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Primary Blast Injury: An Intact Tympanic Membrane Does Not Indicate the Lack of a Pulmonary Blast Injury

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ABSTRACT The tympanic membrane (TM) has long been viewed as an indicator of primary blast injury. A primary blast injury occurs due overpressure occurring as a result of the detonation of high explosives. Cadaver studies indicated pressure required for perforation of the tympanic membrane to be 137 kPa for adults. The accepted range in which other organs (lung, colon, and intestines) are damaged by the pressure wave emanating from an explosion is in the 400-kPa range. The use of the perforation of the tympanic membrane as an indicator of a primary blast injury missed a range of up to 50% of those suffering a primary blast injury to the lung. The status of the tympanic membrane following exposure to a blast does not preclude the need for further investigations for a primary blast injury and the clinician needs to evaluate the patient dependent on their particular exposure to an explosion.

INTRODUCTION

Blast injuries from explosive devices, either from commercial, military, or the improvised variety have long been a risk to military personnel. However, with the rise of terrorism over the past 50 years, it is becoming an issue also for the civilian population, with the targeting of civilian populations increasing.[1,2] The purpose of this article is to explore the effects of detonated high explosives leading to primary blast injury and whether the tympanic membrane (TM) and its perforation status can give an indication of the presence of further primary blast injuries.

A high explosive is a compound that when initiated is capable of sustaining a detonation shockwave to provide a powerful blast effect.[3] By definition, a high explosive will have a detonation velocity of between 3,000 ms^{-1} and 9,000 ms^{-1}.[4]

The perforation of the tympanic membrane has long been recognized as a common by-product of the detonation of a high explosive.[5] Organs typically affected by the shockwave from a high explosive are the air- or fluid-filled organs. These organs are primarily the tympanic membrane, the lungs, and bowels.[3] Furthermore, explosions with enclosed environments or between large structures (i.e., tall buildings) can see the blast wave reflected, leading to increasing morbidity from the explosion. This leads to an unpredictable level of primary blast injury.[6]

BLAST INJURIES

The effects of blast injuries can be categorized into four broad categories: primary, secondary, tertiary, and quaternary.[6]

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Primary blast injuries result from the direct effect of pressure. This change in pressure affects air/fluid interfaces,[3] primarily the tympanic membrane, lungs, and hollow viscera.[6,7] The pressure wave is released following the detonation of a high explosive and theoretically follows a waveform pattern known as the Friedlander curve (Fig. 1).[4] There is an instantaneous increase in pressure to the maximum overpressure, which dissipates over time but leads to an ongoing period of overpressure.[6] This is then followed by a period of underpressure before normalization occurs. The longer duration of the overpressure leads to tearing of organs at sites of fixed attachment.[3]

Secondary blast injuries are those that occur as a result of projectiles released during the detonation of the explosive device and injury occurs via penetrating trauma or fragmentation.[3,6] This can be highly variable, ranging from glass or other items fragmented during the explosion, to items (shrapnel, nails,[8] etc.) strapped to the explosive device and in the case of suicide bombs, bone fragments.[9] Tertiary blast injuries are those that occur as a result of the blast wind. This includes being thrown around by the blast wind and injuries resulting from the collapse of structural objects.[4] Quaternary blast injuries are commonly burns, asphyxia, or from exposure to toxins.[3,6]

THE TYMPANIC MEMBRANE AND PRIMARY BLAST EXPLOSIONS

The tympanic membrane has long been recognized as one of the major organs to be effected by the effects of blast explosions.[3,10,11] This is partly seen due to the lower pressures expected to perforate the membrane when compared to the other organs (hollow) likely to be damaged due to overpressure i.e., lungs and bowel. The effects of overpressure from particular temperatures can be seen in Table I.

The perforation as a result of a blast injury is as variable as the devices used to create the blast, with the perforation injury relating to the proximity to the explosive device as well as the size of the blast. Commonly, injuries due to close proximity

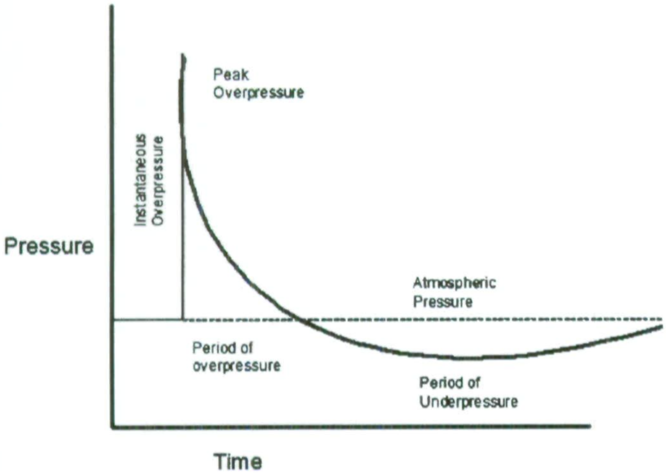

FIGURE 1. The Friedlander curve indicating the theoretical change in pressure following the detonation of a high explosive.

TABLE I. Injuries Resulting From Overpressure

Overpressure (kPa)	Blast Loading
35[12]	Minimum pressure at which tympanic membranes will rupture.
104–121[13,14]	Pressure at which half of tympanic membranes will rupture, minimum threshold for blast lung injury.
202[13,14]	All TM should have ruptured, minimum pressure for fatal primary blast injuries.
290–390[14]	50% fatality rate from PBI.
400–550[14]	95–100% fatality rate from PBI.

TM, tympanic membrane; PBI, pulmonary blast injury.

and large volumes of explosives are jagged with irregular margins and noted clot formation. Cadaver studies by Zawleksi[15] using a bicycle pump showed that the minimum pressure required to perforate a tympanic membrane was 35 kPa, but in a standard population, approximately 50% will have ruptured at 104 kPa. Levels of 1.2 atm (120 kPa) for 50% rupture were recorded by Jensen during his studies,[13] also on cadavers. The experimental models that have been studied all relied on fresh (<24 hours) cadaver data.[13,15] The experiments to quantify this are difficult and become more so when considering combat explosions or those from improvised explosive devices where the increase in pressure is at an uneven rate.

The Friedlander curve that gives the theoretical model of the overpressure generated as a result of the blast overpressure (Fig. 1) looks completely different when measured inside a confined area (Fig. 2). The use of improvised explosive devices that are commonly deployed inside confined spaces including inside buildings, buses, or trains can see the blast wave rebounded and reflected off walls or other immobile structures.[7] This was clearly seen during the Madrid train bombings (Table II). Of the four carriages that were bombed, the largest number of deaths originated in those carriages with the doors shut.[16]

USE OF TYMPANIC MEMBRANE AS A MARKER OF PRIMARY BLAST INJURY

Few studies have been reported on the efficacy of using the perforation of the tympanic membrane as an indicator of primary blast injury, particularly pulmonary blast injury (PBI). Unfortunately, few records exist of the rate of tympanic membrane perforation in those suffering a pulmonary blast injury.

Harrison et al.[10] conducted a study of U.S. troops in Iraq passing through a military hospital due to exposure to improvised explosive devices. Conducted over a 30-day period, 167 patients were reviewed. Of these the breakdown can be seen in Table III and Figure 2.

These numbers indicate those reviewed by a medial team postblast explosion exposure, and whereas the numbers suffering a primary blast injury are low, 110 of 167 suffered some form of traumatic injury.

Of the 12 patients to suffer pulmonary blast injuries, 6 suffered ruptured tympanic membranes as well as the blast lung injury while the other 6 suffered isolated blast lung.[10] Use of this data for tympanic membrane perforation as a biomarker for PBI resulted in a sensitivity of 50% (95% CI, 22–78%) and specificity of 87% (95% CI, 81–92%).[10]

A similar study was conducted in Israel following a 3-year collection of data on victims of 11 bus explosions.[2] In this group were 770 injured people, of which 145 died from injuries, 123 at the scene and 22 subsequently. Of the 647 admitted to hospital, 193 were found to have suffered a primary blast injury. A breakdown of those injured revealed 142 with tympanic membrane perforation only, 31 with combined pulmonary injuries and tympanic membrane perforation, 18 solely with pulmonary blast injuries, and 2 with intestinal blast injury (Fig. 4).[2] This breakdown is similar to the U.S. military's experience in Iraq.

Figure 5 clearly indicates the similar levels of concurrent blast lung and tympanic membrane perforation with the rate of 63% for the Israelis and 50% for the U.S. military when compared to isolated blast lung injuries. These studies give a potential missed rate of pulmonary blast injury of 50% (U.S. Military) and 36% (Israeli) when the basis of investigation of the pulmonary blast injury is based upon the intact status of the tympanic membrane.

A third report from Katz[17] takes a look at those injured by a bus explosion in Israel. Of those injured and requiring admission (29), 8 were deemed to have life-threatening multitrauma. Of these, there were 6 cases of blast lung, with 100% rate of tympanic membrane perforation.

DISCUSSION

The explosion of a improvised explosive is normally targeted at a civilian population, often found within enclosed areas such as buses, buildings, or shops. As a result, the Friedlander curve of the pressure wave following such an explosion resembles Figure 2. Several variables exist in this situation such as orientation to the blast and environment in which the blast occurs.

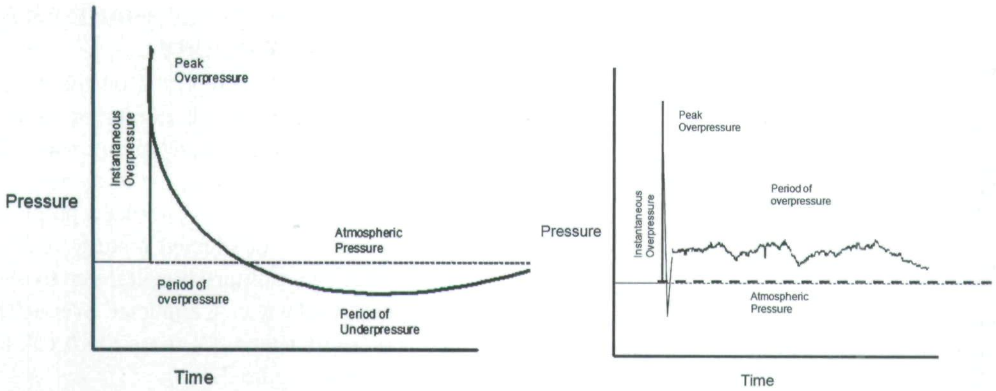

FIGURE 2. Friedlander curves to represent the overpressure in a theoretical environment and within confined space (adapted from Garth[7]).

TABLE II. Fatalities From the 2004 Madrid Train Bombings[16]

	No. of Bombs	Door Status	Fatalities
Train Carriage 1	3	Open	29
Train Carriage 2	4	Closed	64
Train Carriage 3	2	Closed	67
Train Carriage 4	1	Open	17

TABLE III. Breakdown of Primary Blast Injuries From U.S. Troops in U.S. Military Hospital (adapted from Harrison[10])

Primary Blast Injury	Numbers
Tympanic Membrane Rupture	27 (13 bilaterally)
Blast Lung (Total)	12
Tympanic Membrane Rupture and Blast Lung	6
Blast Lung (Isolated)	6

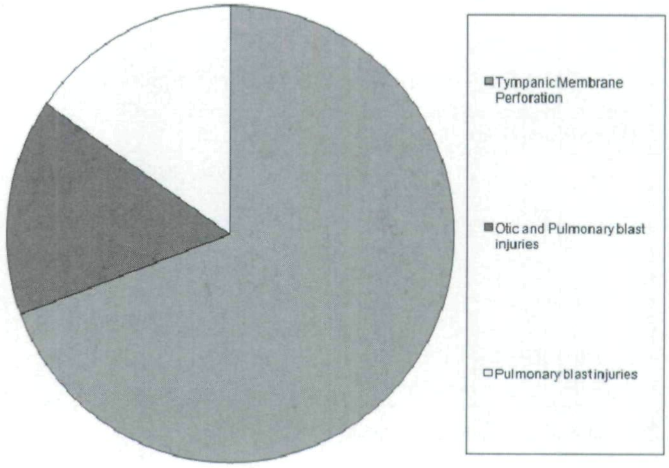

FIGURE 3. Rates of primary blast injury of U.S. military personnel (adapted from Harrison[10]).

Table IV and Figure 5 show the relative pressures considered for the effects on various organs relative to distance from and size of the explosive device. As can be seen, the pressure curves for each organ are separated distinctly; however, the resulting changes in pressure during the detonation of an improvised explosive device (Fig. 2) lead to a potential erratic level of primary blast injury, which is reflected in both the 1-month figures of the U.S. military and the longitudinal study in Israel. Whereas the expected level of injury based upon the distance from the explosion and the size of the blast should equate to a standardized expected level of injury, the environment in which the blast is occurring and the potential for the reflection of the blast wave give a result that is significantly different from the theoretical model.

What should be kept in mind are the relatively small numbers of personnel suffering blast lung when compared to other injuries suffered during an improvised or terrorist explosion. Katz[17] reports 8 critically injured patients with tympanic membrane rupture and 75% with PBI, a small number of patients but large when considering the relatively small numbers of

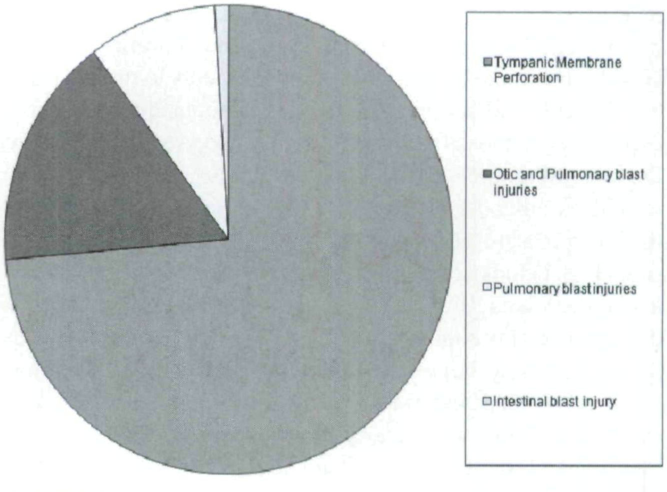

FIGURE 4. Rates of primary blast injury from Israeli bus explosions (adapted from Leibovici et al.[2]).

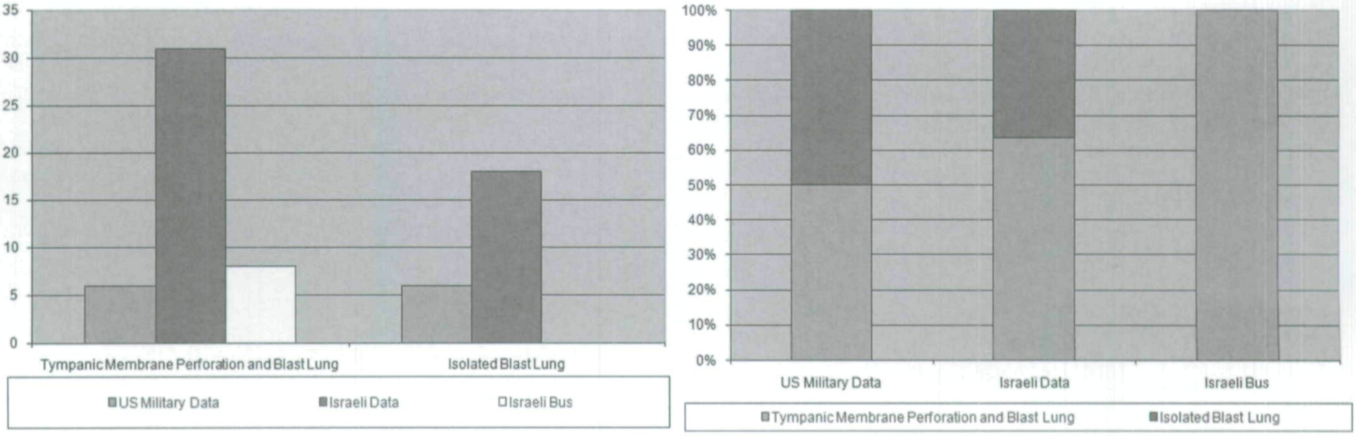

FIGURE 5. Comparison of data collected from U.S. military and Israel bomb blast survivors.

TABLE IV. Morbidity and Mortality, Relative to Distance From and Size of Explosion (meters and TNT) (adapted from Mrena et al.[11])

Symptoms	50 kg	5 kg	1 kg	0.5 kg
Hearing Loss	400 m	300 m	100 m	50 m
Tympanic Membrane Rupture	100 m	60 m	12 m	20 m
Blast Lung	30 m	51 m	9 m	4 m
Death	10 m	4 m	2 m	1 m

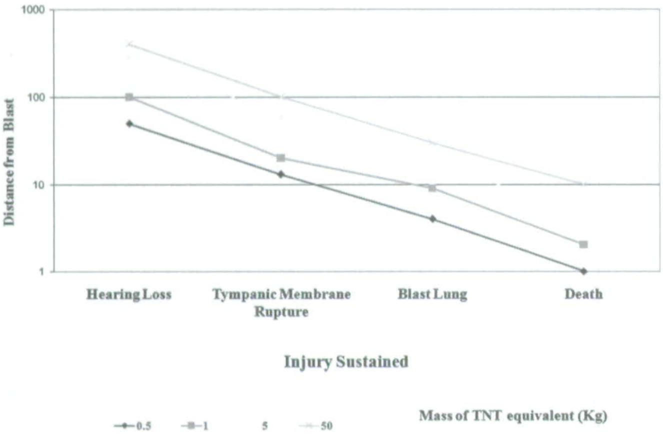

FIGURE 6. Estimations of primary blast injuries relative to the size and distance from blast (adapted from Mrena et al.[11]).

blast lung casualties previously reported. Of the 647 patients reviewed in the Israeli longitudinal study, only 49 suffered blast lung (7.57%) while only 12 of the 167 U.S. service men and women suffered blast lung (7.18%). This can also be seen in the experiences of those treating the casualties in the aftermath of the Madrid train bombings in 2004. The experiences of the treating doctors following the Madrid train bombings in 2004 showed that 43 of the 512 injured suffered a pulmonary blast injury (PBI), with 244 of 1,024 tympanic membranes perforated (23.8%).[16] At Gregorio Maran University General Hospital in Madrid, the closest hospital to the site of the bombings, of the 243 injured seen at the hospital including the 27 patients classified as critical, 17 suffered a pulmonary blast injury. This equated to 7% of the overall injured, yet 63% of the critically injured. Of the total 512 injured in the explosion, 43 suffered a PBI (8.3%).

CONCLUSION

Although the rupture of the tympanic membrane is known to be the first organ affected by the detonation of a improvised explosive device, the effects of improvised explosive devices detonated in a confined space can see the resulting primary blast injuries not conforming to standardized damage, due to the variability of the blast wave, and thus victims of such explosions may suffer blast lung or perforated viscera with an intact tympanic membrane. As such, any survivor of an improvised explosive device needs to be assessed for primary blast injuries with appropriate investigations for further injuries regardless of the status of the tympanic membrane.

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