave, similar to that produced in air blast. If the bottom is soft mud, there may be no reflected wave.

Studies with submerged animals have found that the positive impulse in the underwater blast (the *inte-*

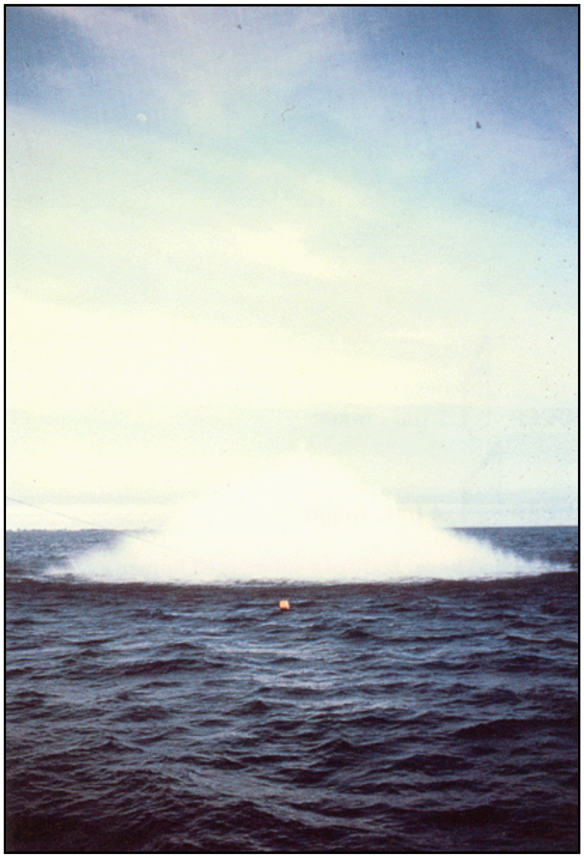


Fig. 7-15. The water surface above an underwater explosion is disrupted due to spallation as the underwater shock wave reflects off the water-air interface as a tension wave.
Source: D. R. Richmond

Fig. 7-16. The gas bubble created by an underwater explosion rises to the surface and expells a plume of water and gas. This follows the spallation dome shown in Figure **7-15.**
Source: D.R. Richmond

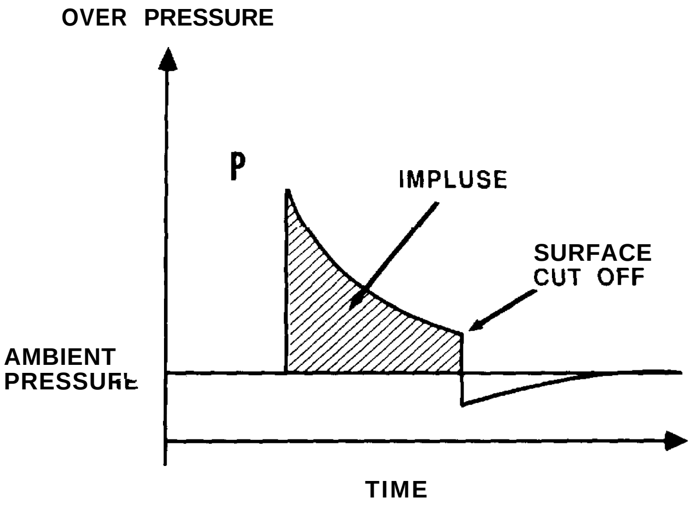


Fig. 7-17. An underwater blast wave is depicted as measured near the surface. There is a nearly instantaneous rise in pressure, with an exponential decay much like that in air blast (Figure 7-2). The incident compression wave is reflected from the surface as a tension wave, which interacts with the positive-pressure shock, effectively cancelling or cutting it off.
Source: D. R. Richmond

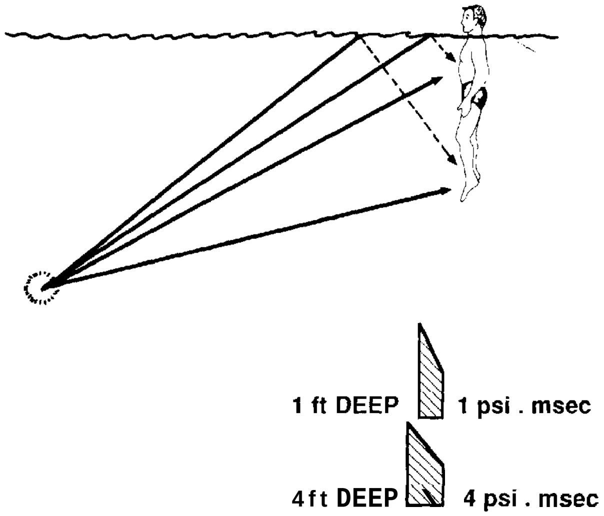


Fig. **7-18.** The effective pressure-time exposure is depicted for the upper and lower body of a submerged human exposed *to* a nearby underwater blast. The reflected tension wave from the surface (▨) cuts off the compression wave at different times, resulting in a greater impulse loading (integral of pressure over time) for deeper structures. For this reason, the gastrointestinal tract is generally more severely injured than the lungs in underwater blast.
Source: D. R. Richmond

gral of pressure over time) is best correlated with injury and mortality (Figure 7-17).[15] For humans, it is estimated that 50% mortality is associated with an impulse of 87 psi-msec. Neither the peak pressure nor the energy (the integral of pressure squared over time) predict injury. Because of the cut-off wave from the surface, waves of high peak pressure with little impulse are common if either the charge or the target are near the surface. At depths of more than 20 feet (equivalent to a few milliseconds of wave travel) the cut-off wave is of little significance. Charges of only 0.125 pounds can kill large animals that are located about 5 feet from the detonation. With a 1-pound charge, death would occur at a distance of 23 feet. This is about three times the lethal range of free-field air blasts.

A person treading water will experience a higher impulse load on the lower portion of the body because the cut-off wave from the surface arrives later than it **does** at the upper body (Figure 7-18). The peak pressures will be essentially the same. Thus, the portions of the body that are deeper in the water (in most cases, the gastrointestinal tract) may be severely injured, while damage to the lungs may be much less. This observation has lead to the misconception that injuries to the gut predominate in all underwater blasts, regardless of the depth of immersion. Sheep tested at 10-foot depths, oriented with their bodies' long axes parallel to the surface (to evenly distribute the impulse load over the body), had essentially the same severity of injuries to their lungs and gastrointestinal tracts.'? In another experiment, sheep were positioned at a 6-inch depth and horizontal to the surface. **If** they **had been** positioned vertically in the water, the blast would have been lethal, but the sheep survived with only moderate degrees of lung and gastrointestinal-tract injury.[16]

The dramatic effect of immersion depth on blast injury dictates that military personnel in danger of impending underwater blast should not tread water but should float on the surface, if possible.

THE MECHANISMS AND PREDICTIONS OF PRIMARY BLAST INJURY TO THE LUNG

Historically, researchers observed the effects of blast on physical objects, and speculated that certain phenomena (such as spallation, implosion, and inertia, which are described in Chapter Six) might be blast-injury mechanisms. These injury mechanisms have never been directly observed in a blast-exposed body; neither do they in themselves lead to a quantitative understanding of blast injury. Therefore we have to

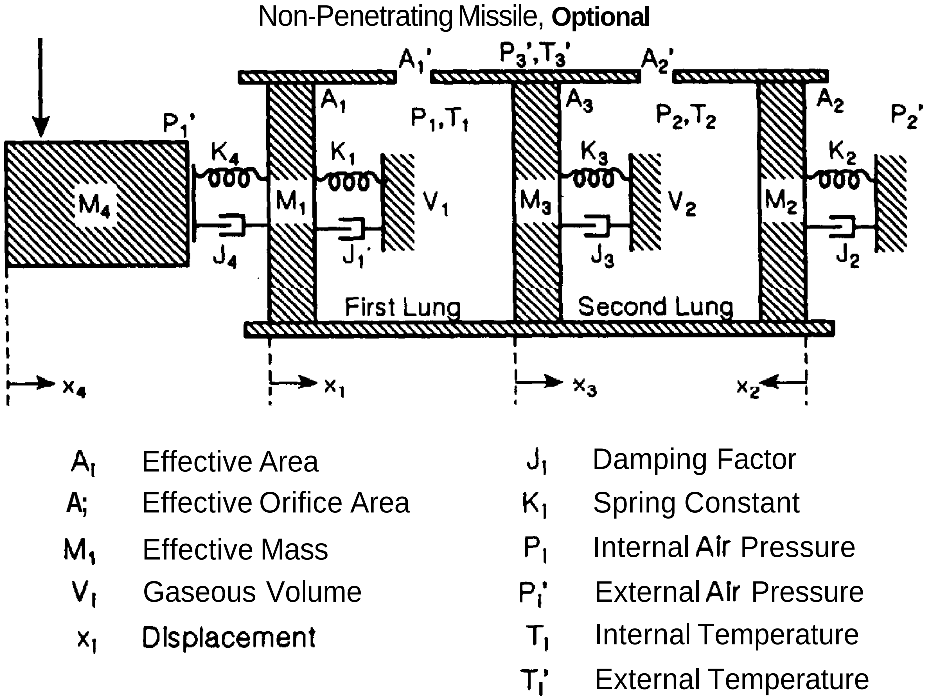


Fig. 7-19. Viscoelastic mathematical model of the thorax to simulate fluid-mechanical responses to rapid changes in environmental pressure and to nonpenetrating missile impact with the chest wall
Source: Reference 8

look elsewhere for answers.

The goal of modeling has been to assemble scientifically sound concepts of blast-injury mechanisms into a form that can be used to predict and understand the occurrence of injury. Such an approach has been successful for understanding tympanic-membrane rupture from blast.'' PBI to the lung has received the most critical attention because its consequences are so serious. Lung damage that allows air emboli to enter the bloodstream is believed to be the primary cause of prompt death from blast effects: at lower blast levels, the loss of pulmonary function is a cause of immediate incapacitation.

The first attempt to model the body's response to blast was proposed in the 1960s, when the viscoelastic properties of the chest and abdomen were mathematically represented by the *viscoelastic thorax model.* This model visualized the thorax and abdomen as two gas-filled compartments, separated from each other and from the outside by moveable walls.[18]

Later, this mathematical model was modified to describe only the thorax, but a separate compartment represented each lung (Figure 7-19).[19] The volume of gas within each compartment would compress as the walls moved inward, and would expand as the walls moved back out. Researchers intended this model to predict lung pressures from the mechanical motion caused by the external force of the blast and then to correlate the maximum lung pressure obtained with predicted mortality.

The model used many mathematical parameters to describe the characteristics of the compartment walls and volumes of gas. Most of these had no direct relationship to physiology, however, so their values had to be selected arbitrarily. When the model was tested against blast waves of very long durations, its parameters could be chosen to give good agreement with observed pressure measurements that had been taken from the esophagi of animals. The maximum esophageal pressure appeared to correlate with the likelihood of mortality.

Direct measurements of the thoracic motion and pressure distribution within the lung were finally made in the 1980s.[20] They clearly showed that the lung did not compress uniformly, but instead contained regions of local compression that moved like waves through the parenchyma. Researchers also found that maximum esophageal pressure did not correlate with the injury found in short-duration blasts. Although the model was correctly based on the concept that the blast pushes in the thorax and compresses the lung, the mechanistic links between such gross phenomena and injury was not understood.

Modern View of the Mechanisms of Primary Blast Injury

The physical processes involved in the body's response to blast actually comprise three steps: *(a)* the body's external surface moves rapidly with the sudden increase in environmental pressure, *(b)* the air-containing organs become distorted, creating stress within the organ tissues, and *(c)* exceeds the strength of the tissue, damage occurs.

The Body's Rapid Response to Blast Loading. The amount of force exerted on the body by a blast wave is called the blast loading; the surfaces of the body that are oriented towards the blast receive the greatest load. The geometry of surrounding structures may deflect the blast wave, or it may focus the wave, particularly inside partially open enclosures where the blast loading can be significantly higher than it would have been in a free field.

The air-containing organs of the body are exquisitely sensitive to changes in air pressure. To remain functional, they rely on natural pressure-equilibrating mechanisms that keep the body's internal air pressure as stable as possible by means of *(a)* the venting of air from the middle ear through the eustachian tube, *(b)* the process of ventilation in the respiratory tract, and *(c)* the expulsion of gas from the upper and lower gastrointestinal tract.

The blast wave causes injury because of its rapid external loading. If the blast loading increases slowly enough, the internal pressures will have time to equilibrate, thus avoiding significant distortions of the tissue. A more sudden loading of the blast force, however, is not balanced by internal forces, and it quickly distorts and injures the air-containing organs.

A better understanding of the mechanics of the body's motion due to blast loading is needed to define the relationship between the blast loading and the subsequent organ distortion.

Organ Distortion and Tissue Stress. The rapid displacement of both the external and internal structures distorts the air-containing organs and stresses their tissues. For example, a pressure differential across the tympanic membrane that cannot be balanced by air flow through the eustachian tube causes a significant distortion of the membrane, with corresponding stresses on it and the stapes. A rapid displacement of the chest wall causes local compressions of the lung parenchyma that cannot be relieved through the airways, thus stressing the lung tissue. A sudden pressurization of the abdominal cavity collapses the air-containing sections of the gastrointestinal tract, which stresses the tissues of the gut wall. However, the precise relationship between organ distortion and tissue stress remains unknown.

Tissue Stress and Injury. Finally, excessive stress within a tissue leads to its mechanical failure. Some structures, such as the tympanic membrane and the organs comprising the gastrointestinal tract, can be mechanically ruptured by excessive stress. At lower levels of tissue stress, the integrity of vascular beds can be compromised, leading to local hemorrhage. The failure of can allow fluids into the lung (hemorrhagic edema) or air into the blood stream (air emboli). Even more subtle mechanical and biochemical damage can occur in the cochlea, resulting in both temporary and permanent hearing loss.

The failure of a material depends not only on its composition but also on its structure and the way in which the external force is applied. For example, a force applied to one end of a steel bar, whose other end is fixed, will result in greater stresses within the bar than if the force were applied uniformly along the bar.

Furthermore, the resulting stress within the material may be concentrated at certain locations called *stress points.* For example, a steel bar that is notched in the middle will fail after fewer applications of an external bending load than a similar steel bar that has no notch, because *(a)* the notch makes the bar weaker, *(b)* the bending will be concentrated there, and *(c)* the stresses will be concentrated there.

Materials have three characteristics that can be used to quantify tissue damage. First, *tensile strength* establishes the conditions at which damage will first occur. When material is pulled along its length, the resulting stress within it is called *tension* Tensile strength is equal to the amount of stress that will cause the material to fail when it is in tension. When the tension exceeds the tensile strength, some materials will rupture, whereas materials that are more plastic will stretch without breaking. In either case, the material is damaged; that is, it is permanently changed and will not return to its original condition after the external force that created the tension is removed. Tensile strength, therefore, establishes the threshold for injury. Table 7-4 lists the tensile strength for a variety of biological and nonbiological materials, each represented by a range that reflects the variation in individual specimens.[21] The values for the biological tissues represent the composite characteristics of their component fibers and their structural arrangements.

Next, *fatigue* is a type of failure that results from repeated exposure to damaging conditions. A paper

TABLE 7-4

TENSILE STRENGTHS OF BIOLOGICAL AND NONBIOLOGICAL MATERIALS

Material	Tensile Strength (MPa)
Common building materials	
Stainless steel	1,000
Silk	400
Oak	120
Marble	6
Biological fibers	
Resilin	3
Collagen	50–100
Biological tissues	
Tracheal membrane wall	0.4–2.2
Mixed arterial tissue	1.4–1.7
Elastic arterial tissue	0.8–1.0
Venous tissue	1.7–3.0
Large intestine	0.45–0.69

clip will break if it is repeatedly bent back and forth. Each bend produces minute damage that accumulates and eventually results in failure. Experimental data for a wide variety of materials show that they have certain properties of fatigue failure in common (Figure 7-20).>’ **A** material’s *ultimate strength* is equal to the level of stress that will produce failure from a single application of an external force. When the stress is purely tension, the ultimate strength is identical to the tensile strength. The *fatigue stress* is the stress that is required to produce failure under repeated applications of the external force, and is often proportional to the external force. For many materials, the fatigue stress decreases by about 20% for each tenfold increase in the number of applications. That is, if a material fails when 1.0 unit of external force is applied 100 times, then it will also fail when 0.8 units of external force is applied 1,000 times, or when 0.6 units of external force is applied 10,000 times, and so on. The *endurance limit* is the level of stress below which the material will not fail no matter how many times the external force is applied. Fatigue properties have not been measured for biological materials.

Finally, *irreversible work* gives a quantitative measure of the severity of the damage. Material will deform when an external force is applied to it, but if the deformation is not too great, the material will return to its original condition when the external force is removed, and any work done by that force will be recovered. For example, an aluminum beverage container that is pushed in only slightly will pop back to its original shape when the force is removed. The onset of damage occurs when the stress equals the tensile strength of the material. As the stress increases beyond the tensile strength, the work done by the excess external force will not be recovered. This is called the irreversible work, and is a direct measure of the severity of the damage done to the material. The beverage container, for example, will remain dented if it is crushed beyond a critical point.

A better knowledge of the properties of tensile strength, fatigue, and irreversible work is necessary to determine the relationship between tissue stress and injury. When the mechanisms of body motion and organ distortion are combined with the properties that describe material failure, researchers will be able to define analytically the relationship between blast and injury in contrast to the empirical relationships described to date.

New Models of Lung Injury

The three steps involved in the body’s physical response to blast can be applied to models that are designed to predict blast-related lung injury. To be useful, these models need to establish three relationships: *(a)* blast to parenchymal distortion, *(b)* parenchymal distortion to tissue stress, and *(c)* tissue stress to injury.

Blast to Parenchymal Distortion. The first step in developing a predictive model of lung injury is to establish the mechanical connection between the external blast loading and distortions to the lung parenchyma. This connection is mathematically represented by *Finite* (FEM), which involves three stages:

First, FEM begins with a geometrically correct *mathematical representation* of the body structure under investigation.[22] Figure 7-21 shows the anatomical cross section of a sheep’s thorax at the level of the seventh vertebra, selected because *(a)* it contains a representative cross section of the sheep’s internal organs, *(b)* it is located where considerable rib motion occurs, and *(c)* it is a common location of lung injury in blast-exposed sheep. The cross section is then broken down into many computational elements, each representing a part of the thoracic geometry and quantifying the

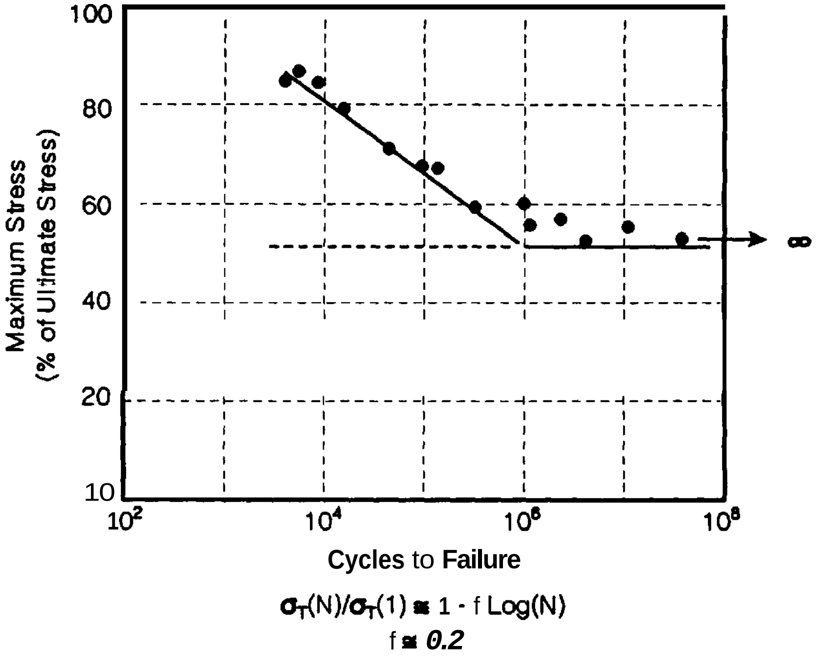


Fig. 7-20. Geometric model of the effects of repeated applications of stress on mechanical failure. The concept of fatigue is used in biomechanical modeling of blast injury to account for repeated exposures.
Source: JAYCOR

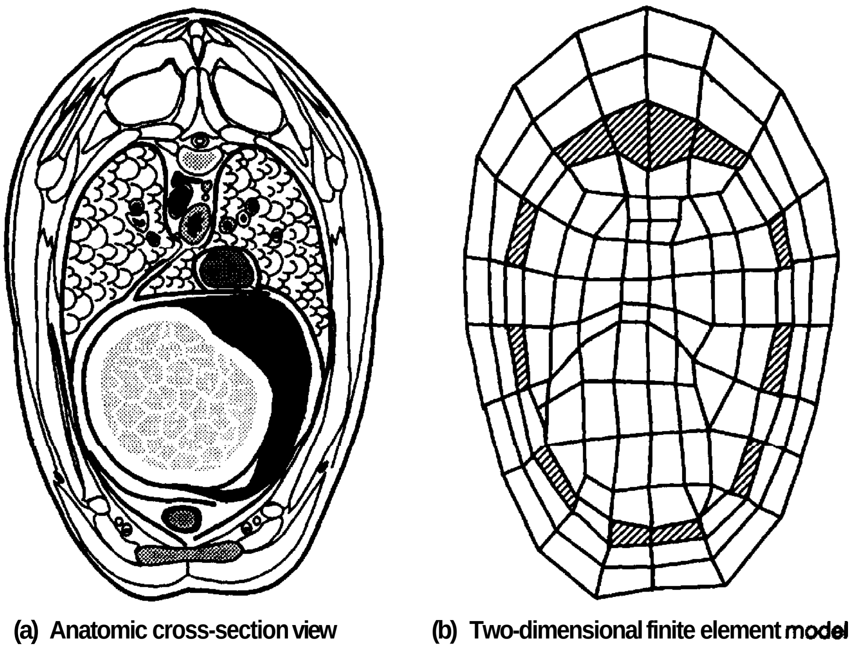
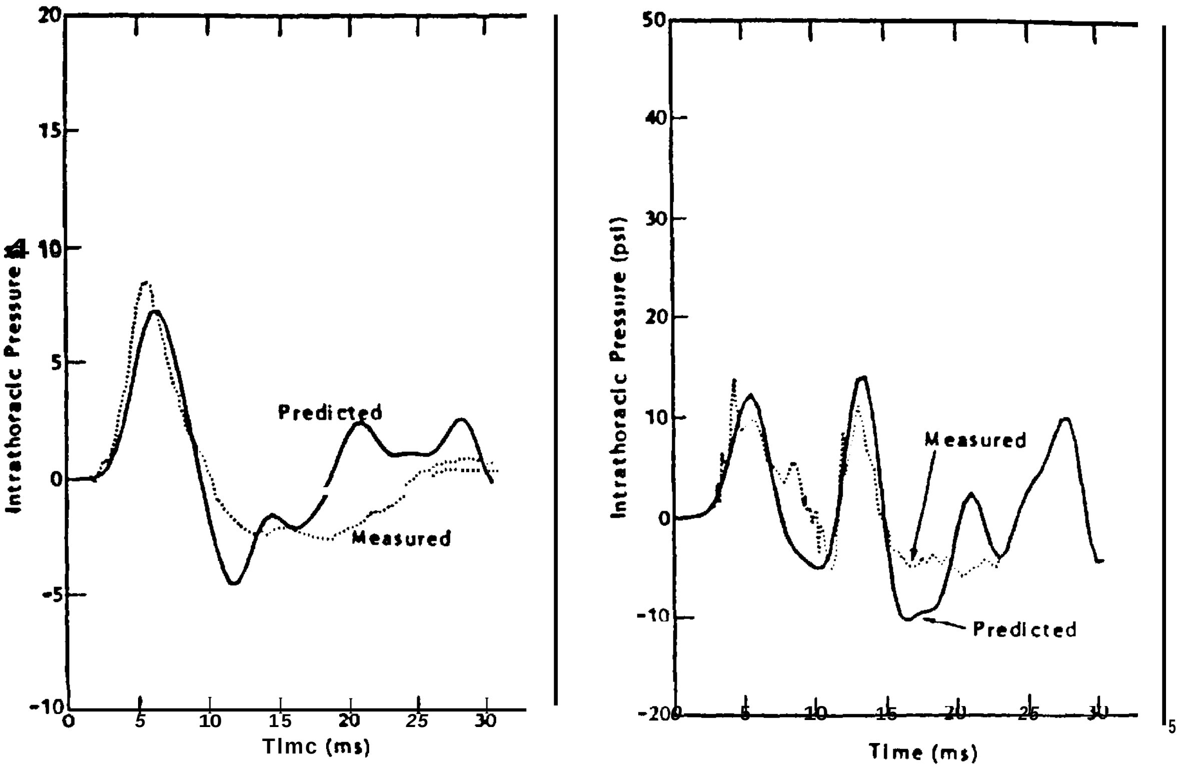

(a) Anatomic cross-section view **(b) Two-dimensional finite element model**

Fig. 7-21. Geometric model of a sheep thorax as represented by *(a)* a simplified anatomical cross section, and *(b)* the Finite Element Model
Source: JAYCOR

mechanical properties for that material. The chest wall contains the rib structure and musculature, which—in the two-dimensional FEM representation—provide inertia to the chest wall. The abdominal cavity, heart, and spinous process are mathematically represented by high-density, incompressible elements that do not readily deform under the rapid body motions caused by a blast. The lung parenchyma has the compressibility of air, but because it also contains tissue, it has a mass density that is one-tenth the mass density of water. These mechanical properties of the lung have been determined in laboratory measurements.[23] The model can be used to predict the dynamics of the chest wall and **lung** parenchyma when exposed to blast.

Next, the prediction is compared with the observed experimental data to verify its accuracy. For example, when the outer surface of a sheep's thorax is subjected to the pressure distribution of a blast wave, the chest wall is set in motion and in turn compresses the parenchyma, setting it in motion as well. The compression wave is transmitted throughout the lung and can be measured in the esophagus, where researchers often place pressure transducers during tests. The predicted intrathoracic pressure is compared with the value measured in the sheep's esophagus (Figure 7-22). FEM predictions also agree with the chest-wall accelerations and velocities that have been observed in specially instrumented test animals, supporting the accuracy of the model's chest-wall description (Figure 7-23).[20,24]

Finally, the location and magnitude of parenchymal distortions are determined. The combination of high compressibility and great inertia causes the lung parenchyma to transmit pressure waves much more slowly than either air or water do. From both theoretical considerations and direct measurements in the laboratory, the pressure-wave speed in the lung is found to be about 30 m/s.[24] Consequently, when the chest-wall velocity becomes a sizeable fraction of this value, concentrations of stress can result near the pleural surface. Other stress points occur because of the geometry of the lung and the presence of the surround-



(a) Exposure to a single peak blast due to a 16 lb TNT charge

(b) Exposure to two 40 psi blast waves separated in time by 7.6 msec

Fig. 7-22. Comparison of predicted intrathoracic pressure and measured esophageal pressure in sheep
Source: Walter **Reed Army Institute** of Research

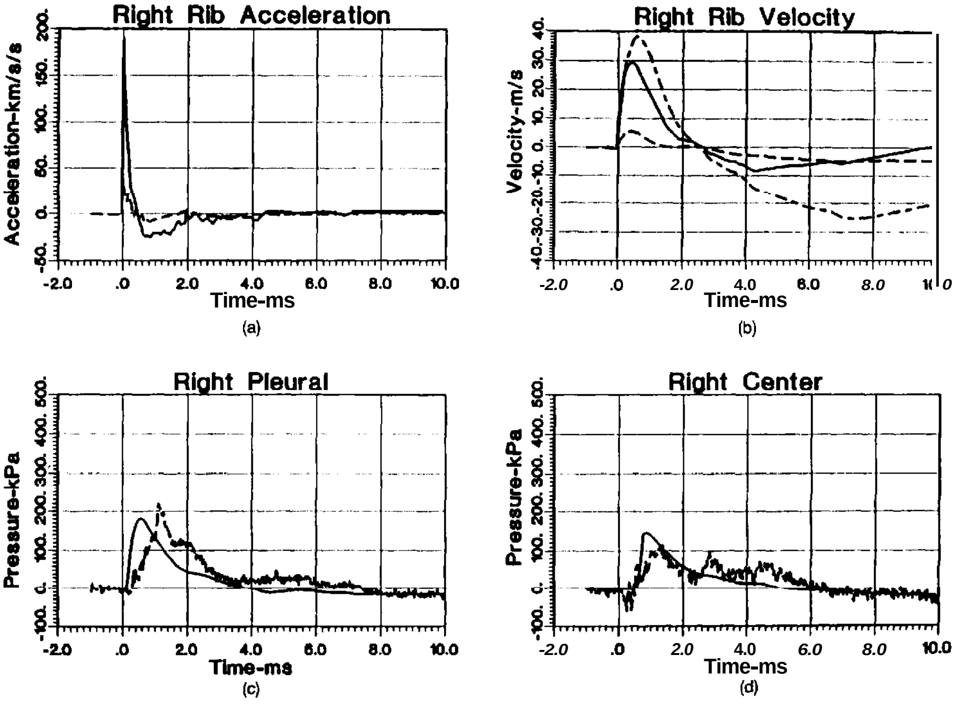


Fig. 7-23. Comparison of predicted and measured thorax dynamics: *(a)* acceleration of the right rib of a sheep subjected to a blast loading due to 1 pound of C4 explosive, *(b)* the consequent rib velocity, *(c)* the pressure in the pleural space just below the instrumented rib, and *(d)* the intrathoracic pressure as measured in an airway in the center of the right lobe
Source: Walter Reed Army Institute of Research

ing organs. For example, high stresses are predicted in the tips of the lobes, along the ribs on the side of the blast, and around the spinous process and heart (Figure 7-24). All are locations where blast injury is commonly observed.

Parenchymal Distortion to Tissue Stress. Compression does not, in itself, produce injury because it occurs in the trapped gas, not the tissue. A relationship between the compressive stress and the tissue stress must be established through a mechanical analysis of the alveolar structure when it is distorted. In principle, this relationship could be determined by FEM analysis of the parenchymal structure, but such work has not yet been done.

However, the FEM model does predict that the parenchymal pressure at the pleural surface varies over time in exact proportion to the velocity at which the chest wall is being deformed, a finding that has been confirmed by direct experimental measurement.[24] The dependence of pressure on velocity is uncharacteristic of the properties of a pure gas, and suggests that tissue distortion is involved.

Tissue Stress to Injury. The final link in the prediction of blast injury is the establishment of a relationship between the tissue stress and tissue failure.

Measurements of tissue stresses in the laboratory have attempted to determine the relationship between stress and distortion in lung tissue. The level of stress rapidly increases as the tissue is stretched to about 150% of its resting length, indicating the onset of a tensile failure. Unfortunately, the existing FEM analyses do not reveal the relationship between the stresses of wave motion within the parenchyma and the magnitude of tissue distortion. Without the establishment of this relationship, the concept of tensile strength cannot be applied.

Although tissue stress cannot quantitatively be related to injury at this time, the concept of irreversible work can be applied. Because the pleural-surface pressure depends on the chest-wall velocity, work done against it will not be recovered when the lung reexpands. Instead, the lost energy will have been dissipated within the tissue.

If the energy dissipation is due to a failure of the underlying tissue, then the irreversible work is a prime candidate for correlation with the severity of damage. There are several experimental observations that support [illegible] (Figure 7-25). First, the relation-

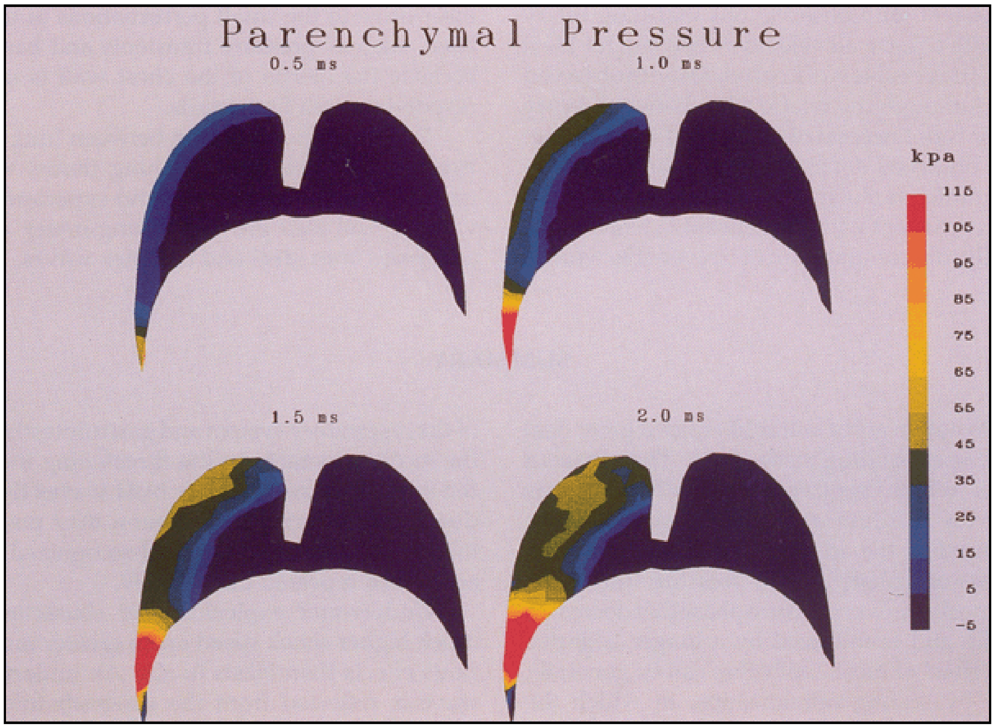


Fig. 7-24. Distribution of compressive stress within the lung parenchyma due to a blast loading on the left side of a sheep, as calculated at various points in time with the Finite Element Model
Source: IAYCOR

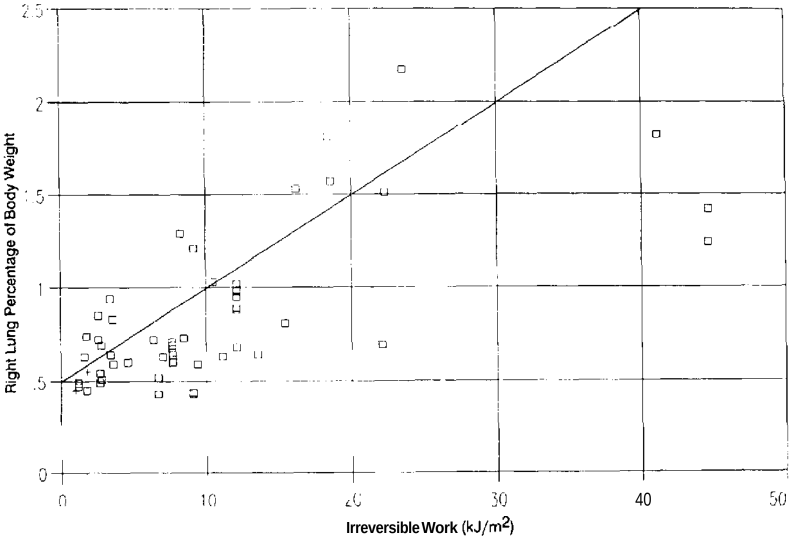


Fig. 7-25. Comparison of observed lung injury in sheep exposed to blast (as measured by the increase in lung weight over that of control animals) with the prediction of the irreversible work done to the pleural surface of the lung. Each data point corresponds to an individual animal where sufficient data were available to describe the blast environment. The exposures include single free-field explosions, multiple free-field explosions, repeated free-field explosions, and explosions inside enclosures.
Source: JAYCOR

ship is consistent with observations that lung injury correlates with chest-wall velocity.[25] Second, for ideal wave forms, irreversible work correlates with observed lethality.[26] Although the relationship between injury and lethality is not necessarily simple, it is encouraging that the observed dependence of lethality on certain blast parameters (such as peak pressure and duration) is also consistent with the concept of irreversible work. Finally, the computation of irreversible work is insensitive to the small perturbations of the external blast, such as pressure transients and baseline drift, because the inertia of the chest wall is too large to respond to such fine details.

Perhaps the correlation between lung injury and irreversible work done on lung tissue, which now unifies previous hypotheses and experimental observations, will also provide a lung-injury model that addresses both ideal and complex waves.

SUMMARY

An explosion in air or water liberates a great deal of energy as an expanding mass of gas. This creates a blast wave, which propagates in all directions throughout the medium at a speed faster than the speed of sound in the ambient medium. The blast wave consists of a sharp rise in pressure (the shock front) and a positive-overpressure phase that decreases exponentially and is followed by a longer negative phase. The effect of most explosives can be generally determined by scaling relationships, in which the physical parameters of the blast wave are proportional to the weight of the explosive divided by the cube root of the distance between the measuring point and the explosion.

At any point in space, the expanding shock front is characterized by the static overpressure — the pressure that is present in all directions and is measured by a sensing surface oriented parallel to the blast wave's path. The strength of the shock front also determines its velocity and the dynamic pressure.

When a blast wave strikes a rigid surface, it is reflected. Depending on the strength and the angle of incidence, the incident wave and the reflected wave interact to create areas of overpressure much greater than in the undisturbed incident wave. In a complicated environment, such as an explosion inside a room or a vehicle, the multiple interactions of the incident and reflected waves result in a complex blast wave.

Human tolerance to air blast has been estimated from experiments with animals. Orientation of the body with respect to the wave front and the presence of reflecting surfaces have important influences on injury potential. For blast waves of less than 20 msec in duration, consideration of both the peak pressure and positive-phase impulse are necessary to predict hazard. For the longer-duration waves that are typical of nuclear weapons, it is only necessary to know the peak overpressure *to* determine risk.

Repeated exposure to blast waves can greatly increase the risk of injury. The air-containing structures of the respiratory system and gastrointestinal tract are the most vulnerable to life-threatening injury. Even the relatively low-intensity blast waves that are produced by the firing of a cannon may pose a risk of injury (in addition to the well-recognized aural hazard) when repeated many times.

Underwater explosions are characterized by a much higher shock speed and a greater range of injurious effects than blasts in air. An underwater blast wave is reflected from the water-air interface as a tension wave that cuts off or cancels the shock front when it interacts with the positive-pressure compression wave. Thus, near the surface, positive waves of very high pressures and impulses with short durations are found. Such a combination would be impossible with air blasts. Injury potential is determined by positive impulse.

Efforts to model the response of the body to the physical interaction with the blast wave have been made, both as aids in predicting the relative hazard of an overpressure environment and as a means of gaining insight into the biophysical events and mechanisms of injury. Simple viscoelastic mathematical models have proven ineffective in repeated or complex-blast environments. Recent attempts to model the body as a complex geometric structure with definable physical properties have led to important predictions of physical events at the body surface (such as chest-wall accelerations and velocity) and within the lung (for example, parenchymal pressure wave phenomena) that have been confirmed with animal experiments. **A** generally applicable model would deal with three important relationships: the blast-wave interaction with the body, the resultant tissue distortions and stresses caused by the motions of the body, and the failure or disruption of the tissues caused by the stresses. Although such a detailed model is presently unavailable, the finite-element model approach has suggested that irreversible work done on the body may be an important correlate of injury.

REFERENCES

1. Meyer, R. 1987. *Explosives.* New York: VCH Publishers.

2. Glasstone, S., and Dolan, P. J., eds. 1977. *The effects of nuclear weapons.* Washington, DC: U.S. Government Printing Office.

3. Rief, F. 1965. *Fundamentals of statistics and thermal physics.* New York: McGraw-Hill Book Company

4. Baker. W. E. 1973. *Explosions in air.* Austin, TX University of Texas Press.

5. Schardin, H. 1950. The physical principles of the effects of a detonation. In *German Aviation Medicine, World War II.* Vol. 2, prepared under the auspices of the U.S. Air Force Surgeon General, 1207–1224. Washington, DC: U.S. Government Printing Office.

6. Courant, R., and Friedrichs, K. O. 1948. *Supersonic flow and shock waves.* New York John Wiley & Sons

7. Swisdak, M. M., Jr. 1975. *Explosion effects and properties.* Part 18 of *Explosions in air* [Technical Report NSWC/WOL-TR-75–116]. Silver Spring, MD: Naval Surface Warfare Center.

8. White, C. S.; Jones, R. K.; Damon, E. G.; Fletcher, E. R.; and Richmond, D. R. 1971. *The biodynamics of airblast* [Technical Report DNA 2738T]. Washington, DC: Defense Nuclear Agency.

9. Richmond, D. R.; Damon, E. G.; Fletcher, E. R.; Bowen, I. G.; and White, C. S. 1966. *The relationship between selected blast-wave parameters and the response of mammals exposed to air blast* [Technical Progress Report DASA-1860]. Alexandria, VA: Defense Nuclear Agency.

10. Clifford, C. B.; Moe, J. B.; Jaeger, J. J.; and Hess, J. L. 1984. Gastrointestinal lesions in lambs due to multiple low-level blast *Milit. Med.* 149:491–495.

11. Dodd, K. T.; Yelverton, J. T.; Richmond, D. R.; Morris, J. R.; and Ripple, G. R. 1990. Nonauditory injury threshold for repeated intense freefield impulse noise. *J. Occup. Med.*

12. Richmond, D. R. Unpublished research performed at Inhalation Toxicology Research Institute, Kirtland Air Force Base, NM, 1982.

13. Richmond, D. R.; Yelverton, J. T.; Fletcher, E. R. 1981. *The biologic effects of repeated blast* [Topical Report DNA-5842F]. Washington, DC: Defense Nuclear Agency.

14. Swisdak, M. M., Jr. 1978. *Explosion effects and properties.* Part 2 of *Explosion effects in water* [Technical Report NSWC/WOL-TR-76–116]. Silver Spring, MD: Naval Surface Warfare Center.

15. Richmond, D. R.; Yelverton, J. T.; Gaylord, C. S.; Fletcher, E. R. 1970. *Underwater blast studies with animals* [Technical Progress Report DASA-24631. Washington, DC: Defense Nuclear Agency.

16. Richmond, D. R.; Yelverton, J. T.; and Fletcher, E. R. 1973. *Farfield underwater blast injuries produced by small charges* [Technical Progress Report DNA-3081T]. Washington, DC: Defense Nuclear Agency.

17. Stuhmiller, J. H. 1989. Use of modeling in predicting tympanic membrane rupture. *Ann. Otol. Rhinol. Laryngol* 98:53–60.

18. Bowen, I. G.; Holladay, A.; Fletcher, E. R.; Richmond, D. R.; and White, C. S. 1965. *A fluid-mechanical model of the thoracoabdominal system with application to blast biology* [Technical Report DASA-1675]. Albuquerque: Defense Atomic Support Agency.

19. Bowen, I. G.; Fletcher, E. R.; Richmond, D. R.; Hirsch, F. G.; and White, C. S. 1968. Biophysical mechanisms and scaling procedures applicable in assessing responses of the thorax energized by air-blast overpressures or by nonpenetrating missiles. *Ann. N. Y. Acad. Sci.* 152:122–146.

20. Stuhmiller, J. H.; Chuong, C. J.; Phillips, Y. Y III; and Dodd, K. T. 1988. Computer modeling of thoracic response to blast. *J. Trauma* 28:S132–139.

21. Yamada, H. 1970, *Strength of biological materials.* Baltimore: Williams and Wilkins Company.

22. Burton, R. 1968. *Vibration and impact.* New York: Dover Publications

23. Fung, Y. C.; Yen, M. R.; and Zeng, Y. J. 1985. Characterization and modeling of thoracoabdominal response to blast waves. Vol. 3, *Lung dynamics and mechanical properties determination,* edited by J. H. Stuhmiller [Final Report for Contract DAMD178828C82062]. La Jolla, CA: JAYCOR, Inc.

24. Vander Vorst, M. J.; Dodd, K. T.; Stuhmiller, J. H.; and Phillips, Y. Y III. 1989. Calculation of the internal mechanical response of sheep to blast loading. In *Proceedings of the Tenth International Symposium on Military Applications of Blast Simulation,* edited by H. Reichenbach and J. H. Ackerman, 422–444. Oberjettenberg, Germany: Wehrtechnische Dienststelle fur Sprengmittel und Sondertechnik.

25. Clemedson, C.-J. 1956. Blast injury. *Physiol. Rev.* 36:336–354.

26. Stuhmiller, J. H. 1988. Bio-mechanical modeling. Paper presented at Live Fire Crew Casualty Assessment Workshop, 18–19 October at Naval Underseas System Center, Groton, CT.

RECOMMENDED READING

Baker, W. E. 1973. *Explosions in air.* Austin, TX: University of Texas Press.

Jonsson, Arne. 1979. Experimental investigations on the mechanisms of lung injury in blast and impact exposure. Ph.D. diss. no. 80, Department of Surgery, Linköping University, Stockholm, Sweden.

White, C. S.; Jones, R. K.; Damon, E. G.; Fletcher, E. R.; and Richmond, D. R. 1971. *The* [Technical Report DNA 2738T]. Washington, DC: Defense Nuclear Agency.