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ORIGINAL ARTICLE

Acceleration-based methodology to assess the blast mitigation performance of explosive ordnance disposal helmets

J. P. Dionne[1] · J. Levine[1] · A. Makris[1]

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Abstract To design the next generation of blast mitigation helmets that offer increasing levels of protection against explosive devices, manufacturers must be able to rely on appropriate test methodologies and human surrogates that will differentiate the performance level of various helmet solutions and ensure user safety. Ideally, such test methodologies and associated injury thresholds should be based on widely accepted injury criteria relevant within the context of blast. Unfortunately, even though significant research has taken place over the last decade in the area of blast neurotrauma, there currently exists no agreement in terms of injury mechanisms for blast-induced traumatic brain injury. In absence of such widely accepted test methods and injury criteria, the current study presents a specific blast test methodology focusing on explosive ordnance disposal protective equipment, involving the readily available Hybrid III mannequin, initially developed for the automotive industry. The unlikely applicability of the associated brain injury criteria (based on both linear and rotational head acceleration) is discussed in the context of blast. Test results encompassing a large number of blast configurations and personal protective equipment are presented, emphasizing the possibility to develop useful correlations between blast parameters, such as the scaled distance, and mannequin engineering measurements (head acceleration). Suggestions are put forward for a practical standardized blast testing methodology taking into account limitations in the applicability of acceleration-based injury criteria as well as the inherent variability in blast testing results.

Keywords Blast · Traumatic brain injury (TBI) · Personal protective equipment (PPE) · Helmet · Test methodologies · EOD

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✉ J. P. Dionne
Jean-Philippe.Dionne@safariland.com

[1] Med-Eng, 2400 St. Laurent Blvd., Ottawa, ON K1G 6C4, Canada

1 Introduction

While the precise mechanism of blast-induced traumatic brain injury is not yet well known, some mechanisms have been investigated, such as skull flexure, the propagation of compression waves in the skull tissue resulting from the blast pressure field acting on the head [1,2], or the induction of brain impairment through whole-body or local (chest) exposure to blast overpressure [3]. Measurements of head global kinematics, while not necessarily directly linked to the mechanism for traumatic brain injury, may nevertheless be a relevant predictor for the level of blast injury severity to the brain [4]. Linear acceleration is extensively used to quantify global head kinematics, and a number of injury criteria are based directly on linear head acceleration, such as the Head Injury Criterion (HIC) [5]. Rotational acceleration has also been deemed to be relevant to traumatic brain injury [6], and a number of injury criteria have been developed over the years based on rotational head data, specifically the works of Ommaya [7], Thibault and Gennarelli [8], the Generalized Acceleration Model for Brain Injury Tolerance (GAMBIT) [9], the Head Impact Power Index (HIP) [10,11], and, most recently, the Brain Injury Criterion (BrIC) [12].

However, the criteria listed above have only been validated for blunt impacts, not for blast loading. Specifically for blast, more sophisticated test rigs have been developed over the last few years including BI^{2}PED [13] and GelMan

[14]. These involve more realistic headforms which simulate the brain, and when equipped with internal pressure transducers or other internal sensors (e.g., accelerometers), may yield more biofidelic responses. Unfortunately, none of these test rigs are widely available, and no blast injury assessments can yet be made from them.

As such, it is not currently possible to assess head injury in the context of blast with a high level of confidence. Nevertheless, it can be assumed that increases in the level of blast exposure (e.g., peak overpressure, maximum blast impulse), which results in higher head loading (e.g., higher head acceleration or HIC value), will likely translate into more severe injuries. For instance, if Helmet A results in a HIC value lower than Helmet B in the same blast configuration, it can be assumed that Helmet A performs better than Helmet B. Alternatively, if a higher HIC value is obtained in blast configuration A than for blast configuration B (everything else being equal), then it can be assumed that configuration A is more dangerous than configuration B in terms of traumatic brain injury. The use of non-validated injury criteria in the context of blast can then be viewed as a way to quantify the blast loading, rather than to offer actual injury predictions and assessments.

For personal protective equipment (PPE) manufacturers, it is critical to be able to compare the effectiveness of protective components such as helmets, so that the next generation of protection being designed and built can be trusted to provide the enhanced protection desired. Given the lack of agreement on blast-induced traumatic brain injury mechanisms, it is understood that accurate injury predictions are not possible.

Standardized test methodologies for the evaluation of personal protective equipment under blast loading must be reproducible, reliable, accurate, and involve test rigs that are readily accessible to multiple test laboratories. Moreover, they need to allow actual helmet systems to be subjected to a representative loading, so that full helmet systems, including the retention system and padding, can be appropriately evaluated.

The recently released National Institute of Justice (NIJ) 0117.01 standard [15] for Public Safety Bomb Suits does incorporate a blast test requirement, which calls for the use of a Hybrid III mannequin supported in a kneeling position through a test rig. The standard also specifies a blast configuration (spherical 0.567 kg of C4 explosive, located 0.6 m away from the sternum, at a height of burst of 77 cm). However, the NIJ 0117.01 standard only involves a qualitative assessment of the performance of a bomb suit (referred to as blast integrity). As such, there currently exists no accepted standardized test methodology to quantify the performance of helmets at mitigating blast-induced traumatic brain injury.

The purpose of this paper is thus to present a quantitative test methodology aimed at evaluating the performance of blast protective helmets in the context of explosive ordnance disposal (EOD) operations. As suggested in NIJ 0117.01, the test method presented makes use of a Hybrid III mannequin, which allows for helmets to be worn in a realistic fashion (keeping in mind the limitations with the biofidelity of the Hybrid III chin), on a mannequin which is at least representative of a human body from the point of view of size, weight, and weight distribution, and that can readily be instrumented at various locations. More specifically, the paper will investigate measurements made directly at the head level: linear head acceleration and rotational head acceleration.

2 PPE blast test methodology

2.1 Hybrid III mannequins and test rigs

The Hybrid III anthropomorphic mannequin was originally developed for the automotive industry, and more specifically, for front-facing crashes. It exists in various sizes (e.g., 5th percentile female, 50th percentile male and 95th percentile male). In the current study, all tests have been conducted with the 50th percentile male version [16] (height: 1.75 m, mass: 77 kg, Fig. 1). For the purpose of blast tests, mannequins are placed on specially designed positioning apparatuses. They are supported under the arms in either an upright kneeling or standing position (Figs. 2, 3). These stands allow the mannequins to fall freely back due to the force of the explosion, thus not interfering with their initial natural response. Only frontal blast exposures were tested, in line with Standard Operating Procedures for bomb technicians facing explosive charges. To provide a baseline by which helmet protective performance can be quantified, unprotected tests were also carried out with the mannequins wearing no protective equipment (Fig. 4).

2.2 Instrumentation and data acquisition

To quantify helmet performance, the mannequins were instrumented with linear and rotational accelerometers (Fig. 5). A triaxial cluster of linear accelerometers was located in the head's centre-of-gravity. The accelerometers were mounted such that values were recorded in three directions: front-and-back (X), side-to-side (Y), and up-and-down (Z). Three rotational accelerometers were also mounted at the head's centre-of-gravity, measuring accelerations about all three axes. In all trials, the instrumentation lines were connected via appropriate power supplies and signal conditioning equipment to a computerized data acquisition system (set to sampling rates ranging from 200 kHz to 1 MHz). The signals from the accelerometers mounted in the head, both linear and rotational, were filtered using a four-pole Butterworth filter set to attenuate signals above 1650 Hz, in

Fig. 1 Hybrid III anthropomorphic mannequin used for blast testing. Humanetics ATD, Huron, OH, USA

Fig. 2 Hybrid III mannequin held in a standing position (explosive ordnance disposal ensemble)

accordance with known standards used in the automotive industry to relate measurements made with mannequins to human injury (SAE J211-1 [17]). The accelerometers themselves have an on-board electrical filter with a −3 dB corner frequency of 13 kHz.

Fig. 3 Hybrid III mannequin held in a kneeling position (explosive ordnance disposal ensemble)

Fig. 4 Unprotected Hybrid III mannequin blast tests. Mannequin donning civilian apparel

2.3 Blast test configurations

For this paper, the data from more than 400 separate experimental blast trials were aggregated. In total, 10 charge sizes were used. The surrogates were placed at a variety of standoff distances, either in a kneeling or standing posture.

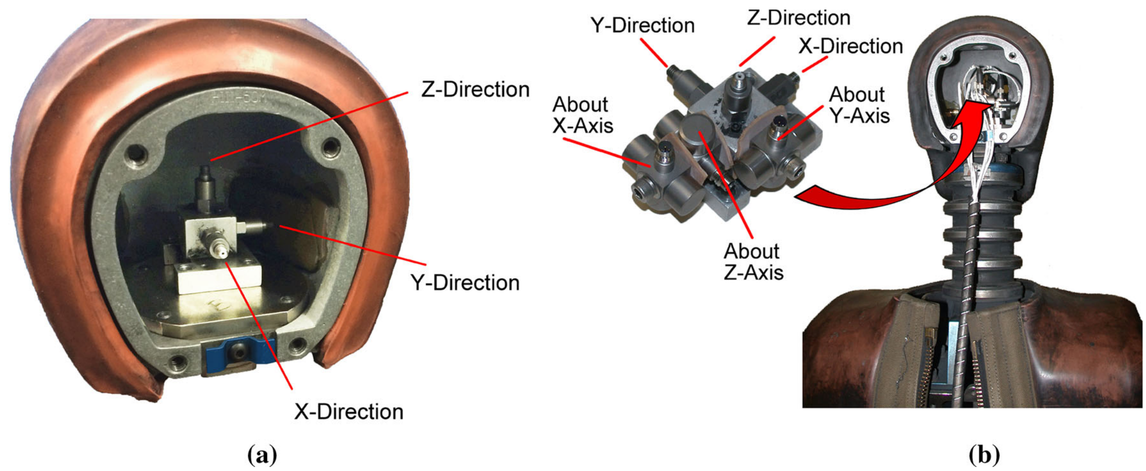


Fig. 5 **a** Linear and **b** rotational accelerometers sets mounted in Hybrid III Head

Humanitarian demining test scenarios (example on Fig. 6) involved small charges (ranging from 50 to 200 g of C4 explosives), while explosive ordnance disposal tests involved larger charges, up to 20 kg of C4 explosive. While most tests were conducted outdoors (MREL, Sharbot Lake, Canada, DRDC Valcartier, Shannon, Canada, or DRDC Suffield, Ralston, Canada), some tests were conducted indoors, at the Canadian Explosive Research Laboratory (CERL, Ottawa, Canada, see Fig. 7). Figure 8 provides a graphical summary of the charge configurations tested.

It should be noted that while the NIJ 0117.01 standard setup (Fig. 6b) suggests a single blast configuration involving a relatively small charge (0.567 kg of C4 explosive) at arm's length (0.6 m standoff), it is also important to evaluate the performance of EOD ensembles against larger explosives at larger standoff distances (e.g., 3.0 m, typical of standoff tools used by EOD technicians). Bomb suits must provide protection against a wide range of blast threats involving both high overpressure and high maximum blast impulse (defined as the area under the pressure-time curve). Figure 9 compares the blast overpressure and maximum blast impulse for a few representative blast scenarios of interest for EOD protection. Although this paper includes some discussions on humanitarian demining blast testing, the focus is on scenarios more typical of explosive ordnance disposal.

3 Blast test results

3.1 Quantifying blast loading through rotational acceleration

Rotational acceleration has often been deemed to be relevant to traumatic brain injury [6], and a number of injury criteria have been developed over the years based on rotational head data, specifically the works of Ommaya [7], Thibault and Gennarelli [8], the Generalized Acceleration Model for Brain Injury Tolerance (GAMBIT) [9], the Head Impact Power Index (HIP) [10,11], and the BrIC [12]. However, these criteria have been validated for blunt impacts, not for blast loading.

Rotational motion can be measured using a set of linear accelerometers, such as the Six Accelerometer Package (SAP) [19], or the Nine Acceleration Package (NAP) [20]. However, blast testing is characterized by high-frequency vibrations which can cause issues when computing rotational accelerations based on a set of linear accelerometers (see Fig. 10). This occurs as vibrational noise gets amplified when multiple signals are combined to compute the rotational accelerations. As such, a more direct measure of rotational motion, which minimizes the number of sensors to be used and some of the associated processing challenges, is preferred for blast conditions.

In a previous study investigating the relevance of rotational acceleration measurements for both blunt impacts and blast exposure [21], it was found that linear acceleration data and rotational acceleration data correlated well with each other, for the specific conditions tested, relevant to EOD operations. The same observation was made when comparing their respective injury prediction models, the HIC (obtained from linear acceleration) and the HIP or BrIC (obtained from rotational acceleration). This suggests that little new additional information is obtained from measuring both linear and rotational head accelerations. And, as linear accelerations are simpler to measure and process, head rotational acceleration is not further discussed in the present paper. All attention is focused on linear head acceleration measurements.

3.2 Quantifying the blast loading through linear head acceleration

While there exist other head injury criteria based on linear head acceleration, the most commonly used one is the

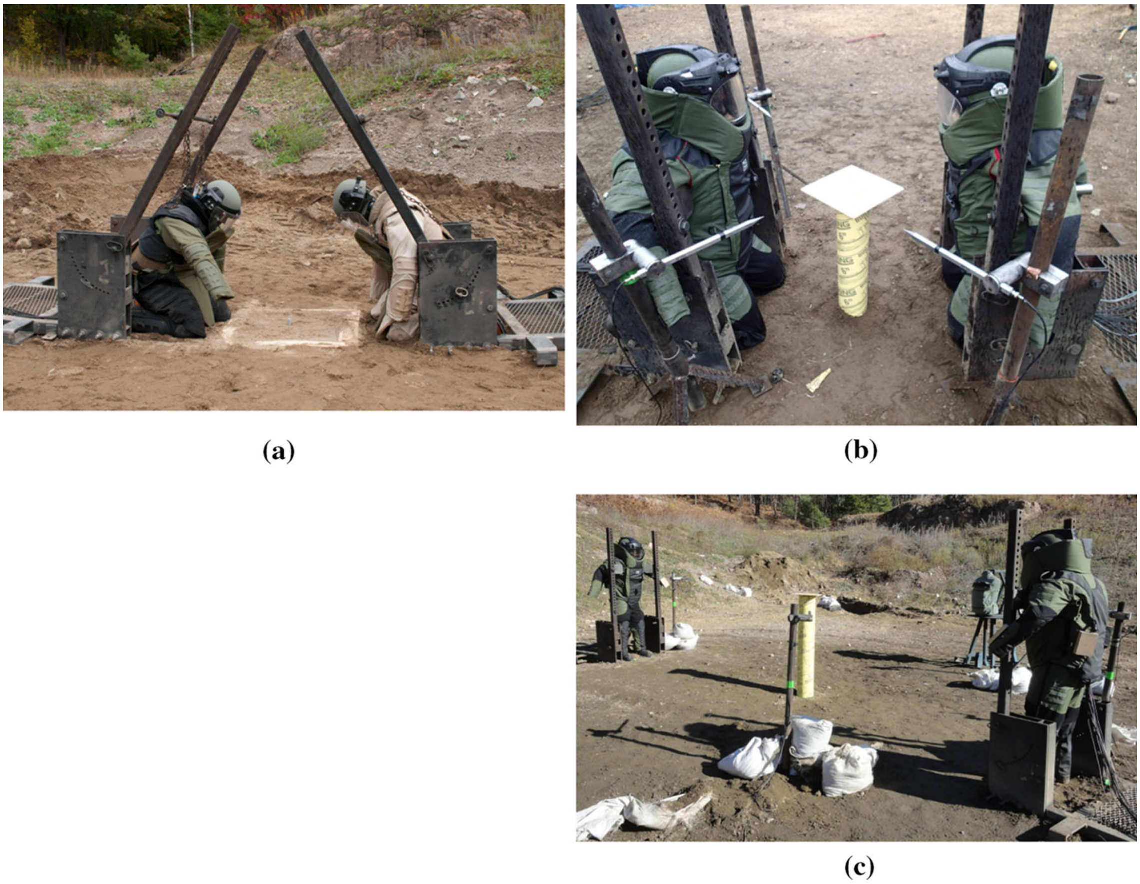


Fig. 6 **a** Humanitarian demining and **b**, **c** explosive ordnance disposal test examples

Fig. 7 Indoor blast chamber test example (CERL, Ottawa, Canada) with an explosive ordnance disposal ensemble

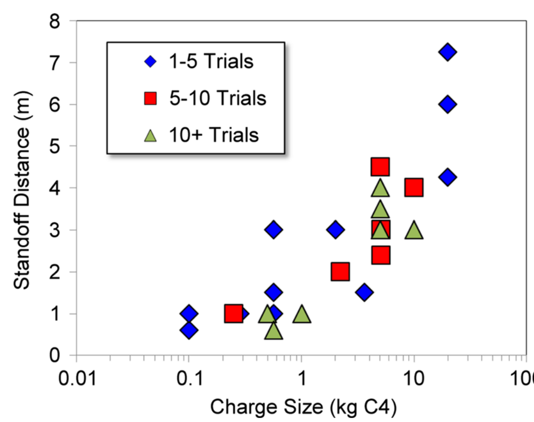


Fig. 8 Charge configurations tested and included in the current analysis

Head Injury Criterion [5]. This model has been developed for the automotive industry. It represents a valuable tool to characterize the head response since it is not limited to the peak accelerations experienced, but rather the overall shape of the measured acceleration signals. This criterion requires the acceleration experienced by the head $a(t)$ to be mathematically integrated over a particular time interval $(t_2 - t_1)$ using this prescribed formula:

$$\mathrm{HIC}_{15} = \left\{ (t_2 - t_1) \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a\,(t)\,\mathrm{d}t \right]^{2.5} \right\}_{\max} \qquad (1)$$

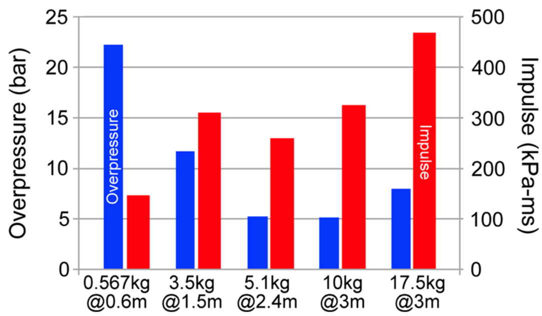


Fig. 9 Theoretical peak overpressure and maximum blast impulse values associated with a few representative explosive ordnance disposal scenarios (spherical blast, using blast equations from Kingery and Bulmarsh [18]). Blast impulse is defined as the area under the pressure-time curve

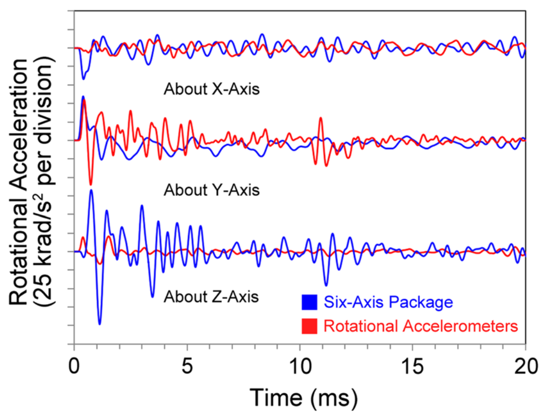


Fig. 10 Examples of blast-induced rotational acceleration data obtained from a Six Accelerometer Package (SAP) and from a cluster of three rotational accelerometers (Kistler Instrument Corporation, Amherst, NY)

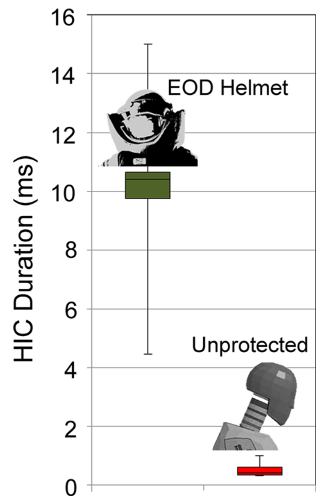


Fig. 11 HIC durations for blast scenarios, for both protected (EOD Helmet) and unprotected cases. All signals filtered at 1650 Hz

The HIC was developed from the Wayne State Tolerance Curve (WSTC) [22] using tests with cadaver heads. In the original tests, the foreheads were impacted against rigid and padded surfaces and the head translational acceleration were then related to the observed fractures of the frontal bone.

It is customary to limit the time interval $(t_2 - t_1)$ to a maximum of 15 ms, which is indicated by the subscript on the left-hand side of the equation. A maximum of 36 ms can also be used. However, in the blast experiments considered in this paper, the maximum HIC durations were always substantially below 15 ms, making the distinction between HIC_{15} and HIC_{36} irrelevant (both would provide the same value), as depicted in Fig. 11 which illustrates the HIC durations from all blast tests considered in the present analysis.

The applicability of the HIC with respect to blast-induced head accelerations can be questioned since the HIC has not been validated for the short-duration, high-amplitude acceleration signals typically encountered in this field. More specifically, the filtering frequency typically used to analyse acceleration signals from Hybrid III mannequins, based on the standard practices described in SAE J211-1 [17], is deemed by some authors not to be appropriate for blast testing scenarios. In particular, Bass et al. [23] compared HIC values obtained by filtering the acceleration signals at the prescribed 1650 Hz (4-pole Butterworth filter) from SAE J211-1, and a higher value of 10,000 Hz deemed to be more inclusive of the potential contribution of blast to the head acceleration. Very high differences in HIC values were reported.

The sensitivity of the HIC for blast scenarios is illustrated in Fig. 12, where HIC values are shown as a function of the selected filtering frequency, for three blast configurations (one typical single test considered for each scenario). In can be seen that while the selected filtering frequency can have a significant effect on the estimated HIC for the unprotected case, especially for the 0.567 kg C4 at 0.6 m case, the effect of filtering frequency becomes practically nil, when considering the protected (EOD helmet) case. The nearly independent HIC values versus filtering frequency correlation indicate that high-frequency loading from the blast wave is successfully attenuated by the EOD helmet.

Even though the current study does not focus on the predictions of actual injuries, the HIC was selected as the parameter of choice towards the quantification of the blast loading to the head. It is calculated using all acceleration data points within a time range relevant to the blast event, in addition to not being sensitive to filtering frequency in the case of EOD protection (Fig. 12). In contrast, the peak head acceleration is representative of only a single data point.

3.3 Correlation between HIC data and blast configurations

As stated earlier, peak head acceleration, and hence HIC, are linked to overall the blast loading of an explosive, such that, in general, the HIC is noted to increase with charge

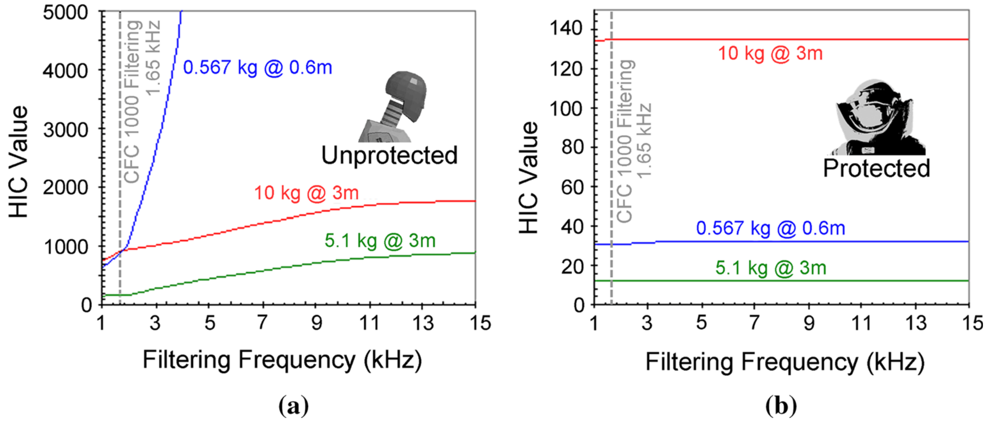


Fig. 12 Graphs showing the dependence of the computed HIC values on low-pass filtering frequency for **a** unprotected cases and **b** protected cases and for three different blasts. For the protected cases, the mannequin wore a bomb suit ensemble

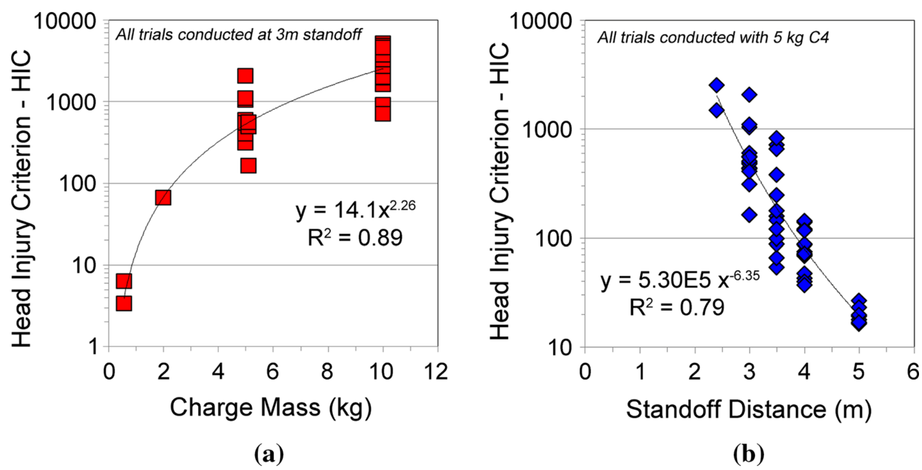


Fig. 13 Head Injury Criterion (HIC) values for an unprotected Hybrid III mannequin plotted with respect to the (*left*) charge mass at a constant 3.0 m horizontal standoff distance, and (*right*) standoff distance using 5.0 kg C4 square-cylinder charges

size at a constant standoff distance and decrease with larger horizontal standoff distances for given charge mass (Fig. 13). However, generalizing these results to encompass all blast configurations requires a more nuanced analysis of the blast loading.

The large variations observed in the data from Fig. 13 for a given condition are due to the inherent variability in blast testing, discussed further in Sect. 4. Yet, the observed variations can be reduced through the use of the scaled distance (a). The scaled distance also has the benefit of combining both the explosive charge mass (m) and standoff distance (d) variables in a single expression. The scaled distance, which has been extensively used in blast physics [24], is defined as:

$$a = \frac{d}{m^{1/3}} \tag{2}$$

where the denominator, the explosive mass to one-third power, represents the scaling factor. When the HIC values measured on an unprotected mannequin are plotted with respect to the scaled distance (Fig. 14), a stronger correlation can be found. Given this bettered correlation, the HIC itself can then be scaled (i.e., the HIC value is divided by the explosive mass to the one-third power) to further increase the overall correlation factor [25]. That is to say, the HIC values are divided by the mass of explosive to the one-third power, in much the same way the scaled distance is calculated. Figure 14 thus also shows the scaled HIC values with respect to the scaled distance. It can be seen that scaling the HIC values provides an even stronger correlation, whereby the spread in the values from the small-, medium-, and large-sized charges collapses into a single curve, and the goodness of fit increases markedly from $R^2 = 0.55$ to $R^2 = 0.71$. It should be noted that these correlations should not be extrapolated, especially at higher scaled distances. The lower scaled distances tend not to be an issue, as excessively high HIC values, ones well passed the highest threshold where death is predicted, do not yield any new or useful information.

3.4 Extension of HIC correlations to larger blasts

The blast mitigation performance of bomb suits are typically evaluated in a few representative scenarios, such as

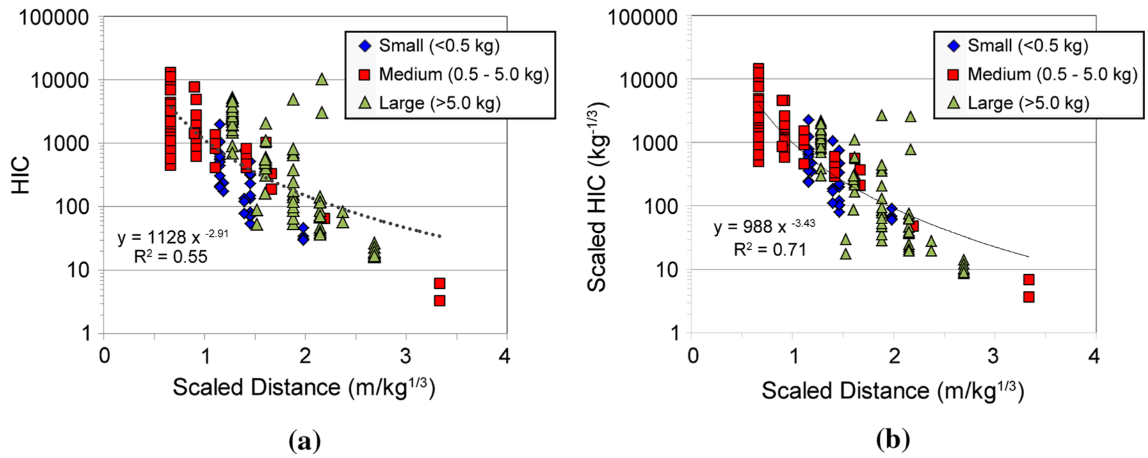


Fig. 14 **a** HIC and **b** scaled HIC plotted with respect to the scaled distance for three different ranges of the charge masses

those noted in Fig. 9. However, during their missions, EOD technicians might face much larger explosive charges, such as in the approach to Vehicle-Borne Improvised Explosive Devices (VBIEDs), also referred to as car bombs. Car bombs may contain very large explosive charges, often exceeding 100 kg. To investigate this scenario, expensive test series could be conducted, involving very large explosives, requiring a large number of repetitions and potential damage to the expensive instrumented anthropometric mannequins. As a much cheaper and simpler alternative, one can proceed with conservative comparisons of different blast configurations, focusing on the blast impulse and peak overpressure. Towards this comparative exercise, a previous study had demonstrated [26] that two main assumptions can be made, in terms of blast injury:

1. When a given configuration has both a higher peak pressure and a higher blast impulse than a reference condition, the configuration is deemed "More Dangerous" than the reference condition.
2. When a given configuration has both a lower peak pressure and a lower blast impulse than a reference condition, the configuration is deemed "Safer" than the reference condition.

These assumptions are deemed conservative, given that peak pressure and maximum impulse fully characterize a Friedlander blast, and that it is reasonable to assume that the combination of these two values somehow correlates with blast injury through blast loading.

In Sect. 3.3, empirical correlations had been devised for the HIC as a function of the scaled distance (combining the charge size and standoff distance). However, these correlations were developed for a limited range of blast conditions, and as such, extrapolating their predictions beyond their range of validity is likely to yield wrong predictions. More specifically, the data used to develop and validate this chart includes charge sizes mostly ranging from 0.567 to 10 kg of C4 explosives. As such, mannequin loading conditions for explosive charges below 0.567 kg, or exceeding 10 kg of C4 explosive, are likely to be invalid, since based on extrapolation of data.

An approach based on the two assumptions listed above can thus become useful, by conservatively extending the use of existing mannequin blast loading charts beyond the range through which they have been developed and validated. This approach consists in assuming that the same HIC will occur for the same pressure and blast impulse. Data can be presented as constant HIC curves as a function of the explosive charge mass and the standoff distance, using the equation highlighted in Fig. 14b.

As such, the constant HIC curves based on the curve fit from Fig. 14b are stopped at 10 kg of C4 explosive, and then extended using constant blast impulse curves for larger explosive charges. This is equivalent to considering the 10 kg data points on each individual curve as the "reference condition", and extending the curves using an approach based on the two assumptions above, i.e., using constant blast impulse curves for charges larger than the reference value. Constant blast impulse curves are used since they generate more conservative (safer) blast configurations compared to a given reference, as compared to constant overpressure curves. This is the approach taken in generating the modified HIC unprotected injury chart, shown in Fig. 15, which exhibits a "kink" in the iso-loading curves at 10 kg, where the constant HIC curves extend to the right through constant blast impulse curves.

A similar process can be made to extrapolate the HIC unprotected chart for explosive charges lower than 0.567 kg C4, but this time, by extending the iso-loading curves using constant peak pressure curves (Fig. 16). This is based on the fact that for explosive charges lower than the reference

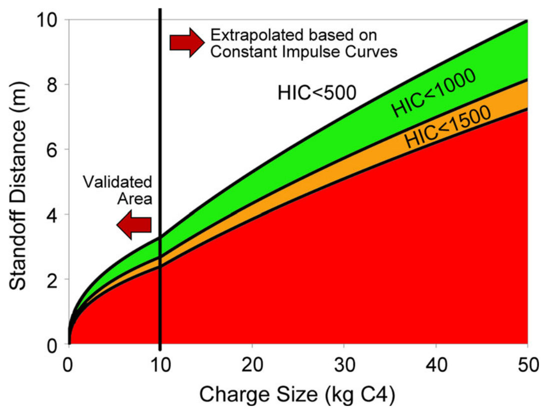


Fig. 15 HIC loading unprotected chart from Fig. 14b, modified beyond a 10 kg C4 charge, for a more conservative assessment based on constant blast impulse curves

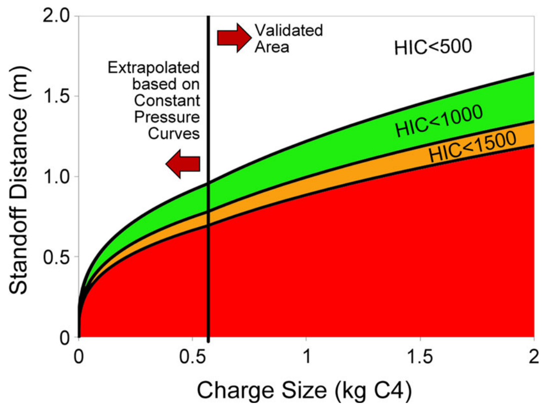


Fig. 16 HIC loading unprotected chart from Fig. 14b, modified below a 0.567 kg C4 charge, for a more conservative assessment based on constant overpressure curves

condition, the threshold for the safer area is governed by the peak overpressure curve.

These extended HIC charts based on extrapolation through constant pressure and constant blast impulse curves are therefore more conservative than what would be predicted by simply applying the equation from Fig. 14b across the entire range of explosive charge masses. Moreover, while the HIC loading unprotected chart was illustrated as an example; the same principles could be applied to any other types of blast charts. It must be kept in mind though, that these curves and the extrapolations through the concepts suggested in this paper do not take into account the effect of reflecting surfaces and complex environments.

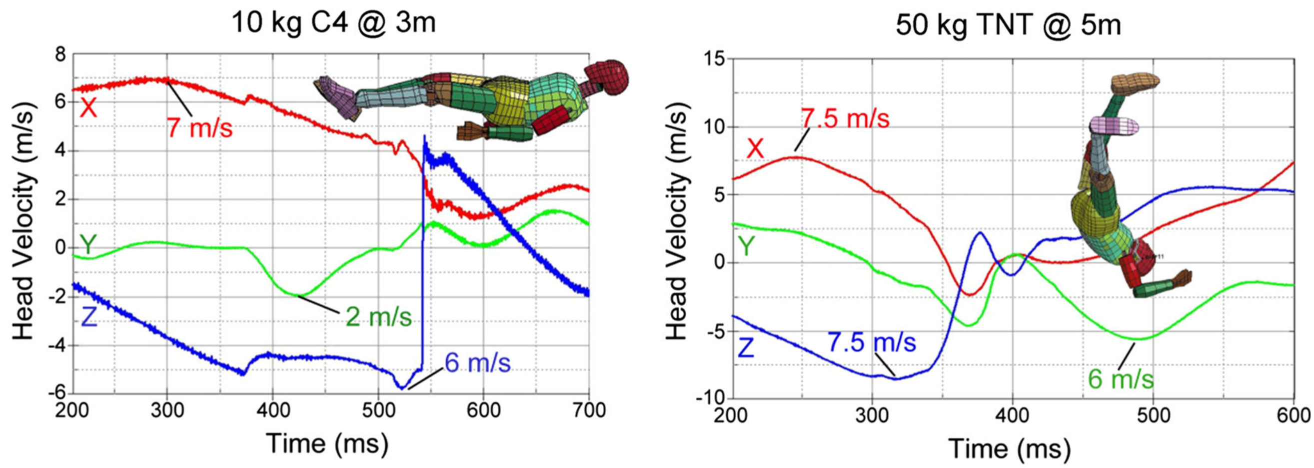
3.5 Expanding the scope of blast-induced TBI: head impacts with the ground/obstacles

While most of the discussions above related to the direct interaction of a blast wave with the head of an individual (wearing or not wearing a helmet), TBI-type injuries can also arise from impacts with the ground or other obstacles, when the body is propelled by the force of the blast. While the direct interaction of the blast with the head can lead to injuries that can be categorized as primary blast injuries, impacts with the ground or obstacles are categorized as tertiary blast injuries. Considering blunt impact injuries arising from blast exposure (tertiary blast injuries) thus expands the scope of what is expected from a "blast protective helmet".

An earlier study (reported in [27,28]), aimed at addressing a perceived gap in terms of tertiary blast injury threat characterization (global body displacement) and associated need for personal protection, provided some quantification of the head blunt impact threat in the context of blast. This study specifically attempted to quantitatively compare the head loading resulting from blunt impact compared to the head loading arising from direct blast exposure. Numerical simulations involving a Hybrid III mannequin model exposed to two different blast configurations were conducted (10 kg C4 explosive at a standoff of 3 m, and 50 kg TNT explosive at 5 m).

The motion of the mannequin involved numerous impacts on the ground with various body parts. Figure 17 only shows the impact yielding the highest impact velocities in each of the two cases investigated. Head velocities in the individual orientations were found to reach values up to 7.5 m/s. Resultant velocity values would yield slightly higher estimates (peaks do not occur at the same time in all three orthogonal directions). While these numbers do not directly translate into injury predictions, such impact velocities are of the order of automotive impacts, and are likely to cause severe damage to the musculoskeletal system and tissues. However, devising protection solutions against such strong blunt impacts is only of relevance if the individual can first survive the direct exposure to the blast wave.

Figure 18 (reproduced from [27]) compares the theoretical overpressure traces [18] for these two configurations, highlighting their peak overpressure and maximum impulse values (it should be noted though, that the effect of blast wave reflection from the ground and resulting Mach stems have not been taken into account). Figure 19 illustrates the overpressure survival curves from Bass et al. [29] with predictions for the same two explosive configurations, for both the unprotected and EOD protection cases (bomb suit). For the EOD case, estimates are based on an average 90% overpressure reduction and a twofold increase in positive-phase duration due to the PPE [30]. Figure 19 reveals that both explosive configurations are highly lethal to unprotected individuals (approximately 1% chance of survival or less). Any additional blunt impact injuries would not affect much the global survival outcome in these two unprotected cases. On the other hand, the survival curves from Fig. 19 indicate a high probability of survival for both protected (bomb suit) cases (approximately 90 and 99% chance). These injury curves



(a) **(b)**

Fig. 17 Simulations of head impact velocities for the most severe impacts observed for a 10 kg C4 charge at a standoff of 3 m (*left*) and for a 50 kg TNT charge at a standoff of 5 m (*right*). Approximate peak velocities are shown for all three individual axes as well as an image of the mannequin just prior to impact (reproduced from [27])

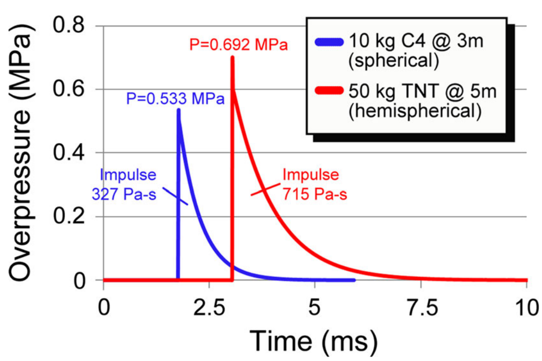


Fig. 18 Theoretical overpressure traces for two specific explosive configurations

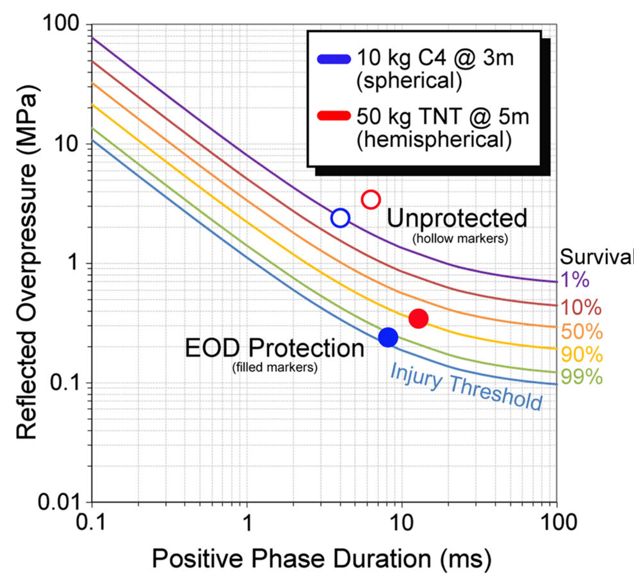


Fig. 19 Overpressure survival curves [29] with the two configurations from Fig. 18 (unprotected and EOD protection)

do not take into account potential tertiary (blunt impact) blast injuries. Therefore, blunt impact protection is highly relevant to maintain the survival predictions at the same levels, as severe impact injuries might arise from impacts at velocities of the order of 25 km/h with the ground or other obstacles. As such, EOD protection (bomb suits) must be designed to provide protection against blunt impact protection (tertiary injuries) in addition to overpressure (primary) and fragmentation (secondary). More specifically, EOD helmets must provide sufficient head impact protection, and bomb suits should be equipped with back protectors to mitigate the potential for spine injury from impacts on the ground or other obstacles after being launched by the blast.

The Hybrid III mannequin is suitable when it comes to assessing tertiary injuries (resulting from blunt impacts with the ground or other obstacles after exposure to blast), given that this is the type of injuries this mannequin was developed for (blunt impact), as opposed to direct blast exposure. As such, application of injury criteria such as the HIC and the BrIC is more appropriate in the context of tertiary blast injuries than in the context of primary blast injuries.

3.6 Helmet blast mitigation results: case study

Even though blast-induced head acceleration might not be directly related to actual injury mechanisms for TBI, such data can be viewed as an indication of the blast loading. As such, it can be used to compare the effectiveness of head protective systems against blast. A previous study [31] included

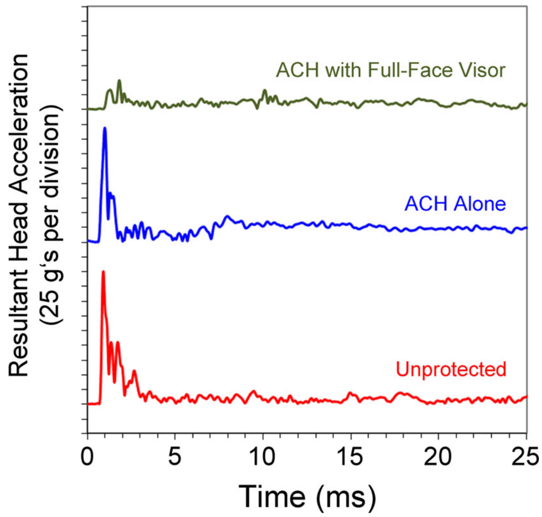


Fig. 20 Blast-induced head acceleration traces for kneeling mannequins facing 0.1 kg C4 explosive at a standoff of 0.7 m in three configurations: ACH helmet alone, ACH helmet with full-face visor, and unprotected

tests aimed at evaluating the blast protection provided by visors (faceshields) attached to military helmets. Hybrid III mannequins dressed in a military tactical protective suit and wearing ACH military helmets were exposed to the blast of high explosives in a blast chamber. Figure 20 shows results for kneeling mannequins facing 0.1 kg of C4 explosive at a 0.7 m standoff. Resultant head acceleration results are shown for three configurations: ACH helmet alone, ACH helmet with a protective visor, and unprotected (no suit, no helmet).

Results first show that the ACH helmet alone does not reduce the loading (amplification observed), compared to the unprotected case. A reduction in blast-induced head acceleration could have been expected based on the added helmet mass, which increases the inertia of the head/helmet system, and thus its resistance to blast-induced acceleration. The amplification in head acceleration for the ACH helmet case may be attributed to the increased projected area of the helmet, compared to the unprotected head. On the other hand, a significant reduction in blast-induced head acceleration is observed when comparing the case of the ACH helmet coupled with a full-face visor (VBS-580 from Med-Eng) to either the ACH helmet alone or the unprotected case. Although the visor does provide some extra mass (thus inertia), it is hypothesized that the significant reduction in head acceleration is attributed to a more "aerodynamic" design stopping the blast from being "caught" between the helmet and the head. This blast mitigation effect is amplified as the visor integrates with the collar from the tactical protective suit, providing a continuous level of protection. In addition, for the full-face visor case, the retention system is fully engaged as the blast load is taken by the helmet/visor system and not by the head/face directly.

This case study provides a useful and relevant example of test scenarios where measurements of blast-induced head acceleration can provide clear guidance related to the effectiveness of one protective solution as compared to another one, or compared to the unprotected case. Moreover, the use of the Hybrid III mannequin is particularly appropriate for these scenarios, given that the helmet system and protective suit can be worn in a realistic fashion. In particular, the various protective components can be correctly integrated (e.g., helmet, visor, collar, suit), which might not be the case if using a test surrogate with a simpler or incorrect geometry.

4 Discussion

4.1 Repeatability of blast testing

One of the most significant issues encountered in blast testing and characterization of the personal protective equipment in general is the variability of the blast itself. The uncertainty factor associated with pressure readings and impulse calculations are typically on the order of 2.0 and 1.3, respectively [32]. The uncertainty factor is a single coefficient used to describe the range of the variation, whereby the maximum and minimum values are calculated as the product and the quotient of the average value and uncertainty factor, respectively. Indeed, in 184 trials conducted over the previous fifteen years using "lollipop-style" side-on reference pressure gauges with spherical, 0.567 kg C4 explosive charges measured at 60 cm horizontal standoff distance (i.e., the blast configuration used in the NIJ 0117.01 Bomb Suit standard [15]), the peak pressure, maximum impulse, and positive-phase durations were catalogued indicating a marked amount of scatter (see Fig. 21). This scatter is clearest when the measurements and their respective standard deviations are normalized with respect to their averages, where the normalized standard deviation, or coefficient of variation, is noted to be 0.275 and 0.262 for peak pressure and maximum impulse. This phenomenon runs counter to test studies investigating ballistic penetration where coefficients of variation typically do not exceed 0.05. To combat this trend, many tests are conducted with each PPE option, and the relative intensity of the blast is logged such that the strength of the blast is incorporated into the decision-making model.

For PPE testing, the variation in test results is further compounded by the mechanical variability of the test set-up. For instance, graphs from Fig. 14 for mannequin HIC measurements show a very high level of variation. When testing for PPE, additional sources of variability include the exact standoff distances, the positioning accuracy of the mannequin, the calibration of the mannequin, how the bomb suit/helmet is worn.

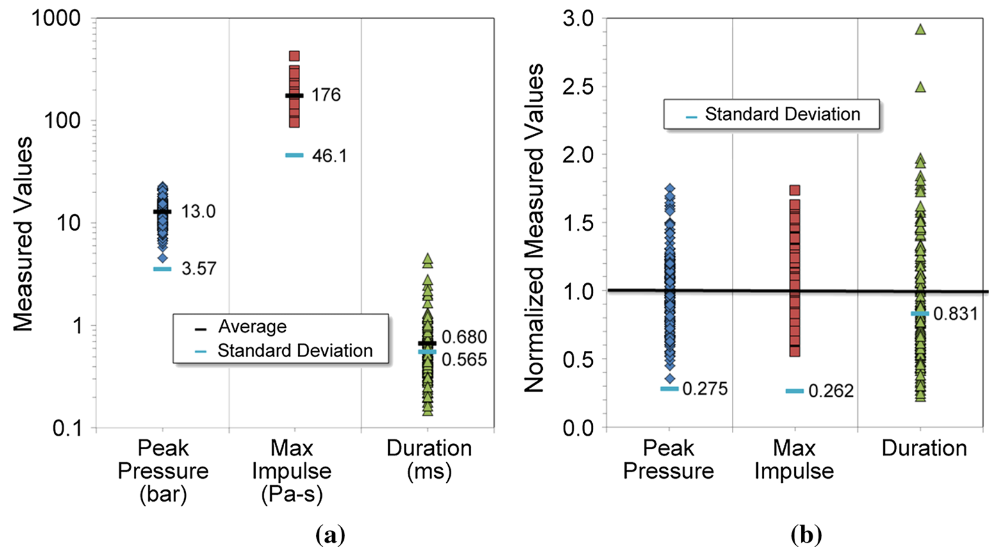


Fig. 21 **a** Raw and **b** normalized peak pressure, maximum impulse and positive-phase durations. Also noted are the averages and standard deviations

4.2 Quantitative blast testing methodology

The NIJ 0117.01 standard [15] only currently includes a *qualitative* blast testing requirement, referred to as the "bomb suit integrity test", even though a number of test methodologies had been developed towards inclusion in this standard [23]. The National Institute of Justice claims that "blast overpressure protection test measures do not provide sufficient confidence levels to recommend test methods and protective performance requirements" [15]. The absence of widely accepted blast injury criteria, coupled with the high variability in blast testing discussed in Sect. 4.1, both contribute to the difficulty in adopting a quantitative blast testing methodology for PPE faced by NIJ.

This being said, the absence of a quantitative blast protection test requirement in a standard for PPE aimed at providing blast protection represents an important gap. Due to the lack of such quantitative blast requirement, there is a risk that a bomb suit only providing little blast protection might still get certified as per the NIJ 0117.01 standard. It is therefore imperative that the next revision of the NIJ 0117 standard incorporate a quantitative blast testing method, despite the challenges related to variability and injury criteria.

Focusing on the head level, here are some recommendations:

- A Hybrid III mannequin can be used. While lacking any blast exposure validation and not appropriately representing the head's internal organs (e.g., the brain), the Hybrid III mannequin is representative of a 50th percentile individual in terms of weight and weight distribution, and allows for relatively appropriate donning of PPE. The Hybrid III can also be instrumented for head acceleration and ear overpressure (through minimal modifications of the head), thereby providing relevant measurements at the head level, sensitive to the helmet protection. The Hybrid III mannequin is also a standardized test apparatus readily available, as opposed to specialized head surrogates currently developed in various research laboratories, which are unique, not standardized, and not readily available to test laboratories and PPE manufacturers for standardized testing.
- Head acceleration (triaxial) and ear overpressure are relevant measurements to be made at the head level, when it comes to blast injury. While potentially not precisely related to injury mechanisms, these measurements are likely to correlate with blast injuries. Widely available instrumentation should be mandated.
- It is recommended to introduce two explosive blast configurations, since bomb suits must be effective at mitigating blasts characterized by both a large peak overpressure (e.g., 0.567 kg C4 at 0.6 m standoff), and a large blast impulse (e.g., 10 kg C4 at 3 m standoff), as highlighted in Fig. 9. High overpressure levels will impose a higher stress on the bomb suit components (yielding shearing, tearing), while high impulse levels will cause higher accelerations, thus a higher direct impact loading.
- Fragmentation and blast tests should not be mixed. Blast testing should be conducted with "pure" explosives, free of fragments.
- A minimum number of explosive tests should be conducted, to take into account the inherent variability with blast testing, while also considering the high costs associated with blast testing of bomb suits. A statistical study should be conducted to arrive at a recommended number of tests.
- The average of measured resultant head accelerations or HIC values obtained from all tests should be calcu-

lated. The average should be compared with a carefully selected threshold requirement, as opposed to having requirements for every single individual measurement (to minimize the effect of outliers). Baseline blast tests conducted with existing EOD helmets could be used to set realistic threshold values.

5 Conclusion

The present paper has focused on the appropriateness of blast testing of PPE using Hybrid III mannequins, for a number of reasons including availability, cost, weight, size, appropriate instrumentation, ability to don protective equipment, etc. However, it is recognized that more advanced head surrogate models are being developed, which take into account new developments in the search for blast-induced traumatic brain injury mechanisms. Unfortunately, there is no convergence yet on head surrogates and appropriate measurements to be made at the head level towards blast injury assessment. Moreover, the newly developed head surrogate models are not readily available to helmet manufacturers and laboratories involved in standard testing. As such, the authors believe that in the absence of a widely accepted injury mechanism, relying on the Hybrid III mannequin and understanding that reductions observed in mannequin readings should translate into associated injury reductions is the most appropriate compromise to a standardized test methodology.

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References

1. Bolander, R., Mathie, B., Bir, C., Ritzel, D., VandeVord, P.: Skull flexure as a contributing factor in the mechanism of injury in the rat when exposed to a shock wave. Ann. Biomed. Eng. **39**(10), 2550–2559 (2011). doi:10.1007/s10439-011-0343-0
2. Cernak, I., Wang, Z., Jiang, J., Bian, X., Savic, J.: Ultrastructural and functional characteristics of blast injury-induced neurotrauma. J. Trauma-Inj. Infect. Crit. Care **50**(4), 695–706 (2001)
3. Cernak, I., Savic, J., Ignjatovic, D., Jevtic, M.: Blast injury from explosive munitions. J. Trauma-Inj. Infect. Crit. Care **47**(1), 96–103 (1999)
4. Haladuick, T., Cronin, D.S., Lockhart, P., Singh, D., Bouamoul, A., Ouellet, S., Dionne, J.P.: Head kinematics resulting from simulated blast loading scenarios. In: Personal Armour Systems Symposium (PASS), Nuremberg (2012)
5. Versace, V.: A review of the severity index. In: Proceedings of the Fifteenth Stapp Car Crash Conference, pp. 771–796 (1971). doi:10.4271/710881
6. King, A.I., Yang, K.H., Zhang, L., Hardy, W., Viano, D.C.: Is head injury caused by linear or angular acceleration? In: Proceedings of the Annual Conference of the International Research Council on Biomechanics of Injury (IRCOBI), Lisbon (2003)
7. Ommaya, A.K.: Head Injury Biomechanics. George G. Snively Memorial Lecture, Denver, Association for the Advancement of Automotive Medicine (1984)
8. Thibault, L., Gennarelli, T.: Brain injury: an analysis of neural and neurovascular trauma in the nonhuman primate. In: 34th Annual Conference of the Association for the Advancement of Automotive Medicine, Scottsville (1990)
9. Newman, J.A.: A generalized model for brain injury threshold (GAMBIT). In: Proceedings of International Conference on the Biomechanics of Impact (IRCOBI), pp. 121–131 (1986)
10. Newman, J.A., Shewchenko, N., Welbourne, E.: A proposed new biomechanical head injury assessment function–the maximum power index. Stapp Car Crash J. **44**, 215–247 (2000)
11. Newman, J., Barr, C., Beusenberg, M.C., Fournier, E., Shewchenko, N., Welbourne, E., Withnall, C.: A new biomechanical assessment of mild traumatic brain injury. Part 2: Results and conclusions. In: Proceedings of the International Research Council on the Biomechanics of Injury conference (IRCOBI) (2000)
12. Takhounts, E.G., Craig, M.J., Moorhouse, K., McFadden, J., Hasija, V.: Development if brain injury criteria (BrIC). Stapp Car Crash J. **57**, 243–266 (2013)
13. Ouellet, S., Bouamoul, A., Gauvin, R., Williams, K.V., Martineau, L.: Development of a biofidelic head surrogate for blast-induced traumatic brain injury assessment. In: Proceedings from the 2012 Personal Armour Systems Symposium Conference (PASS), Nuremberg (2012)
14. Simmonds, K.E., Matic, P., Chase, M., Leung, A.: GelMan: a physical model for measuring the response to blast. NRL Rev. 156–158 (2004)
15. Public Safety Bomb Suit Standard, NIJ Standard-0117.01: U.S. Department of Justice, Office of Justice Programs, Washington (2012)
16. National Highway Traffic Safety Admin., DOT, 49 CFR Ch. V (10-1-11 Edition), Part 572—Anthropomorphic Test Devices, Subpart E—Hybrid III Test Dummy (1997)
17. Instrumentation for Impact Test, Part 1, Electronic Instrumentation, SAE J211-1 (1995)
18. Kingery, C., Bulmarsh, G.: Airblast parameters from TNT spherical air burst and hemispherical surface burst. ARBRL-TR-02555. US Army Ballistic Research Laboratory, Aberdeen Proving Ground (1984)
19. Kimpara, H., Nakahira, Y., Iwamoto, M., Rowson, S., Duma, S.: Head injury prediction methods based on 6 degree of freedom head acceleration measurements during impact. J. Automot. Eng. **2**, 13–19 (2011). doi:10.20485/jsaeijae.2.2_13
20. Mital, N.K., King, A.I.: Computation of rigid body rotation in three-dimensional space from body-fixed linear acceleration measurements. J. Appl. Mech. **46**(4), 925–930 (1979). doi:10.1115/1.3424679
21. Levine, J., Dionne, J.P., Bueley, D., Makris, A.: Blast and impact induced linear and rotational head acceleration. In: Proceedings from the 2014 Personal Armour Systems Symposium Conference (PASS), Cambridge (2014)
22. Lissner, H.R., Lebow, M., Evans, F.G.: Experimental studies on the relation between acceleration and intracranial pressure changes in man. Surg. Gynecol. Obstet. **111**, 329–338 (1960)
23. Bass, C.R., Davis, M., Rafaels, K., Rountree, S., Harris, R.M., Sanderson, E., Andrefsky, W., Dimarco, G., Zielinski, M.: A methodology for assessing blast protection in explosive ordnance disposal bomb suits. Int. J. Occup. Saf. Ergon. **11**(4), 347–361 (2005). doi:10.1080/10803548.2005.11076655
24. Baker, W.: Explosions in Air. University of Texas Press, Austin (1973)

25. Levine, J., Dionne, J.P., Makris, A.: Blast injury charts for EOD scenarios based on scaled explosive parameters. In: Proceedings from the 21st Military Aspects of Blast and Simulation (MABS), Jerusalem (2012)
26. Dionne, J.P., Levine, J., Makris, A.: Development of a blast severity comparative tool. In: Proceedings from the 22nd Military Aspects of Blast and Simulation (MABS), Oxford (2014)
27. Dionne, J.P., Cheng, M., Levine, J., Makris A.: Tertiary blast injury and the need for impact protection. In: Proceedings from the 2016 Personal Armour Systems Symposium Conference (PASS), Amsterdam (2016)
28. Levine, J., Cheng, M., Dionne, J.P., Makris, A.: Launched distance by the force of the blast. In: Proceedings from the 23rd Military Aspects of Blast and Simulation (MABS), Halifax (2016)
29. Bass, C.R., Rafaels, K., Salzar, R.: Pulmonary injury risk assessment for short-duration blasts. J. Trauma-Inj. Infect. Crit. Care **65**(3), 604–615 (2008). doi:10.1097/TA.0b013e3181454ab4
30. Nerenberg, J., Dionne, J.P., Makris, A., Fisher, G.: Evaluation of the ABS-LPU Ensemble for Compliance with US Army Advanced Bomb Suit Program. UXO Countermine Forum, Orlando (2002)
31. Dionne, J.P., McKenzie, I., Levine, J., Makris, A.: Higher mobility PPE alternative to EOD suits for specific military operations. In: Proceedings from the 2012 Personal Armour Systems Symposium Conference (PASS), Nuremberg (2012)
32. Ohrt, A.P., Dailey, T.G., Bogosian, D.D.: Statistical variation of airblast parameters from bare and cased explosive cylinders. In: Proceedings from the 22nd Military Aspects of Blast and Simulation (MABS), Oxford (2014)