REDUCTION OF BLAST INDUCED HEAD ACCELERATION IN THE FIELD OF ANTI-PERSONNEL MINE CLEARANCE

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ABSTRACT

The blast wave that is generated from the detonation of an anti-personnel mine can induce significant accelerative loading to the head of a deminer, when the wave collides with the victim. The injury potential posed by the resulting head acceleration in the context of demining, has not been previously studied. Instrumented anthropomorphic surrogates were used to evaluate the protective capabilities of various types of helmet systems employed in demining, for a range of mine threats, as defined by the explosive content. The HIC_{15} method of assessing injury potential was applied to the measured accelerations. A spectral analysis of signals was also performed. The injury analysis indicates that blast induced head acceleration can reach injurious levels, depending on the type of head protection employed and the explosive content of the anti-personnel mine. For the highest blast loading tested, there was a high probability for a fatal head concussive injury when a military helmet is worn without a visor, or when no head protection is worn. Properly designed helmet systems, which included a full-faced visor mounted on stable helmet platforms, were demonstrated to provide significant protection against blast-induced head acceleration.

KEYWORDS

Blast-Induced Head Accelerations, Mannequins, Anti-Personnel Mines, Injury Criteria, Helmets

IN THE CASE OF AN ACCIDENTAL DETONATION of an anti-personnel (AP) mine, a blast wave is generated, compressing the gases behind it and propagating away in all directions, along with an impulsive burst of fragments and an intense fire flash. The impact and ensuing interaction of the blast wave with the victim can induce violent, uncontrolled, accelerative motion of the body, and between body parts. Under extreme conditions, intense blast loading can lead to shearing of body parts, in the form of traumatic amputations, such as those observed in victims of many terrorist bombings, or victims stepping on landmines. Less dramatic forms of blast injury that have not been well understood or documented include blast-induced accelerations of the head, chest and groin. Although there have been some pioneering studies conducted with human surrogates [Makris, 1997, RCMP, 1996, Fournier, 1995] that have elucidated the potential of blast-induced accelerative injuries in the context of bomb (or explosive ordnance, EOD) disposal, there have been no previous systematic investigations to assess the relevance of these types of injuries in the context of demining.

In the clearing of AP mines, the explosive content of AP mines is typically much lower (i.e., less than 500 g of TNT) than other explosive ordnance and devices, however the separation distance between the victim and the source of the explosion is usually relatively short (i.e., less than 1 m). In most demining accidents, the flesh wounds and damage to the extremities, caused by high velocity fragmentation and the overpressure associated with the blast wave, usually receive the most attention. The effects of blast-induced acceleration are rarely understood by medical staff on site, and thus

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symptoms of such potential injuries are neither sought nor detected. In the worst case, this threat may be a contributing factor in a fatality, but due to other more visible injuries sustained, is rarely, if ever, considered. Symptoms of closed head concussive injury have been reported in mine victims, although it has not been clear if such injuries were a consequence of accelerative loading (from the blast), or decelerative impact (with the ground) [Dept. of Defense, 2000].

In developing, or deploying, protective equipment for use in demining theatres, there needs to be an appreciation of all threats posed by the detonation to the operator. There are several ongoing investigations with objectives to assess the effectiveness of different protective components in terms of blast integrity, overpressure attenuation, and fragmentation resistance [Makris, 2000, Nerenberg, 2000]. Moreover, various international efforts underway are attempting to assess the type and severity of injuries that can be sustained, in the particular context of clearance of blast type AP mines.

The current study focuses on evaluating the effectiveness of different concepts of protective head gear, in terms of their ability to reduce the blast-induced head acceleration measured in the head of human surrogates. To facilitate this, Hybrid II mannequins (pedestrian model) were instrumented with a triaxial cluster of accelerometers in the head. Special test rigs were designed which permitted the mannequins to be accurately and reproducibly supported in many common positions used in performing demining activities, including kneeling, standing, and crouching. For the purposes of this study, the mannequins were dressed in particular protective ensembles, which included body protection interfacing with head gear, and placed in the widely used kneeling position at a representative distance from a range of simulated AP mines. An attempt was then made to analyze the data and assess the injury potential posed by blast-induced head acceleration for the different head gear and mine threats tested using the Head Injury Criterion (HIC).

EXPERIMENTAL DETAILS

MANNEQUIN POSITIONING AND INSTRUMENTATION: The experimental investigation involved the use of Hybrid II mannequins, representing the 50th percentile North American male (height: 1.75 m, mass: 77kg). The pedestrian model of the mannequins was employed, as it was necessary to place the human surrogates in a variety of demining positions. The mannequins were tuned on site throughout the test effort for a relatively realistic initial response when subjected to the blast loading. Limited experience with both Hybrid II and Hybrid III anthropomorphic test devices in explosive blast environments, indicated that the Hybrid II version would suffice for the purposes of this initial investigation, as its design seemed to be more robust and required less structural maintenance. Furthermore, in consideration of the results presented, the displacement implied by the acceleration traces allows one to consider the response of the head alone, i.e., the head response decouples from the response of the Hybrid II chest and is not sensitive to the particular construction of the neck.

To obtain systematic and meaningful data, a high emphasis was placed on positioning the mannequins consistently and realistically in the context of demining. When performing blast tests, the need for controlling the position of the mannequin is further emphasized. The strength of a blast wave decays at a rapid rate with respect to distance, governed by approximately $1/R^3$, where R is the radial distance from the blast origin. This implies that small changes in distance from the mine can result in dramatically different levels of blast loading on the human surrogate and the protective gear donned. The task of positioning is made more difficult by the relative complexity and diversity of the positions typically used in demining, which include kneeling, squatting, standing, crouching and prone.

In order to achieve effective positioning, and to do so in a blast environment, an “advanced” positioning apparatus was designed and constructed. The apparatus consists of a large base structure with two supporting arms, which can be set at a range of angles from near-horizontal to vertical. The arms are far enough apart that a 50th percentile male mannequin dressed in a personal protective ensemble easily fits between them. On these arms, by means of adjustable brackets, sit two cross-bars which connect (by means of chain links) to specially designed plates at the mannequin's hips and shoulders. This was accomplished by introducing two lateral attachment plates along the spinal column, below the neck and at the hips, in a manner which would have a minimal effect on the initial response. The cross-bars are not rigidly attached to the supporting arms but are held in place by the mannequin's weight. Every component on the apparatus can be adjusted by discrete amounts in order that positions can easily and accurately be recreated, within some practical constraints. The use of small link chains and the movable cross-bars allow the mannequins to move freely during the initial blast event, thereby preserving the initial bio-fidelity of the mannequin's response.

The versatility of the test apparatus allows the mannequins to be placed consistently in all of the aforementioned demining positions, however, for this study, only the kneeling position was utilized. In all tests, two mannequins were utilized in order to obtain two sets of data for each mine blast. Figure 1 shows a typical set up where the mannequins were supported in a kneeling position, prior to a mine detonation, via means of two separate positioning rigs located diametrically opposite to each other. For the purposes of this study, the mannequins were all placed with their head (tip of nose), sternum, and hips separated from the mine at 0.78-0.82 m, 0.66-0.68 m, and 0.72-0.74 m, respectively. These distances were derived from field measurements of a deminer prodding for a potential mine with a prodder of approximate length 40 cm (+/- 10 cm). Although it was not possible to control the mannequin positioning with higher precision, this was deemed a dramatic improvement compared to alternate positioning techniques previously utilized (where harnesses, ropes and other jigs were employed), with which the best achievable scatter in distance to the mine for the different body parts of head, sternum, and hips was 0.10, 0.06, and 0.18 m, respectively.

Figure 1 - Mannequins placed in kneeling position, dressed in HDE with Sport-1 helmet on mannequin 1 (left), HDH-1 helmet on mannequin 2; simulated mine 0.66 m from both sternums

In order to quantify the performance of the various protective equipment evaluated, each mannequin was instrumented with a tri-axial cluster of accelerometers (PCB 350A03) at the centre of gravity of the head. All instrumentation lines were connected via appropriate power supplies and signal conditioning equipment to a computerized data acquisition system whose sampling rate was 83.3 kHz. The sensors were calibrated prior to each test series and found to exhibit insignificant drift in their calibration. Processing of the acceleration data entailed calculating resultant accelerations (from the individual x-, y-, and z- components of acceleration), and filtering the data using a four-pole Butterworth filter set to remove signals above 1650 Hz. This filtering is performed in accordance with standards set to permit correlation of measurements in mannequins with injuries suffered by humans (SAE Channel Class 1000). It should be noted that a 1650 Hz filter may not be the most suitable choice for blast exposure of mannequins, as this value has been derived from studies of occupants in automotive crash tests, which can differ from blast exposure in pulse shape and duration.

MINE THREATS: Since actual AP mines are not readily available, simulated mines were extensively used for the purposes of this study. The quality control associated with actual mines, and thus, the reproducibility of test conditions, is inferior to the simulated mines used. These consisted of C4 plastic explosive uniformly packed into injection molded puck-shaped plastic containers, and buried with 1 cm of overburden in front of the mannequins. Three sizes of simulated mines were used containing 50, 100 and 200 grams of C4, chosen to represent the explosive yield over the entire range of blast type AP mines.

EQUIPMENT TESTED: The tests performed for this study were part of an overall test program to develop a full range of lightweight protective equipment for humanitarian demining and mine clearance. The HDE Demining Ensembles (by Med-Eng Systems) were worn over the mannequins for most tests, along with different hand and arm protection concepts. The HDE Demining Ensemble is designed to provide full frontal protection to the deminer through a unique and advanced combination of energy absorbing and ballistic materials. A prominent feature of the ensemble is that there is a rigid chest plate that protrudes from the front of the jacket and overlaps with the outer surface of the lower portion of a visor. This provides continuous frontal protection and serves to reduce the possibility of the blast entering the facial region and dislodging the visor from the wearer's head.

Several head and facial protection concepts have been designed and tested as part of this study, all of which employ a helmet as a platform for mounting a full-face polycarbonate visor for blast and fragmentation protection. Three styles of helmets were developed; the *HDH* helmets, which utilize a military PASGT-style helmet with an advanced retention system (one of which is visible in Fig. 1; right mannequin); the *Sport* helmets, which use a lightweight sporting helmet (visible in Fig. 1; left mannequin); and the *Hardhat* helmets, based on a construction hardhat, a solution sometimes deployed in humanitarian demining theatres. Two different versions of each style were developed, each employing slightly different concepts in construction and design, in order to evaluate a larger number of possible solutions for providing head and facial protection. Another layout tested is a system commonly used by military forces engaged in demining, where a standard military PASGT-style helmet is worn in combination with a set of safety goggles for protecting the eyes. As a benchmark for assessing the effectiveness of the different head protective systems, tests were also conducted with unprotected mannequins exposed to identical blast conditions.

RESULTS

BLAST INDUCED HEAD ACCELERATION: When the head of a victim is subjected to a sudden and violent loading, such as that produced by the blast wave generated from a detonating mine (or other explosive device), it is postulated that a range of closed head concussive injuries can result, ranging from minor to unsurvivable. Figure 2a illustrates the individual (x-, y-, z-) components of induced acceleration and resultant, measured from the head of an unprotected mannequin facing a simulated mine containing 200 g C4, placed at 0.80 m from its nose. It can be discerned that the dominant contribution to the overall resultant acceleration in the initial loading phase is found in the x-direction (anterior-posterior), i.e., the dominant direction of blast propagation, which one would intuitively consider to be more significant than an acceleration in lateral (y-) or vertical (z-) directions. When the mannequin is fitted with protective gear, the reduction in resultant acceleration is created primarily by a reduction in the x-component. Although the Hybrid II neck is not biofidelic, the relatively short durations associated with the initial blast interaction and head response result in the essential decoupling of the head from the body. Even very large accelerations, occurring over 1 ms do not produce significant displacements of the head (Example, 1000 g acceleration for 1 ms produces an implied motion of about 5 mm, not all will be differential between the head and neck, so the effect of neck compliance is limited).

Figure 2b presents typical resultant acceleration traces experienced by the mannequin's head, wearing different helmets in the same position and exposed to the blast from a simulated mine with 200 g C4. A sharp jump in the acceleration experienced is observed for the unprotected case, "No

Helmet", i.e., 588 g's. This value can be greatly reduced when appropriate protective gear is worn, as evidenced from the traces of the mannequin wearing an HDH-1 (87 g's) and Sport-1 helmet (277 g's). The factors attributed to this dramatic reduction include the presence of a *full-faced visor* to aerodynamically deflect the blast wave, a suitable retention system, and the deflection and energy absorption of the helmet components. The design of the HDE Demining Ensemble also contributes in reducing the head loading through the flared out rigid chest plate in the front of the jacket which interfaces with the bottom of the full-faced visor fitting behind it. This feature prevents the blast from entering and directly loading the facial region. If an open-faced PASGT-style helmet is worn with protective goggles, the peak acceleration measured can actually be higher than that measured when wearing no protection (i.e., 798 g's) and is drastically higher than that measured for the HDH-1 and Sport-1 helmets at the same blast conditions. It is proposed that the absence of a full-faced visor and the flared-out ear cups of the PASGT-style helmet design, result in a poor aerodynamic interaction, resulting in an augmentation of the induced head acceleration, despite the increase in total mass of the head system over the unprotected case.

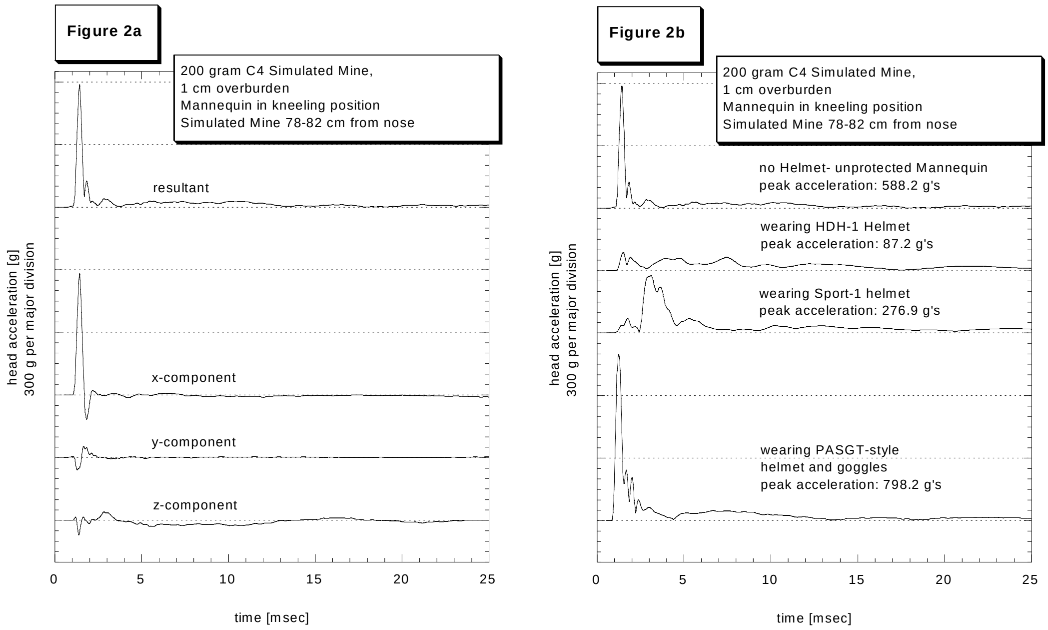


Figure 2 – a) components and resultant head acceleration, b) resultant head acceleration for mannequins wearing different protective equipment

Figure 3 illustrates that as the explosive threat in the AP mine is increased from 50 g to 100 g to 200 g C4, the resultant head acceleration experienced also increased for all helmet configurations tested. In comparing the average peak head acceleration measured among the different helmet options, and across the range of AP mine threat sizes, as presented in Fig. 3, it is apparent that the HDH helmets were most effective in attenuating the head accelerations transmitted to the head, followed by the Sport helmets (permitting for some scatter in the data). From the full-faced visor options tested, the Hardhats, as a group, performed the poorest in reducing the acceleration. Facing 100 and 200 grams of C4, it is apparent that wearing a helmet with no visor (PASGT-style helmet with goggles) can be worse than wearing nothing at all, from the perspective of frontal blast-induced head acceleration experienced.

INJURY CRITERIA

A simple surrogate for the force experienced by the mannequin head is peak resultant center of gravity head acceleration. This surrogate has the twin advantages of being easily measured and easily calculated. Support for this injury measure comes in 29 helmet standards in the AGARD Advisory Report on Dummies for Crash Testing [AGARD, 1996**]**. These standards are largely based on requirements from motor vehicle and cycling impacts. Eighteen of these standards incorporate a fixed acceleration or force limit. Another ten use an acceleration criterion with some duration limits. These duration limits include the use of the Gadd Severity Index (GSI) [Gadd, 1966], a combined injury criterion using an average acceleration and a time duration similar to the HIC. Though the applicability of these standards to a blast environment is uncertain, the more recent fixed acceleration standards incorporate a 300 g threshold for injury (this threshold is indicated in Fig. 3).

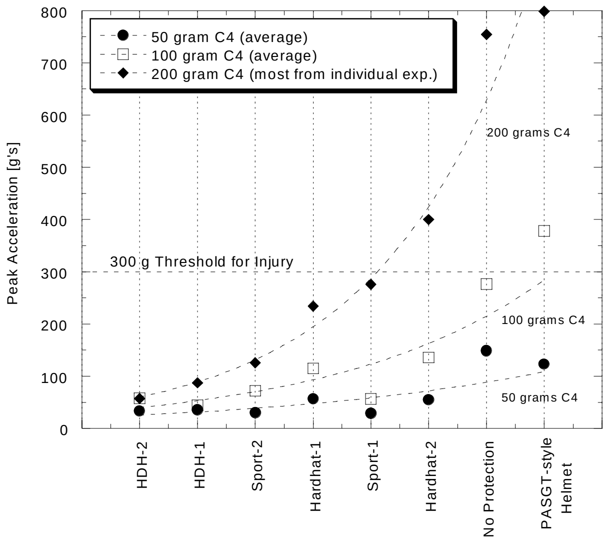


Figure 3 – Average peak resultant acceleration, measured at center of gravity of mannequin's head. Mannequins in kneeling position, facing simulated mines of 50, 100 and 200 gram C4, 0.78-0.82 m from head (at nose)

HEAD INJURY CRITERION: For the purposes of the present investigation, it was deemed necessary to use a criterion for head injury assessment that includes the peak resultant acceleration and duration. In attempting to determine the duration of the resultant acceleration traces computed, there can exist considerable ambiguity in identifying the pertinent duration of the signal that should be considered in an injury assessment evaluation. The Head Injury Criterion, or HIC, developed by Versace (1971), is described by the following expression:

$$HIC = \max\left\{(t_2 - t_1)\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}\right\}$$

where t_1 and t_2 are the initial and final times during which the HIC attains a maximum value, and $a(t)$ is the resultant acceleration measured at the centre of gravity of the head. In this study the HIC_{15} is being employed where the maximum time interval between t_1 and t_2 is 15 ms. By integrating the acceleration trace over a specific time interval, this criterion has the advantage of taking into account the duration of the acceleration pulse. Moreover, by imposing the maximum condition, it is ensured that the HIC calculation takes into account only the duration of interest in the acceleration pulse.

Figure 4 presents graphical examples of the calculation of a HIC_{15} value from the resultant acceleration traces computed from two separate tests, along with the corresponding t_1 and t_2 used for the calculation. Figure 4a corresponds to the top trace in Fig. 2b where the mannequin was not wearing any head protection. In this case, the peak acceleration measured was 588.2 g's with a corresponding HIC_{15} value of 1536.6. The time duration over which the integration was performed is indicated by the vertical dashed lines, and in this case was 0.324 ms. Figure 4b corresponds to the second trace in Fig. 2b in which the mannequin was wearing the HDH-1 helmet. In this example the peak acceleration was 87.2 g's and the HIC_{15} value was 95.3; the interval of integration was 13.73 ms. Figure 5 provides a summary of the average HIC_{15} values calculated for all of the experiments performed for this study. It can be discerned that when facing the simulated mines containing 50 and

100 g C4, that the HIC_{15} value tends to be well below 500 for almost all head protection systems tested, while for the simulated mine with 200 g C4 the HIC_{15} values are significantly higher. Injury severity increases non-linearly with HIC_{15} value, thus a larger HIC_{15} would imply less protection offered, or conversely a higher probability for incurring life-threatening head concussion injuries.

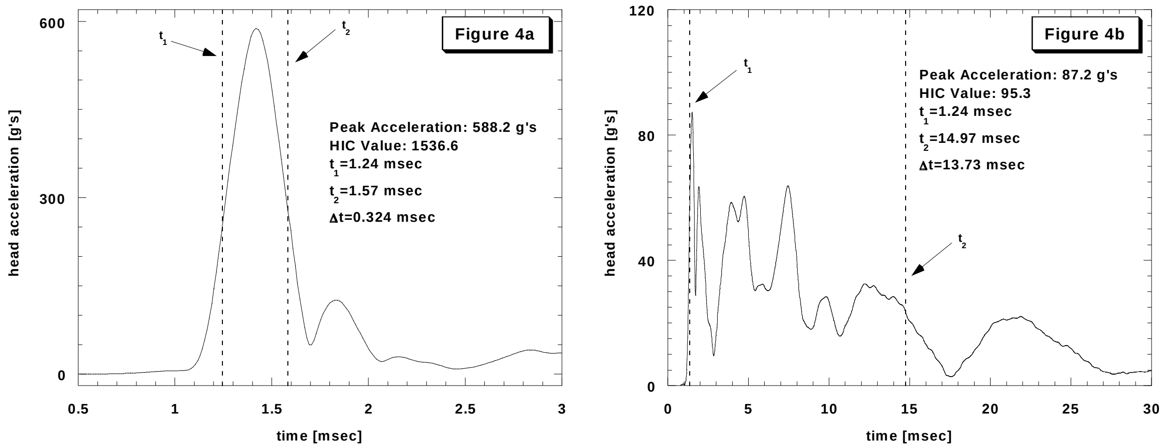
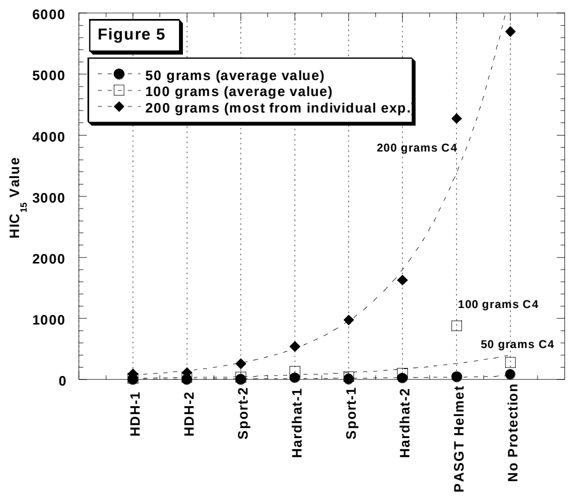


Figure 4– Sample HIC_{15} calculations. a) for unprotected mannequin facing 200 g C4, b) for mannequin donning HDH-1 helmet facing 200 g C4 (same as top and second traces in Fig. 2b)

In order to relate HIC_{15} values to potential for injury, the expanded Prasad/Mertz probability curves have been utilized [Prasad, 1985]. These are plotted in Fig. 6. In principle, for a particular HIC_{15} value, there exists a probability of incurring all injury severity levels, denoted by the Maximum AIS scale (MAIS), albeit at very different amounts, due to the asymptotic nature of the functions.



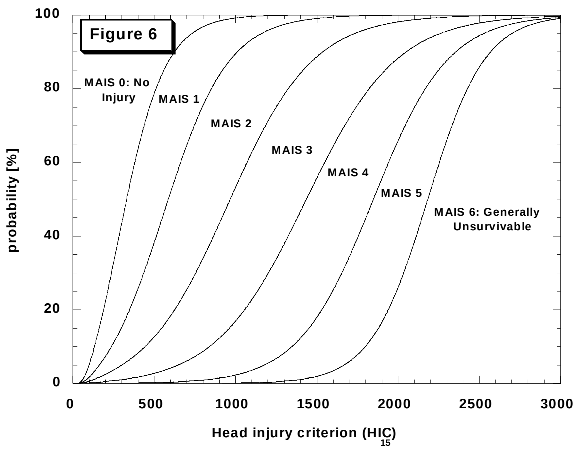


Figure 5– Average HIC_{15} value calculated for acceleration measured at center of gravity of mannequin's head. Mannequins in kneeling position, facing simulated mines of 50, 100 and 200 gram C4, 0.78-0.82 m from head (at nose)

Figure 6– Prasad/Mertz probability curves

HEAD INJURY POTENTIAL

Using the HIC_{15} and the Prasad/Mertz curves, the probability of injury severities (MAIS) are presented in Table 1 for the case when the mannequins faced the blast from simulated mines containing 200 g C4. For purposes of illustration, the case of the 200 g C4 mine is highlighted over the smaller mines since the HIC_{15} values span a much greater range (i.e.,0-6000), than when the mannequins faced the 50 and 100 g C4 simulated mines (refer to Fig. 5). For each helmet type listed in Table 1, the corresponding peak value of acceleration is listed along with the corresponding HIC_{15} value. The helmets listed on the left hand side of the table are in approximate order of increasing peak g-level and HIC_{15} value. In most cases, these values correspond to a single experiment, except where indicated. The probability distribution of the injury severities that can be sustained are tabulated in columns.

In general, and in agreement with Fig. 3, it can be seen that the use of a stable helmet with a full face visor greatly reduces the potential for injury. In reference to the results for the mannequin wearing the HDH helmets (versions -1 and -2), it can be seen by using the HIC_{15} calculation and the Prasad/Mertz curves, that there is over 93% probability that no injury (MAIS0) would be sustained for the acceleration experienced. At the other extreme, when wearing no protection, or wearing the PASGT-style helmet with no visor, the HIC_{15} values are high enough so as to create a 100% probability of a fatal injury.

	Peak Accel. [g's]	HIC_{15} Value	Injury Potential Based on HIC Value and Prasad/Mertz Curves						
			MAIS0	**MAIS1**	**MAIS2**	**MAIS3**	**MAIS4**	**MAIS5**	**MAIS6**
HDH-1	87	95	95.4	3.0	1.0	0.5	0.1	0.0	0.0
HDH-2	57	112	93.1	4.6	1.5	0.6	0.2	0.0	0.0
Sport-1	277	977	1.0	10.7	37.3	35.2	13.7	2.0	0.1
Sport-2	126	261	64.8	23.2	8.0	3.1	0.8	0.1	0.0
Hardhat-1	234	544	16.4	39.3	29.3	11.6	3.1	0.3	0.0
Hardhat-2	400	1628	0.0	0.5	6.8	26.1	38.9	23.7	4.0
PASGT -no visor	799	4276	0.0	0.0	0.0	0.0	0.0	0.0	100
No helmet	754(avg.)	5696 (avg.)	0.0	0.0	0.0	0.0	0.0	0.0	100

Table 1 – HIC_{15} values and associated probability of injury, for mannequins facing 200 g C4 simulated mine, 0.78-0.82 m from nose.

Of interest, with respect to the performance of the HDH helmets, is that the HDH-2 experienced a lower g-level than the HDH-1,while its HIC_{15} value was actually higher. This points to the sophistication of the HIC_{15} method which takes into account the associated time duration of the accelerative loading of the head. Despite having a lower peak g-level, the duration and shape of the pulse made the acceleration experienced more injurious (higher HIC_{15} value). The lack of consideration of the duration of the loading in estimating the injury potential appears to be a shortcoming of using a injury criterion based on peak acceleration only.

	Peak Accel. [g's]	HIC_{15} Value	Injury Potential Based on HIC Value and Prasad/Mertz Curves						
			MAIS0	**MAIS1**	**MAIS2**	**MAIS3**	**MAIS4**	**MAIS5**	**MAIS6**
PASGT 50 g C4	123	42	99.8	0.2	0.1	0.0	0.0	0.0	0.0
PASGT 100 g C4	378	883	1.8	15.7	40.7	30.1	10.2	1.3	0.1
PASGT 200 g C4	799	4276	0.0	0.0	0.0	0.0	0.0	0.0	100
No helmet 50 g C4	149 (avg.)	82 (avg.)	96.9	2.0	0.7	0.3	0.1	0.0	0.0
No helmet 100 g C4	276 (avg.)	279 (avg.)	60.9	25.6	9.0	3.5	0.9	0.1	0.0
No helmet 200 g C4	754 (avg.)	5696 (avg.)	0.0	0.0	0.0	0.0	0.0	0.0	100

Table 2 – HIC_{15} values and associated probability of injury, for mannequins facing 50, 100, & 200 g C4 simulated mines, 0.78-0.82 m from nose.

The Sport helmets were the best performing helmets after the HDH helmets in providing protection against blast-induced head acceleration. For the Sport-1 helmet, the HIC_{15} in combination with the Prasad/Mertz curves indicate that there is a very high probability of a head concussive injury with a 72% chance of either a moderate or serious injury occurring (MAIS2 / MAIS3), but with only a 2% likelihood of a critical injury (MAIS5). Wearing the Sport-2 helmet resulted in a much lower peak acceleration, a lower HIC_{15} value, and a lower probability of injury than the Sport-1, as a 65% certainty of no injury (MAIS0) is predicted.

The Hardhat helmets were the poorest performing helmets overall, of the helmets which have a full face visor. There is a likelihood that some level of injury would be sustained while wearing the Hardhat-1 as there is a 39% probability of a MAIS1 injury, and 29% chance of a MAIS2. The response while wearing the Hardhat-2 is certain of creating some level of injury, as there is a 0% chance of a MAIS0, and a 26%, 39%, and 24% chance of an MAIS3, MAIS4, or MAIS5 injury, respectively.

The injury analysis presented thus far is based entirely for the situation when the kneeling mannequin faces the blast loading from the detonation of surrogate blast type AP mines containing 200 g of high explosive, representing the largest blast type AP mine threat. If the explosive content of the surrogate mines is reduced, one would expect a significant decrease in the accelerative loading of the mannequin's head and thus a reduction in the overall head injury potential. This is illustrated in Table 3, where the head injury probability distributions are presented, for the case of the kneeling mannequin wearing the PASGT-style helmet, as well as the non-helmeted (unprotected) head, as a function of the explosive content of the surrogate mines, i.e., 50, 100, and 200 g C4. A reduction in the explosive content from 200 g C4, results in survivable outcomes for both the PASGT-style helmet and the non-helmeted head when employing the HIC_{15} and Prasad/Mertz curves. The HIC_{15} value for the non-helmeted mannequin, would indicate a 61% probability of no injury being experienced at 100 g C4. For the smallest of the mines tested, containing 50 g C4, HIC_{15} values indicate that there would not likely be any injury sustained from blast-induced head acceleration, with a probability of at least 97% for the unprotected surrogate and 99% for one wearing an open-faced PASGT-style helmet.

Table 2 clearly illustrates the effect of mine size, i.e., explosive content, on injury severity that may be experienced. Although the data would suggest that the 50 g charge does not appear to pose a serious threat to the deminer from the perspective of head concussion, the injury outcome could increase drastically if the stand-off distance between the deminer and the mine was reduced. An augmentation in the HIC_{15} may also be achieved through a change in the position of the mannequin, from kneeling to one where the head would find itself receiving a higher blast loading. Studies are currently underway to investigate the effects of stand-off distance and demining position for different blast AP mines.

Recent injury data collected from accidents involving deminers [Dept. of Defense, 2000] would suggest that fatalities from blast-induced head accelerations are not common, despite the relatively low level of head and facial protection worn, if any. Although there are many limitations concerning the reliability of the injury data reported, e.g., accurate reporting of the relative position of the deminer with respect to the blast, initial conditions, etc., it would appear that the HIC_{15} may be suitable in the context of demining. Further analysis of the injury data is required to advance the understanding of head injury beyond this initial study.

SPECTRAL ANALYSIS OF HEAD ACCELERATION

Explosive blasts from the detonation of ordnance or AP mines are intrinsically high rate events. To determine the effect of potential high frequency content in these tests, a spectral analysis was performed for the test results which are presented in Tables 1&2. The power spectral density was calculated from the unfiltered x-component (anterior-posterior) of the head acceleration measured at the center of gravity of the head. As discussed above, the x-component of the acceleration is the dominant component in these frontal blast impacts.

Representative plots of power spectral density for tests with the mannequin wearing an HDH-1 helmet, a Sport-1 helmet, and No Helmet are shown in Figs. 7a, b, & c, respectively. For the HDH-1 helmet, the head acceleration occurred over a relatively long time period (approximately 10 ms). This limited the appearance of spectral components above 1000 Hz and produced a power spectrum with a relatively steep roll-off. In contrast, a representative power spectrum of the head acceleration seen with the Sport-1 helmet in Fig. 7b shows much more high frequency spectral power. Indeed, the peak power spectral density occurs at approximately 5 kHz. The x-acceleration trace for this test shows a large oscillatory acceleration event occurring over approximately 5 ms. Furthermore, the representative test with No Helmet whose spectral response is shown in Fig. 7c, has substantial power spectral density to nearly the Nyquist cutoff (41.6 kHz). With no helmet, blast impingement directly on the mannequin head causes a very sharp head x-acceleration of approximately 0.8 ms duration.

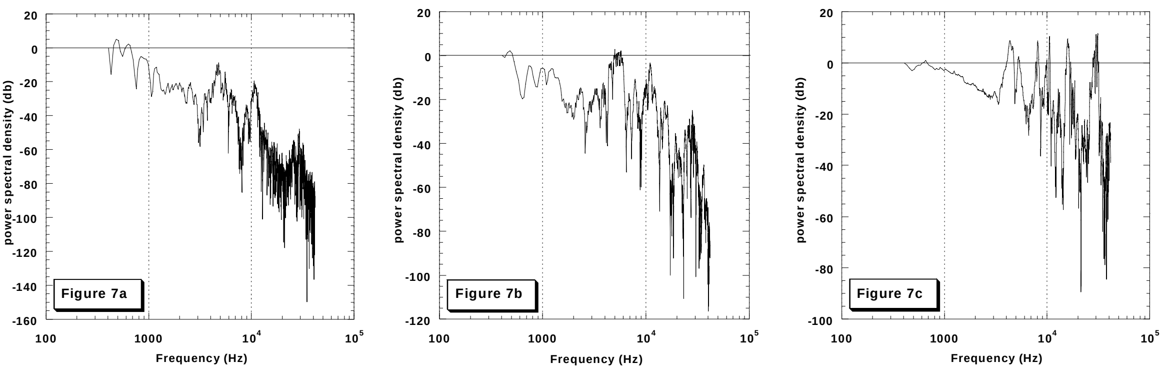


Figure 7—Power spectral density vs. frequency; a) for HDH-1 helmet facing 200 g C4, b) for Sport-1 helmet facing 200 g C4, c) for unprotected mannequin (no helmet) facing 100 g C4

It is the difference in the duration of the blast/structure interaction that determines, to a large extent, the frequency dependence of the power spectrum. The frequency of peak spectral power density is shown in Fig. 8 for several tests with charges of 50 g C4, 100 g C4, and 200 g C4. It is clear from the figure that, peak spectral power can occur at frequencies of greater than 10 kHz. Both the HDH helmet and the Hardhat helmet showed power spectrum peaks that were consistently below 1000 Hz. In contrast, the Sport helmet and the mannequin head with no helmet showed power spectrum peaks significantly above 1000 Hz.

Within the tests of the PASGT-style helmet, the peak spectral power tends to fall with strength of the blast from 200 g C4 down to 50 g C4. This might be expected from the decreased strength of the blast for the smaller charges; less powerful blasts decrease the frequency of the response . However, this was not observed for the mannequin wearing no helmet. This behaviour of the power spectrum peak in the unprotected mannequin may be the result of structural resonance in the Hybrid II skull or may be the effect of dynamic forcing and unstable local gas-dynamic effects on the head.

These results have implications in the calculation of standard injury functions using mannequin components. The HIC function is calculated for the mannequin center of gravity using acceleration components that have been filtered with a CFC 1000 filter (3 dB rolloff at 1650 Hz). However, nine of seventeen tests at all levels of blast intensity shown in Fig. 8 have peak spectral power more than an octave above 1650 Hz. This suggests that the CFC 1000 filter may have an uncontrolled effect between tests. Further, the base rate of data sampling is 83.3 kHz which implies a Nyquist cutoff frequency of 41.6 kHz. The existence of substantial spectral power in frequencies 20 kHz and above for some test cases suggests that there might be a need for anti-aliasing filtering before digitizing the acceleration sensor output.

Table 3 indicates the HIC_{15} and peak acceleration values for the Sport-1 and the HDH-1 helmets obtained using different filter frequencies. For the HDH-1 helmet case, where the peak spectral power is below 1650 Hz, the filter cut-off frequency is found to have a minimal effect on the calculated HIC_{15} and peak acceleration values. For the Sport-1 helmet case, on the other hand, the value of the HIC_{15} is found to be extremely sensitive to the filter cut-off frequency. This is due to the presence of large spectral powers at high frequencies of the order of 5000 to 10000 Hz. This implies that although the HIC_{15} calculation using a 1650 Hz cut-off frequency seems appropriate for the HDH-1 helmet case, a larger cut-off frequency may have to be selected to filter the Sport-1 helmet signals. This is necessary to account for important parts of the signal at high frequencies, so that the HIC_{15} calculation using a 1650 Hz filter cut-off frequency may still be relevant in tests where large spectral powers at high frequencies are observed.

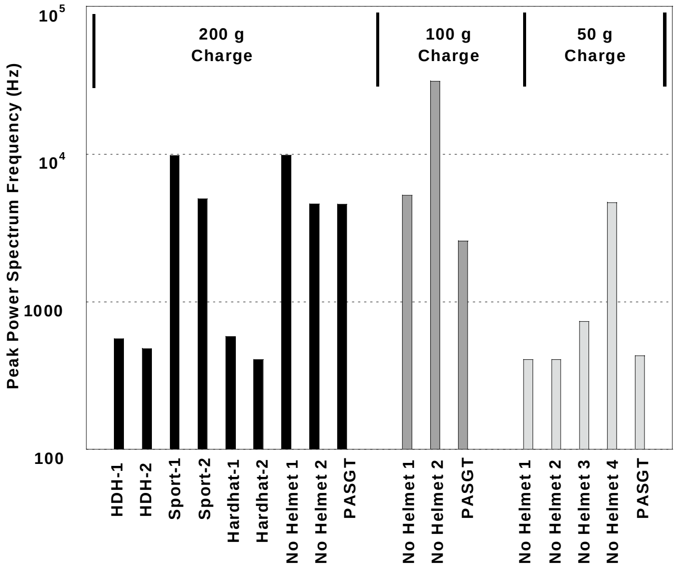


Figure 8— Peak power spectral density frequency of mannequin head center of gravity x-acceleration

The effect of strains in human brains implied by acceleration at frequencies higher than 10 kHz is unknown. The implied strains from 10 kHz forcing are relatively small, even from very large acceleration levels. For instance, the implied displacement for a 10 kHz half sine acceleration of 2000 g peak is approximately 0.06 mm. It is not clear whether this strain is injurious at such a rate, nor whether the response of a human head will be similar. Skull natural frequencies have been measured between 1385 and 4792 Hz [Khali, 1979]. However, the flesh and brain of the human head is likely to act as a well damped low pass filter for such high frequency excitation.

	HDH-1 Helmet (200 g C4)		**Sport-1 Helmet (200 g C4)**	
Filtering Frequency	**Peak Accel. [g's]**	**HIC_{15}**	**Peak Accel. [g's]**	**HIC_{15}**
1650	87	95	277	977
5000	116	107	587	1255
10000	120	111	1083	3081
20000	120	112	1270	8804

Table 3—Effect of filtering frequency on peak acceleration and calculated HIC_{15} value

CONCLUSIONS

Through the use of instrumented anthropomorphic mannequins, placed in representative demining positions using an innovative test rig, a systematic investigation of the accelerative effects of a mine detonation on the head of a deminer has been performed. Results indicate the paramount importance of wearing a full face visor attached to a stable helmet platform in order to dramatically reduce the peak head acceleration induced by the blast. Wearing a helmet without a visor has been demonstrated to provide no better protection against blast induced acceleration than wearing no protection at all.

In order to evaluate the potential for injury associated with the accelerations experienced, the HIC_{15} has been calculated for the measured acceleration histories. It was shown that when facing the range of blast type AP mines containing smaller amounts of explosive (50 and 100 g C4), the experienced accelerations present a relatively low probability for a life-threatening head concussive injury, as the HIC values calculated were sufficiently low. However, facing the 200 g C4 simulated mine, the HIC values would suggest a significant possibility of life-threatening head injuries, depending on the equipment donned. Wearing no helmet, or a helmet with no visor, was found to be fatal based on the HIC_{15} values calculated for the larger blast type AP mines. The injury predictions afforded by the HIC_{15}, combined with the Prasad/Mertz curves, seem to be consistent with injury data collected from accidents involving deminers. The results would suggest that a larger blast loading to the head, accomplished through either explosive content, proximity to the mine, or positioning may make the difference between a non-injurious situation, or a life threatening head acceleration injury.

A spectral analysis of the measured acceleration traces was performed in order to further understand the nature of the blast induced head acceleration. In several traces it was observed that the greatest spectral density was found to be well above the frequency used for filtering. The existence of substantial spectral power in frequencies 20 kHz and above for some test cases suggests that there might be a need for anti-aliasing filtering before digitizing the acceleration sensor output. Furthermore, the selection of the appropriate filtering frequency may have to be further investigated. In the cases where there is high spectral power at high frequencies, the filtering frequency can have a significant effect on both the peak acceleration and the HIC_{15} value. The importance and effect of these higher frequencies on humans is not understood and needs further investigation.

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