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Introduction

It is well established from numerous documented cases of bomb blasts that, under certain conditions (determined by the amount and proximity of explosive), the transmitted shock wave and associated overpressure generated by the detonation of an explosive device can cause critical and fatal injuries to the thorax, e.g., “blast lung.” As such injuries tend to be internal and thus difficult to detect, there has been considerable debate in recent years on the significance of the blast overpressure injury in the context of demining/mine clearance compared to more visible injuries, such as, amputation of extremities, fragmentation wounds and blindness. A wide range of personal protective ensembles are currently deployed in the field, incorporating disparate stackings of materials over the thoracic region.

The purpose of this study is to quantitatively assess the relative effectiveness of different laminations for blast overpressure protection to the deminer’s chest. The range of test candidates included variations of ballistic flakvests, or aprons comprised entirely of soft ballistic materials with different numbers of layers, as well as the recently developed and field tested HDE Demining Ensembles by Med-Eng Systems Inc., in both their Basic and Enhanced forms. The HDE Ensembles consist of a hybrid combination of blast-energy absorbing components mixed with soft and rigid ballistic materials while the Enhanced HDE uses an extra layer of high density rigid ballistic material overtop the Basic layout. A “chest simulator,” instrumented to measure transmitted blast overpressure as well as Hybrid II mannequins with pressure sensors and accelerometers mounted inside the chest, were both used as test surrogates to evaluate the effectiveness of different systems. In addition, a first attempt is also made to elucidate the significance of the blast overpressure injury (if any) in the particular context of the blast type AP mine threat by comparing with benchmark values.

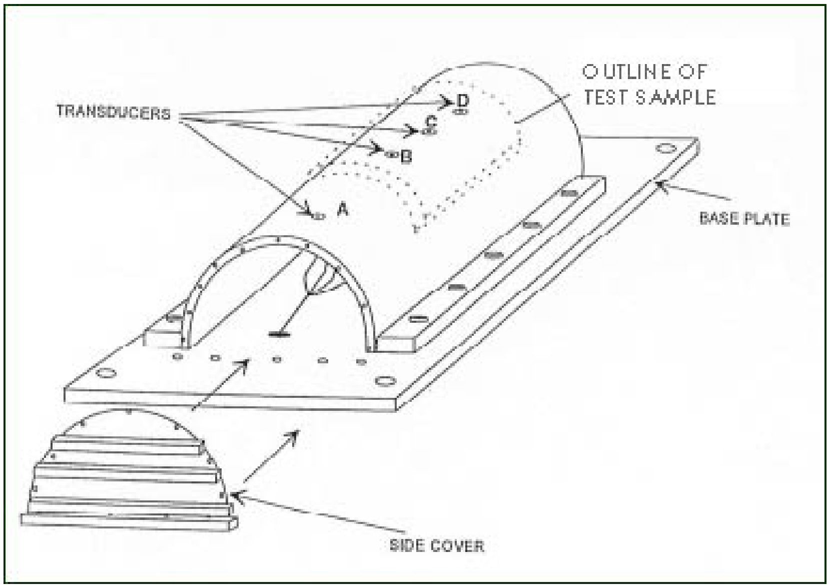


Figure 1: Schematic of chest simulator, illustrating location of pressure transducers and location of a sample during a test.

Experimental Details

Experiments performed for this study were realized on two fronts. Initial testing of protective thoracic laminations was performed in a blast chamber utilizing a chest simulator and representative blast threats. In order to conduct a form of validation for the chest simulator experiments and to perform tests more representative of a demining scenario, blast tests with instrumented anthropomorphic mannequins were also carried out.

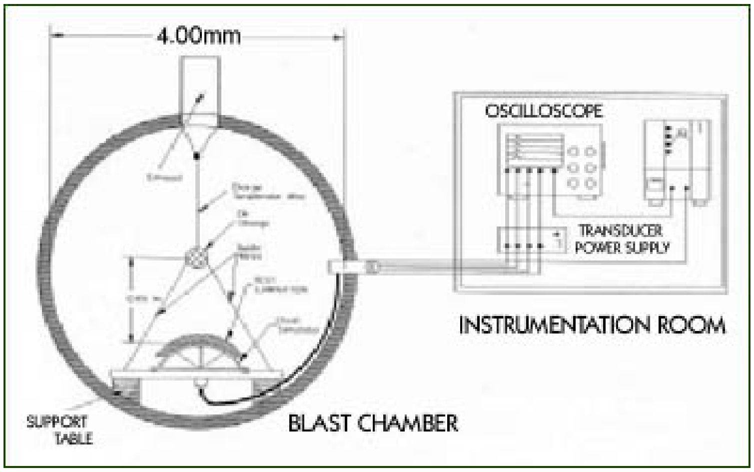


Figure 2: Schematic of blast chamber facility used for chest simulator experiments.

Blast Testing with Chest Simulator

The chest simulator is comprised essentially of a curved aluminum plate (12.7mm thick) bolted down on a flat aluminum base plate; this structure allows laminations to be evaluated on a contour roughly similar to the human torso (Figure 1). A number of pressure transducers can be flush mounted at the surface of the device. The chest simulator was placed within a blast chamber where different charges of high explosive were set off at a representative distance to reproduce the overpressure threat of detonating mines. The pressure sensors then record the overpressure transmitted through a protective lamination placed on the surface of the chest simulator. A cross-sectional view of the experimental facility, featuring the chest simulator within the blast chamber, with a test sample in place and the charge suspended overhead, is depicted schematically in Figure 2.

A “rigid” non-compliant surrogate for the chest has been employed as a conservative means of assessing the injury from the transmitted blast overpressure wave. In reality, the chest is compliant and other injuries may occur as a result of the physical compressive motion (total compression, rate of compression, acceleration) of the thoracic wall. The transmitted overpressure wave is deemed to be a very important parameter that can govern the ensuing behavior of the thoracic cavity and contained organs.

The charge sizes chosen for the chest simulator experiments were 115g and 250g of C4 plastic explosive molded into spheres and initiated by a blasting cap inserted in their centers. The 250g charge size was chosen to approximate the blast strength of a PMN landmine, as it is among the largest and most proliferate of the blast type AP mines; the 115g charge size was adopted to represent a range of smaller mines. The PMN contains 249g of TNT, which is of considerably less explosive strength than 250g of C4. However, 250g of C4 was selected by taking into account the difference in explosive yield between TNT and C4 and that a mine will typically detonate on or slightly below the ground, thus creating a hemispherical blast wave. For equal mass of explosive, a hemispherical blast wave is stronger than a spherical blast produced by a charge detonated in air.

The charge of explosive was hung at three different distances from the chest simulator: 0.65m, 0.55m and 0.45m. The distance of 0.65m was chosen based on the approximate distance of the sternum of a small-statured deminer to the typical location of a mine being cleared when the deminer is in a kneeling position using a prodder of 40cm (+/- 10cm) in length (based on actual field measurements, Figure 3). The two smaller distances were also used in order to examine the effect of distance on the pressure experienced.

Full-Scale Blast Tests with Anthropomorphic Mannequins

Full-scale tests involved instrumented anthropomorphic Hybrid II mannequins placed in positions representing those used by deminers. The mannequins were instrumented with a pressure transducer (PCB) mounted at the sternum along with a tri-axial cluster of accelerometers (PCB) placed in the torso of the mannequin in order to measure chest accelerations.

Simulated mines, consisting of C4 plastic explosive packed snugly into injection molded puck-shaped plastic containers, were buried with one cm of overburden in front of the mannequins, which were in kneeling-on-one-knee positions. Three sizes of simulated mines were used containing 50, 100 and 200g of C4 chosen to represent a wide range of blast type AP landmines. The mannequins were placed in the kneeling position with their sternums 0.66 to 0.68m from the simulated mine, which accurately represented the typical distance a deminer's sternum would be from a mine while prodding in a kneeling position using a prodder approximately 40cm (+/-10cm) in length (Figure 3). The mannequins were tested while wearing the HDE in both its Basic and Enhanced forms, a standard flakvest and not wearing protection. A picture of a typical test setup is provided in Figure 4. For greater detail concerning this experimental procedure, please refer to [Appendix 1]. This method of testing is currently under consideration for use by the Canadian Center for Mine Action Technology (CCMAT).

Results

Before delving into the results, it is useful at this point to define some terms which will be used. A typical reference trace, obtained when no lamination was present over the chest simulator, is shown in Figure 5. The peak overpressure is described as the maximum height of the signal. The positive phase duration is described as the time from when the signal rises above zero to where it falls back to approximately zero. The pressure rise time duration is the time for the signal to rise from zero up to the maximum peak pressure. The average rate of peak pressure rise is then defined as the ratio of the peak overpressure and the rise time duration. The peak overpressure, positive phase duration and average rate of peak pressure rise are all parameters of the blast wave that can play varying roles in any transmitted overpressure injuries to the thorax; the peak overpressure is deemed to be the dominant parameter.

Deminer prodding for a mine in kneeling position while donning HDE Demining Ensemble, HDH-1 Helmet, and prototypical hand protector, by MES. Typical distance from sternum to end of prodder is 0.65-0.70m.

Photo c/o Med-Eng Systems

Results of Blast Testing with Chest Simulator

When a lamination is placed on top of the simulator and a charge detonated, the overpressure history is modified in profile, duration and peak, depending on the composition of the lamination. This example is illustrated in Figure 6. In this plot, the pressure traces of four experiments are shown in which a 250g sphere of C4 was detonated 0.65m above the chest simulator. The top trace is the reference, or unprotected, pressure trace. It shows a typical triangular blast profile, i.e., a sudden rise in pressure followed by a decay. The second trace down exhibits what the overpressure profile looks like beneath the chest lamination of the Basic HDE. The peak pressure and the rate of pressure rise have been greatly reduced while the duration has elongated. On the third trace under the Enhanced HDE, the peak overpressure and the rate of peak pressure rise have both been further reduced while the positive phase duration has been further elongated. The bottom trace in Figure 6 is that obtained beneath a commercially available demining apron composed of only soft ballistics. Its profile bears a much closer resemblance to the reference pressure with a sharp rate of pressure rise, a high peak and a short duration.

Typical setup for full-scale tests with mannequins. Mannequins donning HDE Demining Ensemble, HDH Helmets, and prototypical hand protector by MES.

Photo c/o Med-Eng Systems

Depending on the charge mass, the stand-off distance and the material composition, the different laminations tested serve to alter the peak overpressure measured. Figure 7 illustrates the average peak overpressure measured at the chest simulator wall across six different laminations and with no lamination present for two charge sizes (115 and 250g of C4) at three stand-off distances of charge to chest simulator (0.65, 0.55 and 0.45m; shown in Figures 7a, b and c, respectively).

In examining Figure 7, several key trends are discernable. Not surprisingly, the reference pressure, i.e., no lamination on the chest simulator, as well as the transmitted overpressures across all laminations tested increase with charge mass and decreasing stand-off distance from the charge. The Basic and Enhanced HDE greatly reduce the peak overpressure measured at both charge sizes and all three distances with the Enhanced HDE slightly outperforming the Basic model. Under the HDE laminations, the peak overpressure measured does not rise dramatically with increasing reference pressure (less than 20 bar), indicating the ability of the HDE to withstand and attenuate a wide range of blast overpressures. Due to this trend, the reduction factors actually increase with decreasing distance to the 250g charge from 87 to 93 percent for the Basic HDE and from 93 to 96 percent for the Enhanced HDE.

The lamination composed of 3x layers of soft ballistic material (where x refers to a nominal number of layers) is also able to attenuate the blast overpressure but by less than the HDE chest laminations. Furthermore, as the reference overpressure increases, the overpressure measured under the 3x layers also increases significantly (note the difference in measured values for the 115g versus the 250g charges). With fewer layers of soft ballistic material (i.e., x layers, ½x layers and the standard flakvest), slight pressure attenuation is only capable at lower blast strengths (i.e., the blast from 115g of C4 at 0.65 m distance). However, once the blast strength increases (i.e., 250g C4 at 0.65m or the stand-off distance is reduced for both charges (to 0.55

and 0.45m) these laminations actually amplify the overpressure measured. In fact, the amplification observed is often great enough that the maximum capability of the pressure transducers is exceeded (marked by dashed line at 200 bar).

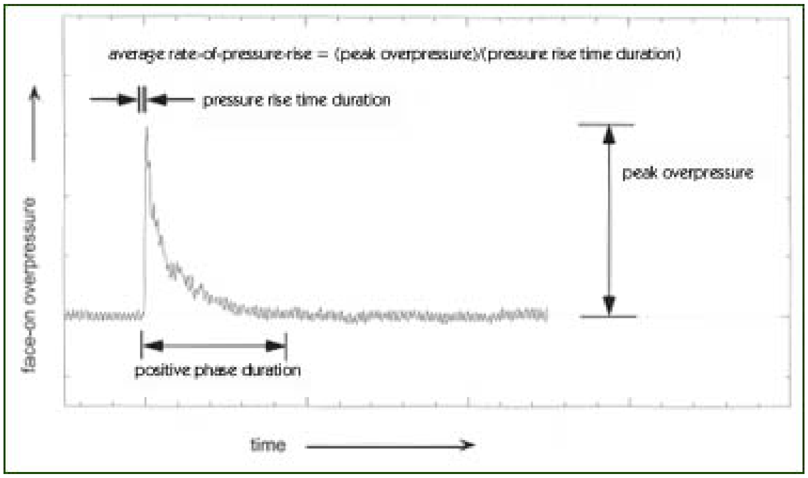


Figure 5: Definitions of measurements used in analysis (typical pressure trace obtained on bare chest simulator)

The superior overpressure attenuation capability of the chest laminations from the Enhanced and Basic HDE is a result of their material compositions containing rigid ballistic materials, soft ballistics and blast attenuating foam. The interaction of the shock wave with a combination of rigid and soft materials allows for a shock wave “decoupling,” greatly reducing the peak pressure transmitted through the jackets. When a blast wave interacts with a series of hard and soft/lower density materials, which have greatly different acoustic impedances, the blast wave cannot effectively transmit across the interfaces for a range of blast intensities. This results in the blast wave front becoming dispersed and attenuated before reaching the chest wall, as large portions of the blast energy are reflected rather than being allowed to transmit. Moreover, the presence of the blast attenuating foam serves to reduce the rate at which the pressure rises, reduces the peak overpressure attained and spreads out the overpressure loading over a longer duration when compared to the incident pressure and the reading obtained beneath a soft ballistic lamination (Figure 6). The superior performance of the Enhanced HDE over the Basic HDE is a result of its high density ballistic plate in place facing the blast. The high acoustic impedance of this external plate along with its increased inertia serve to further reduce the transmitted peak overpressure loading. For further illustration of the effect of foam on the attenuation and spreading of blast overpressure waves, please see [Appendix A, 2&3].

The laminations composed only of soft ballistics do not effectively attenuate the peak overpressure except for a very limited range of low blast wave strengths. In large part, this is due to the absence of an effective decoupling system to reduce the peak pressure of the transmitted wave. In addition, the lack of energy absorbing foam does not permit an absorption and redistribution of the blast energy over a longer time period at more benign pressure levels.

The relatively light soft ballistic within these laminations can be rapidly accelerated and "slapped" onto the chest, violently causing a pressure surge over a short time frame.

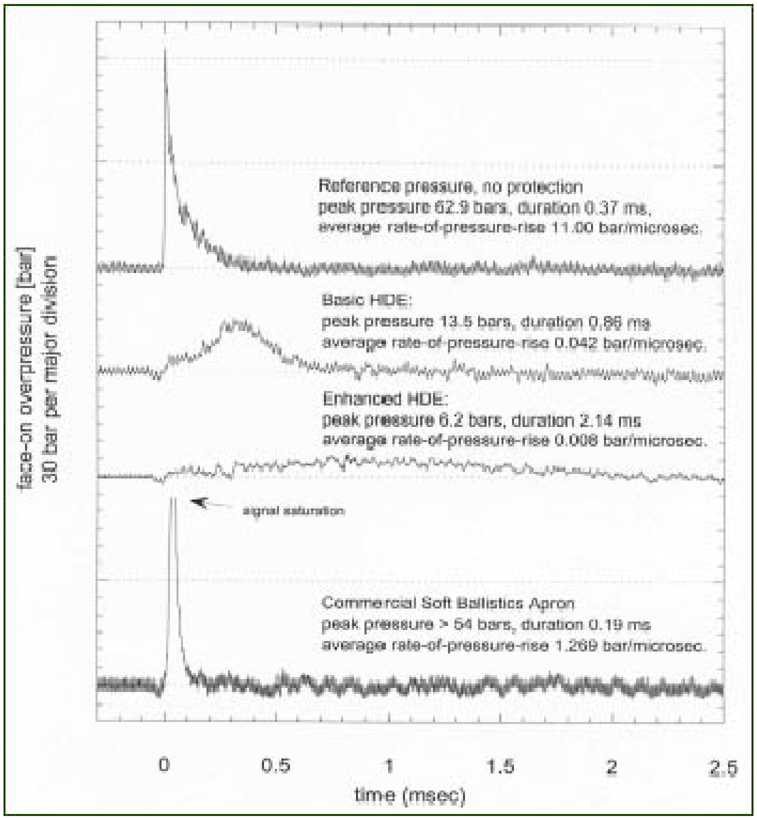


Figure 6: Typical traces of overpressure measured on chest simulator, for bare simulator, Basic and Enhanced HDE, and commercial soft ballistics apron; when facing blast from 250g of C4 at 0.65m stand-off.

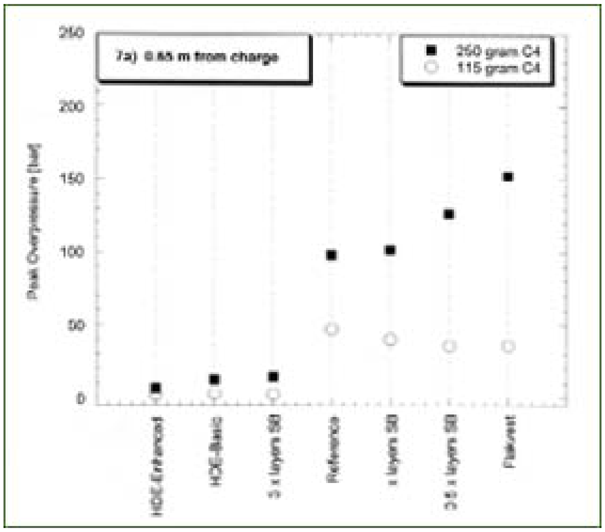
The relatively heavier lamination composed of 3x layers of soft ballistics, however, seems to attenuate the blast overpressure for this range of blast conditions. This attenuation is due in part to the larger inertia (mass/unit area) that the large number of layers possesses and the inherent damping of the wave as it tries to traverse across the multitude of layers. It makes it more difficult for the wave to accelerate the lamination onto the chest wall, thereby keeping pressure levels low. However, as stated, the pressure attenuation becomes less effective with increasing threat.

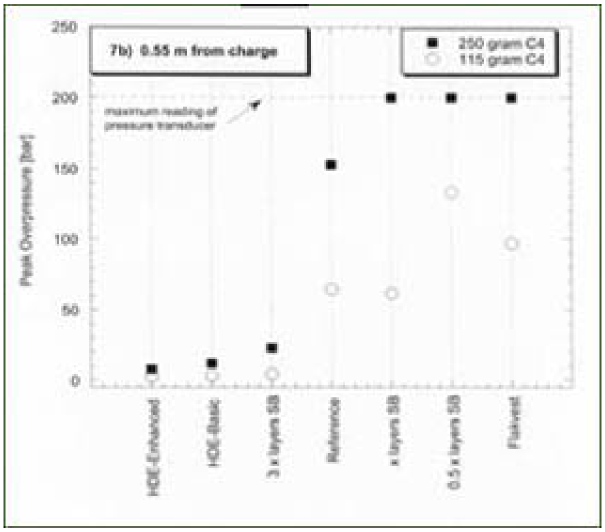
Results from Full-Scale Testing with Mannequins

Figure 8 provides a summary of the average peak overpressure measured at the sternum of the mannequins over the three charge sizes (50, 100 and 200g C4) while wearing the different protective systems. It can be seen that the best performing lamination is the Enhanced HDE followed by the Basic HDE, both of which greatly attenuate the incoming overpressure from the simulated mine. The flakvest, which is composed only of soft ballistics, is able to attenuate the pressure from the 50 and 100g charge, but when faced with the blast from the 200 gram blast, it amplifies the pressure measured compared to the case of "no protection" over the mannequin chest.

In addition to illustrating the effectiveness of the HDE systems and the shortcomings of using a soft ballistic flakvest under some demining related blast threats, the full-scale tests performed with the mannequins confirm the same trends observed with the chest simulator.

The average peak resultant acceleration measured in the mannequins over the three charge sizes and donning the various protective gear is plotted in Figure 9. The Enhanced HDE is best able to attenuate acceleration over the unprotected case followed by the Basic HDE for the full range of conditions tested. The wearing of a soft ballistic flakvest, while capable of attenuating the acceleration at lower blast strength (less than 100g C4), amplifies it at higher strength (200g C4). These trends are identical to those observed for overpressure. This result is also further validation of the value of performing initial experiments with the relatively simple and controlled setup of the chest simulator.





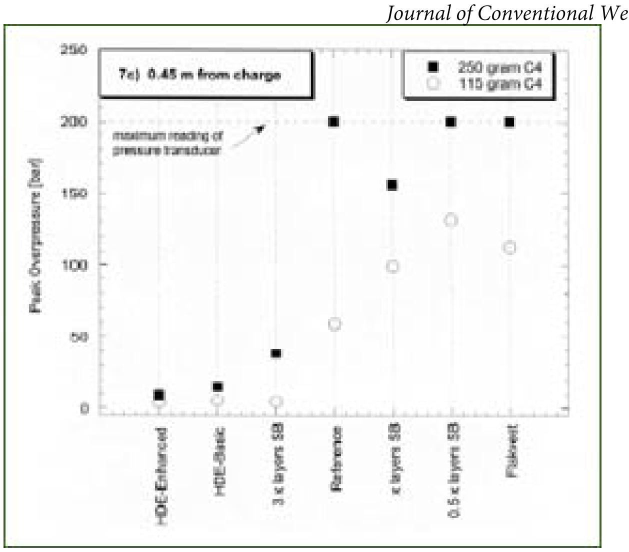


Figure 7: Average peak overpressure measured on chest simulator for different chest laminations exposed to 250g and 150g C4 charges at different stand-off distances: a) 0.65m, b) 0.55m and c) 0.45m.

Correlation of Data with Injury Thresholds

It is generally accepted that there are at least three contributing factors that govern blast overpressure injury to humans in the torso region. The foremost factor is believed to be the peak overpressure level of the wave loading the torso. The rate of pressure loading as well as the duration of the positive pressure phase are also important factors that determine if injury will occur and the extent of the injury. Based on theoretical models and experimental data deduced from tests involving biological subjects exposed to blast, one can obtain curves that describe the estimated injury and survivability thresholds for a human subjected to a blast [Appendix A, 4]. These curves consider only two of the factors that may increase the chance of injury: the peak pressure and the duration over which the pressure acts. Obviously, the higher the pressure at an increased duration, the greater the chance for injury or death. Insufficient data exists to quantitatively include the effects of the rate of peak pressure rise, and, hence, this influence to injury has not been explicitly considered in the above injury curves.

Experimental data from the full-scale tests involving mannequins has been plotted in Figure 10 with respect to the injury thresholds published in [Appendix A, 4]. On the vertical axis is side-on overpressure while on the horizontal axis is the positive phase overpressure duration, both presented in a logarithmic scale. Plotted in the figure are two threshold curves. The dashed lower line is the lung damage threshold while the solid upper line represents the 99 percent survivability threshold. If one experiences a blast, characterized by a peak pressure and duration that lands beneath the lung injury threshold, then this graph would indicate that one is unlikely to experience lung damage. Equivalently, if the blast data is positioned above the threshold, then one would likely experience injury to the lung. In a similar fashion, one has a less than 99 percent chance of survival (or a greater than one percent chance of death) if the blast data are within (i.e., above) the 99 percent survivability threshold. One should note that such injury thresholds do not consider the escalation of injury that commonly exists due to the compounding effects of different forms of injury, including fragmentation wounds, head acceleration and concussions, amputation of extremities, contamination and infections.

Figure 10 plots the data obtained from the pressure transducer at the chest of the mannequin when facing the blast from simulated mines containing 50 and 200g of C4 at a distance of 0.66-0.68m from the sternum. It is discernible that the blasts from the 50 C4 mine, whether measured beneath a protective lamination or not, fall well below the injurious level. The blasts from the 200g C4 mine, however, are generally higher in pressure and, therefore, are closer to the lung injury threshold or straddle it.

The validity of the injury threshold curves at the left half of the graph, characterized by relatively high peak pressures and short durations, may be limited, as the threshold curve is an extrapolation. In reality, one would expect that human tolerances to very steep pressure loadings in a short duration would lower the injury threshold. This expectation would imply that data points located on the upper left region of Figure10 would actually be more injurious than indicated on the basis of the injury threshold curve currently plotted.

Further to this point, however, is that it is most likely that the data plotted in the lower right portion of the figure is far less injurious than indicated. The injury thresholds plotted are based on pressure histories with the typical triangular blast profile, i.e., a sharp sudden rise in pressure followed by a smooth decay (an example of which is the top trace in Figure 6). The data plotted on the lower right, all of which are points corresponding to the Basic and Enhanced HDE, do not have such a profile, examples of which are illustrated in Figure 6. The main difference is the relatively shallow rate of pressure rise exhibited by these hybrid chest laminations. The difference in the rate of pressure rise between that measured beneath the HDE laminations and the reference pressure, or that under a soft ballistics lamination, is of several orders of magnitude. Whereas, the rate of pressure rise beneath the soft ballistics apron is 1.269 bar/sec the rate beneath the Basic HDE is a mere 0.042 bar/sec and under the Enhanced HDE it is further reduced to 0.008 bar/sec.

The human body has a much greater ability to endure an impact, a force or an overpressure if that impact/force/pressure is applied relatively slowly, rather than suddenly. If pressure is increased relatively slowly, then the inherent elasticity of the body organs and bones has a chance to respond in a way that minimizes or prevents damage. But if the pressure rises suddenly and rapidly to a dangerous level, the probability and level of injury is higher. Therefore, while the overpressure measured beneath the Basic HDE lamination appears to be injurious when examining Figure 10, if one disregards the fact that the pressure profiles did not have steep pressure rises, it is very likely that these overpressures are far from injurious if one considers the relatively slow rise in overpressure.

The threshold of injury for gross chest acceleration is generally accepted to be 60 g's. However, this value is based on data obtained by the automotive industry, which does not study such short duration events, such as blast loading. The limit of 60 g's may, thus, be considered as conservative, but exceeding this limit does imply a higher likelihood that injury would occur. Examining the data in Figure 9, it is apparent that for a smaller range of explosive charges (50 and 100g) that chest acceleration injury is not expected to be injurious. But, as the charge mass increases to 200 g's, the injurious threshold is exceeded bearing in mind that the exactness of this threshold has not been completely validated. Note that the chest of such mannequins used for the present study are not calibrated nor were they designed for repeated explosive blast loading. The data presented should be considered in a relative sense only and not as an absolute indication of injury or no injury.

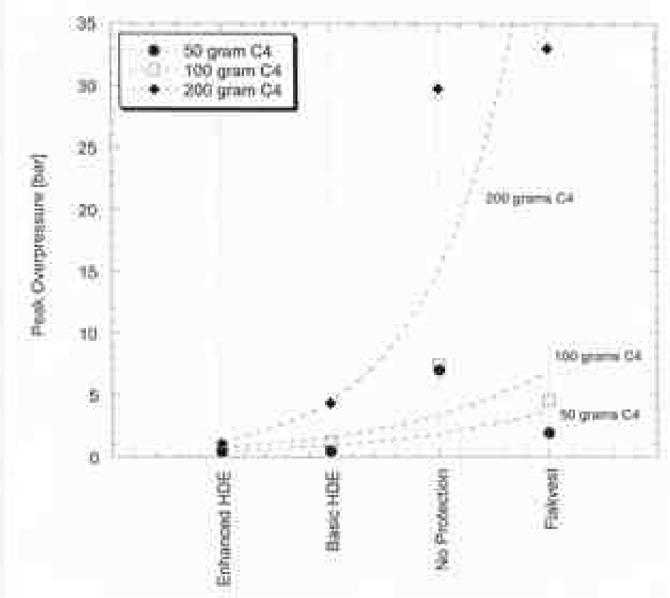


Figure 8: Average peak overpressure measured at sternum of mannequins in kneeling-on-one knee position, facing simulated mines of 50, 100 and 200g C4, buried with 1cm overburden, 0.66-0.68m from sternum.

Conclusions

Blast chamber experiments performed with the chest simulator confirm that transmitted overpressure increases with increasing charge size and decreasing stand-off distance. Experiments have also revealed that protective laminations, which consist entirely of soft ballistic material, can undergo a transition in performance from attenuation to amplification. This transition is dependent on the number of layers of soft ballistic material relative to the blast wave loading profile. For instance, when the explosive charge was increased from 115 to 250g C4 at 0.65m, there was a transition in transmitted overpressure across the ½ x layers of soft ballistic material from attenuation to amplification. The same behavior occurred when the blast loading was augmented through a decrease in stand-off distance from 0.65 to 0.55m (10cm closer) for the 115g C4 charge. However, the use of a lamination that is comprised of both rigid and soft materials, including a blast energy absorbing layer, did not exhibit the same transition and was demonstrated to dramatically improve protection levels. The relative performance in attenuation effectiveness of different protective laminations, observed with a chest simulator, can be further confirmed in tests more closely resembling actual field conditions--using instrumented automotive crash test mannequins in representative demining positions.

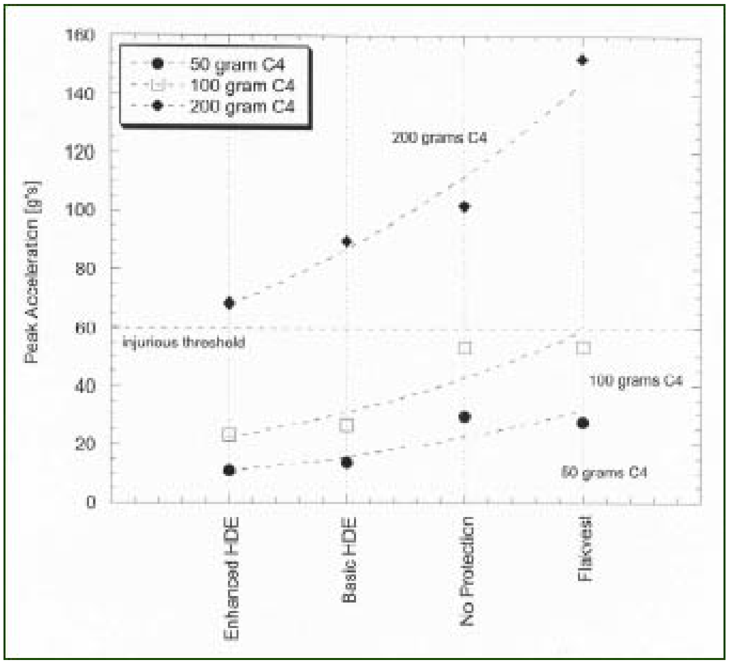


Figure 9: Average peak acceleration measured at chest of mannequins in kneeling-on-one-knee position, facing simulated mines of 50, 100 and 200g C4, buried with 1cm overburden, 0.66-0.68m from sternum.

The studies involving mannequins indicate that for the range of mine threats and demining conditions investigated it is unlikely that one would die from overpressure injury alone, even when wearing no protection or donning equipment which can amplify overpressure, such as a flakvest. However, the data obtained for the 200g C4 simulated mine at 0.66-0.68m from the sternum straddles the lung injury threshold. Furthermore, if one considers the effects of stand-off distance, it becomes apparent that, by decreasing the distance from the mine by seemingly small amounts, the potential for life threatening internal thoracic injury increases markedly. This trend is particularly apparent when wearing only soft ballistic protection. To further illustrate the critical significance of stand-off distance, consider that a reduction from 0.65 to 0.45m increases the theoretical peak reflected overpressure at a flat surface from the detonation of a 200g C4 charge by over 200 percent.

When the type of injuries that can occur due to a mine detonation are considered, such as severe lacerations, trauma and amputations and these injuries occur in geographical regions that are not well served by medical facilities, any reduction in overall injury to the body is beneficial. Wearing proper protective apparel can reduce the possibility of overpressure injury by reducing the peak over pressure and the rate of pressure rise experienced.

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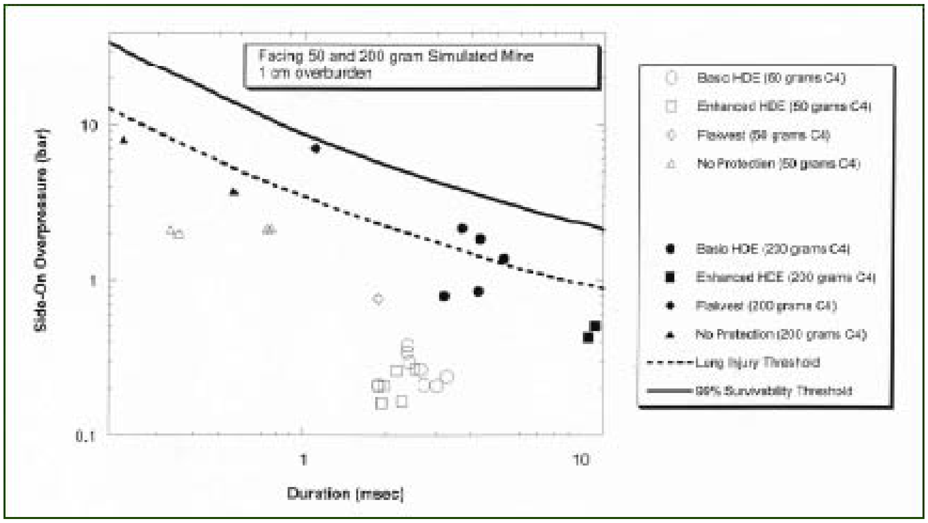

Figure 10: Duration and peak of overpressure measured at the sternum of mannequins in kneeling-on-one-knee position, facing simulated mines of 50 and 200g C4, buried with 1cm overburden, 0.66-0.68m from sternum; plotted against lung injury and 99 percent survivability thresholds.

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