Head Kinematics Resulting from Simulated Blast Loading Scenarios

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Abstract:
Blast wave overpressure has been associated with varying levels of traumatic brain injury in soldiers exposed to blast loading. In realistic blast loading scenarios, the mechanisms of primary blast injury are not well known due to the complex interactions of the blast wave with the human body, and the high acceleration experienced over very short time durations. The purpose of this study was to investigate head kinematics resulting from a range of simulated blast loading conditions corresponding to varying standoff distances, and differing heights of burst. This study considered peak linear acceleration, and the head injury criteria (HIC) to examine the effect of blast wave interaction on head kinematics using a validated multi-body model. A modified version of the GEnerator of Body Data (GEBOD) 50thpercentile male was validated against experimental blast data using a Hybrid III 50th percentile male ATD. The blast wave was applied using an air blast function via the application of pressure loads corresponding to the detonation of a conventional spherical charge using an equivalent mass of TNT. This approach applied the blast shockwave, a rapid increase in pressure, temperature and density, and included Mach stem effects. As expected, the results demonstrated that head acceleration increased with decreased charge standoff distance, and severe head injury may occur in close proximity to blast as the head injury criterion threshold was exceeded for all explosive sizes at close proximity. The presence of a Mach stem resulting from an elevated charge has been found to increase the potential injury zone surrounding an explosive charge compared to a free field blast; this could be addressed through increased standoff or enhanced blast protection.

1. INTRODUCTION

In recent and ongoing conflicts including operations Enduring Freedom (Afghanistan) and Iraqi Freedom, there has been a significant increase in the threat posed by Improvised Explosive Devices (IEDs) [1]. Recently, these devices have increased in both size and prevalence [2] with explosive-related head injuries being the subject of many previous studies. However, the mechanisms and thresholds pertaining to head injuries from blast are still under investigation. There are four defined categories of blast related injury. Primary blast injury is associated with the interaction between an explosive pressure wave and the body which commonly damages air-filled organs such as the lungs, gastrointestinal tract, and ears. Secondary blast injury results from explosive debris or fragmentation impacting the body, while tertiary blast injury is caused by the displacement of the body and the subsequent impact with surrounding obstacles or the ground. Quaternary injury is the result of other factors including burns or inhalation of dust and gas particles. [3]

Recently, primary blast injury has been linked to varying levels of traumatic brain injury (TBI) in soldiers exposed to blast loading [4]. The Defense and Veterans Brain Injury Center (DVBIC) estimates that 202,281 US service personnel were diagnosed with TBI between 2000 and 2010, with the majority (77%) of those affected suffering from mild traumatic brain injury (mTBI) [5]. The head injury mechanism corresponding to blast exposure is not well understood. This difficulty stems from the inability to measure intracranial phenomena in living subjects, the high accelerations of the head experienced over very short time duration, and the complex interactions between a blast wave and the human body. The purpose of this study was to use a multi-body model to predict head kinematics resulting from a range of simulated blast scenarios.

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14. ABSTRACT

Blast wave overpressure has been associated with varying levels of traumatic brain injury in soldiers exposed to blast loading. In realistic blast loading scenarios, the mechanisms of primary blast injury are not well known due to the complex interactions of the blast wave with the human body, and the high acceleration experienced over very short time durations. The purpose of this study was to investigate head kinematics resulting from a range of simulated blast loading conditions corresponding to varying standoff distances, and differing heights of burst. This study considered peak linear acceleration, and the head injury criteria (HIC) to examine the effect of blast wave interaction on head kinematics using a validated multi-body model. A modified version of the GEnerator of Body Data (GEBOD) 50thpercentile male was validated against experimental blast data using a Hybrid III 50th percentile male ATD. The blast wave was applied using an air blast function via the application of pressure loads corresponding to the detonation of a conventional spherical charge using an equivalent mass of TNT. This approach applied the blast shockwave, a rapid increase in pressure, temperature and density, and included Mach stem effects. As expected, the results demonstrated that head acceleration increased with decreased charge standoff distance, and severe head injury may occur in close proximity to blast as the head injury criterion threshold was exceeded for all explosive sizes at close proximity. The presence of a Mach stem resulting from an elevated charge has been found to increase the potential injury zone surrounding an explosive charge compared to a free field blast; this could be addressed through increased standoff or enhanced blast protection.

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2. BACKGROUND

2.1 Head Injury

When blast waves, which travel faster than the speed of sound in air, interact with the body, the large pressure differential results in rapid accelerations of the body creating a high-frequency stress wave that propagates through tissue. Experimental models to evaluate head response and the potential for brain injury have included a variety of techniques and test species in order to develop a reproducible model of trauma that exhibits anatomic, physiologic, and functional responses similar to those described clinically [6]. Applying these models to blast-induced traumatic brain injury produces significant difficulties in determining the measureable parameters that are associated with a specific physical or psychological symptom as these symptoms often do not become apparent for some time following the insult. In a recent study by Rafaels *et* al [7], blast injury was investigated using an animal model (rabbit) and a scaled overpressure corresponding to fatal head injury was proposed. The authors also noted the challenges in developing primary blast injury tolerance scales. Traditional injuries relating to non-impact acceleration of the head include: diffuse axonal injury (DAI), indirect contrecoup contusions, tissue stresses produced by motions of the brain hemispheres relative to the skull and each other, as well as subdural hematomas produced by a rupture of bridging vessels between the brain and the dura matter [8]. Symptoms of severe TBI include: unconsciousness, amnesia and severe headaches while symptoms pertaining to mTBI include: insomnia, vertigo and memory deficits [5]. There is often no visible injury pattern associated with blast inflicted TBI, and thus it cannot be identified through direct observation or medical imaging. Furthermore, the symptoms inflicted by mTBI resemble to those pertaining to post-traumatic stress disorder, and thus a patient may have been misdiagnosed or suffering from comorbidity [9].

Previous studies have shown that global head accelerations resulting from an explosive event are very high for very short durations [10]. Furthermore, tertiary blast injury resulting from the impact of the head with the ground could exceed accelerations observed during the primary blast injury [10]; however the focus of this study was on the short-term head kinematics resulting from direct interaction with a blast wave.

2.2 Head Injury Metric

Currently, there are no validated head injury metrics to predict head injury resulting from a blast event; however, several common head injury metrics are based on head Center of Gravity (CG) acceleration and provide a starting point for assessing the severity of a blast wave on the head. It should be emphasized that the metrics used in this study are not being proposed to predict blast mTBI, but only to provide a frame of reference in this study for predicted head kinematics and injury.

The Head Injury Criterion (HIC) is the most commonly used head injury metric for accelerative head injuries, developed for use in the automotive industry with a time integral of the resultant linear acceleration of the head over the duration of the insult.

$$\boldsymbol{HIC = \left[\frac{1}{\tau_2-\tau_1}\int_{\tau_1}^{\tau_2} a(t)dt\right]^{2.5}(t_2-t_1)} \quad (1)$$

In this study the HIC_{15} metric was used with the corresponding Federal Motor Vehicle Safety Standards tolerance level of 700 [11]. The HIC is integrated over an optimized time interval of the acceleration produced by blast wave interaction with the head. There are several limitations to the HIC. It is generally defined for accelerations longer than 1ms and some blast accelerations may be shorter [12]. Also there is an assumed time dependence of the tolerable average acceleration which leads to predictions that short-duration / high acceleration events and long-duration / low acceleration events yield equal risks of closed head injury [12]. Furthermore, the HIC is not injury specific and does not account for variation in brain mass or include a description of the internal brain kinematics associated with head injury.

It has also been observed that force applied to an unrestrained head produces both linear and rotational acceleration [6]. An injury metric based on rotational velocity and acceleration has been investigated as a potential injury metric to estimate injury thresholds from mild concussions to diffuse axonal injuries [13].

Additionally the head impact power (HIP) injury metric has been developed to incorporate the rate of change of translational and rotational kinetic energy and relates to a pass/fail tolerance curve [12]. The HIP was developed by reconstructing impacts occurring in American football, and associating the kinematic levels to an injury severity. Both the HIP and another rotational metric have been shown in a previous study [14] to produce comparable tolerance results when evaluating a blast scenario, and thus were not considered here.

2.3 Blast Waves and Explosive Loading

The blast sequence of a chemical explosive begins with a detonation wave travelling through the explosive charge causing a violent decomposition of the charge material producing heat and combustible gas. The rapid expansion of these gases produces a high pressure, high temperature state; when this state is formed in a medium such as air it results in the generation of a blast wave [15]. Some important characteristics of a blast wave include the arrival time, positive phase duration, and peak pressure [16]. The pressure wave resulting from a blast is often described using the terms static, incident, or side-on pressure, corresponding to the pressure that would be observed in the flow field. However, when the wave interacts with a structure, the pressure is described as the reflected or dynamic pressure, which includes the static pressure and interaction of the flow field with a structure.

The incident and reflected pressures decay exponentially with increasing standoff distance: the distance between an explosive and target. In this study the standoff distance was defined as the distance along the ground from the center of gravity of the GEnerator of Body Data (GEBOD) head to the center of the explosive charge (Figure 1), consequently this resulted in slightly higher standoff for explosives with heights of burst vertically further from the GEBOD head height.

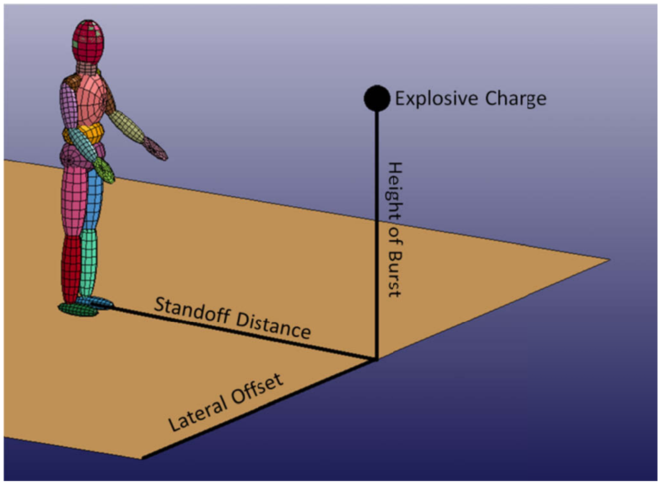


Figure 1 - GEBOD model setup and orientation.

When a blast wave interacts with the ground (Figure 2), it produces a reflected wave front. This reflected wave then accelerates through the pre-compressed hot gases and joins with the incident wave producing a Mach stem. The moving point of intersection between the incident wave, ground reflected wave and the Mach stem is called the triple point.

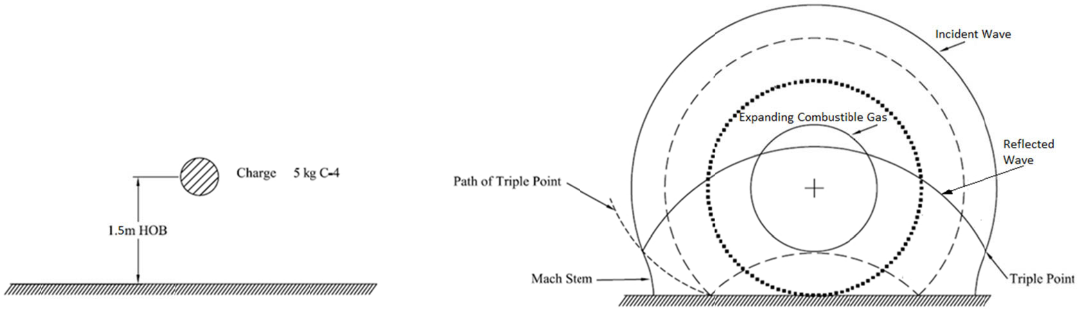


Figure 2 - Air blast ground interaction, (adapted from [17]).

The path of the triple point and thus the relative height and size of the Mach stem phenomena depends on the charge size, standoff distance and the height of burst (HOB) of the explosive. The Mach front increases the pressure observed by the target from the blast and once, formed the triple point height increases with increasing standoff distance from the explosive (Figure 3) [18].

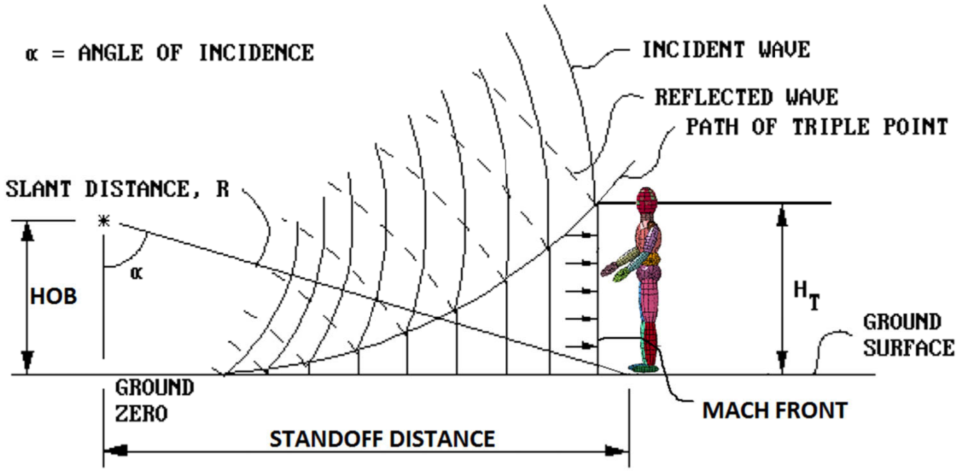
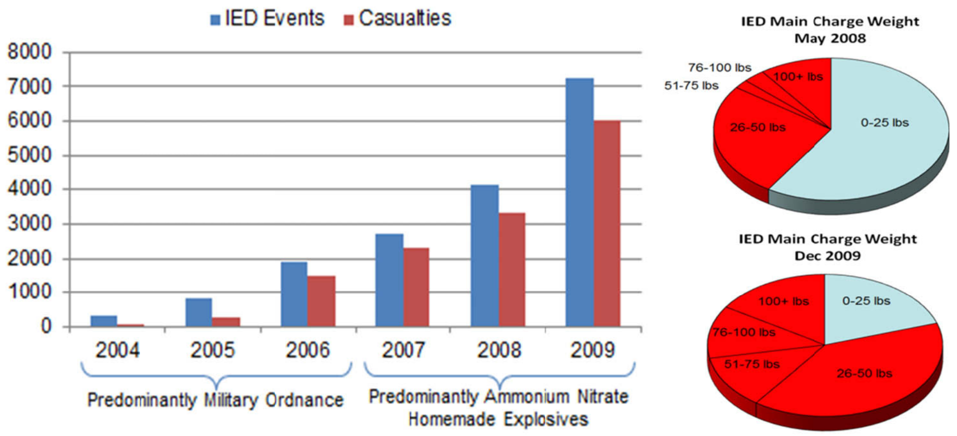


Figure 3 - Air blast and the subsequent path of the Mach stem triple point, (adapted from [18]).

2.4 Improvised Explosive Device Characteristics

In Operation Enduring Freedom, $^{1193}/_{2876}$ NATO fatalities were attributed to IEDs [1]. In more recent years, IEDs in Afghanistan have been primarily produced using homemade explosives (Figure 4) [2], leading to increasing IED size. In the current study, explosive charges of 5kg, 10kg, and 20kg C4 were investigated to be directly comparable to experimentally collected pressure data from blast tests conducted at Defense Research and Development Canada (DRDC) - Valcartier. TNT equivalency is often used as a reference to express the output of a high explosive based on the specific energy of their detonation (specific energy of TNT = 4520kJ/Kg) [15]; C4 has a TNT pressure equivalent factor of 1.34 [15].



2].

2.5 Model Validation

The GEBOD multi-body model (Figure 1) includes representations of body segment mass, joint location, and joint kinematics. A 50th percentile male GEBOD model was recently validated against experimental data to predict head kinematics resulting from blast exposure in a study by Lockhart *et* al [19]. In this study a static HOB was investigated in conjunction with varying standoff and small explosive sizes.

The model was validated against several scenarios with 5kg C4 charges at a 1.5m HOB with varying standoff distances ranging from 3m to 4m. These blasts were applied experimentally to a 50th percentile male Hybrid III dummy instrumented with several head accelerometers to measure linear and rotational accelerations. The same blast conditions were then modelled using enhanced blast loading techniques and applied to the GEBOD model, providing comparable results based on peak acceleration (Figure 5).

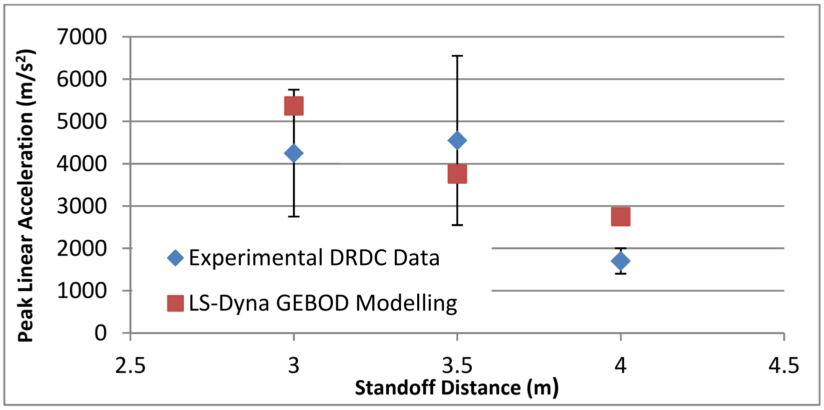


Figure 5 - GEBOD peak linear acceleration against experimentally collected data for different standoff distances

3. METHODS

3.1 Blast Loading

Three explosive sizes, 5kg, 10kg, and 20kg C4 charges (6.7kg, 13.4kg, and 26.8kg TNT equivalent weight) were applied to the GEBOD model over varying standoff distances from 2.5m to 7.5m, these charges were modelled at 0.5m, 1m, and 1.5m heights of burst. These explosive sizes and HOB were chosen in accordance with the IED study (Figure 3), as well as to be comparable with experimentally collected pressure data from DRDC – Valcartier. All explosives were set with zero lateral offset from the GEBOD head center. A total of 20 simulations per explosive size and height of burst were performed giving a total of 180 simulated blast events modelled to determine the effect of varying the standoff distance and height of burst on head kinematics. Each blast scenario considered was modelled using explicit finite element hydrocode (LS-Dyna, LSTC) which utilizes a version of conventional weapons (ConWep) equations [20]; the method used in this paper was previously validated by Lockhart *et* al [19]. The blast was applied to the outward facing normals of the GEBOD using the *Load_Blast_Enhanced keyword (LS-Dyna, LSTC). This keyword defines an air blast function via application of pressure loads resulting from the detonation of a conventional explosive [21], based on the equivalent mass of TNT, the coordinate of explosive charge center, and a defined ground plane. This approach utilizes incident pressure, reflected pressure, ground reflection, as well as Mach stem effects, and applies the blast shockwave to a target by simulating a rapid increase in pressure, temperature, and density.

The incident pressure histories for a 5kg charge, at 4m standoff with a 1.5m HOB; for this particular explosive setup the triple point height would be approximately mid-thigh (Figure 6). At a height of 1.5m, which is above the Mach front, one can observe the dual pressure peaks created by the incident and reflected pressure waves respectively. Whereas at a height of 0.75m, which is just below the triple point, the blast waves converge into a single pressure peak with a higher maximum pressure than that of the incident wave.

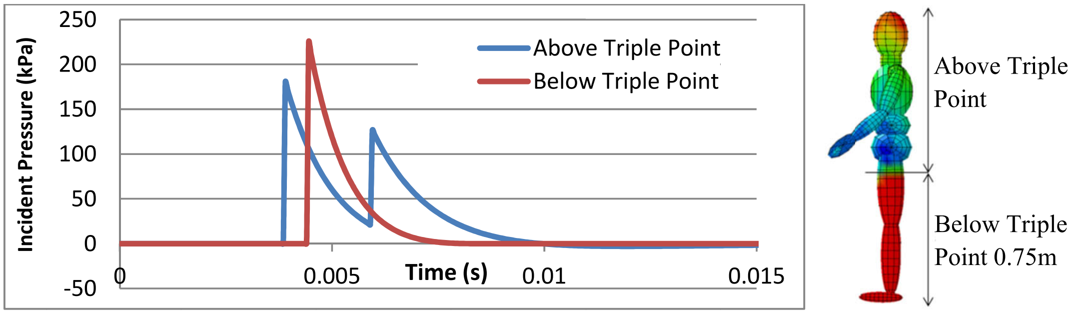


Figure 6 - Pressure history versus time of target locations above and below the Mach stem triple point for 5kg C4 at 4m with a 1.5m HOB.

3.2 Kinematic Response to Blast

The kinematic response was evaluated from the center of gravity of the GEBOD head for each blast event. The acceleration versus time data was extracted for each situation, and filtered using a CFC1000 filter with a cut-off frequency of 1650Hz, as was done in the experimental trials. This acceleration data was then evaluated based on the peak resultant acceleration and the HIC_{15}injury metric. A previous investigation determined that the GEBOD model head mass was lower than that of the Hybrid III dummy [19], thus in this study the head and neck mass was increased from 4.2kg to 4.54kg to be comparable.

4. RESULTS AND DISCUSSION

4.1 Pressure Validation

Three experimental blast tests were used to validate the incident pressure traces applied to the GEBOD model. The experimental cases, conducted at DRDC – Valcartier, included 5kg C4 charges, with a HOB and target height of 1.5m, applied at standoff distances of 3.5m, 4m, and 5m (Figure 7). For each distance two repeated tests were undertaken, and the static pressure was measured using side-on lollipop gauges to give two independent pressure profiles. These profiles were then compared to the simulated GEBOD blast environment using the same blast setup and orientation. The incident pressure applied to the GEBOD model gives comparable peak pressures and relative area under each pressure curve to that of the experimental pressure data.

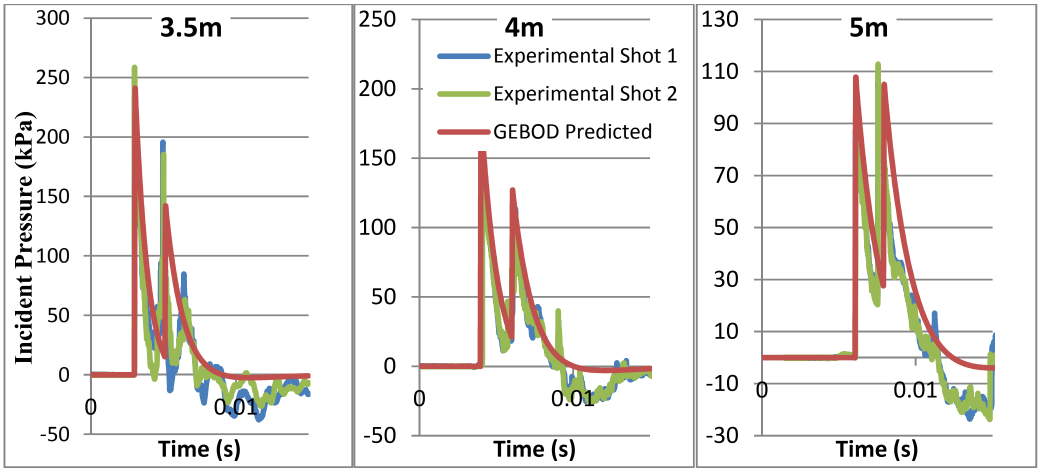


Figure 7 - Validation of GEBOD incident pressure versus experimentally collected pressure data.

4.2 Resultant Acceleration

In the current parametric study, the standoff distance from the center of gravity of the GEBOD head to the center of the explosive charge was varied from 2m to 7.5m (ground distance). The HOB of the charge was set at 0.5m, 1m, and 1.5m with no lateral offset from the target. Figure 8 shows the peak head acceleration as the blast wave reaches the head versus the standoff distance of the explosive charge.

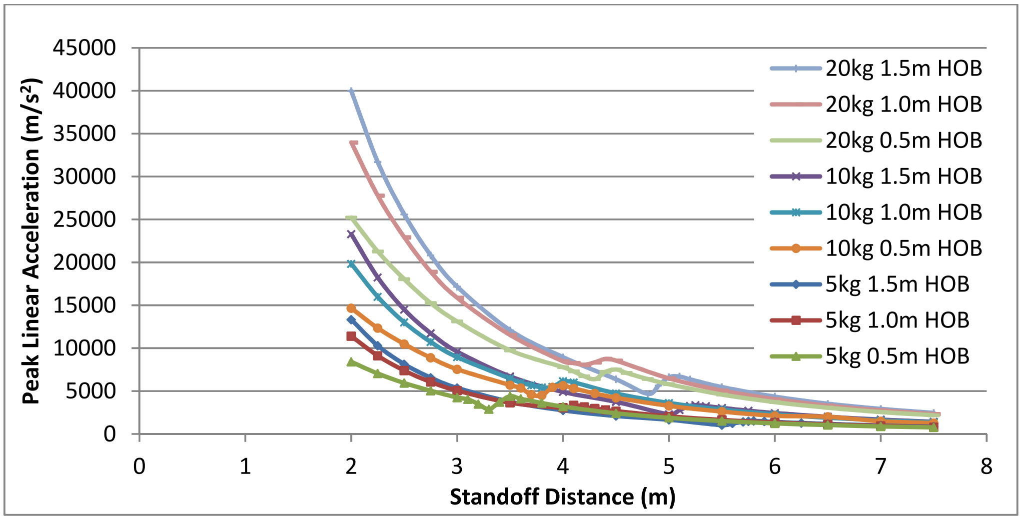


Figure 8 - Peak acceleration versus standoff distance, for all explosive sizes and HOB.

4.3 HIC$_{15}$

The predicted HIC$_{15}$ results (Figure 9) followed a trend similar to the resultant acceleration (Figure 8) with the close proximity blasts yielding HIC values greatly exceeding the tolerance level, with a quick degradation of the curve until the Mach stem effect caused a slight increase in the HIC values. As expected, larger explosive sizes resulted in higher acceleration values and thus a higher potential for head injury.

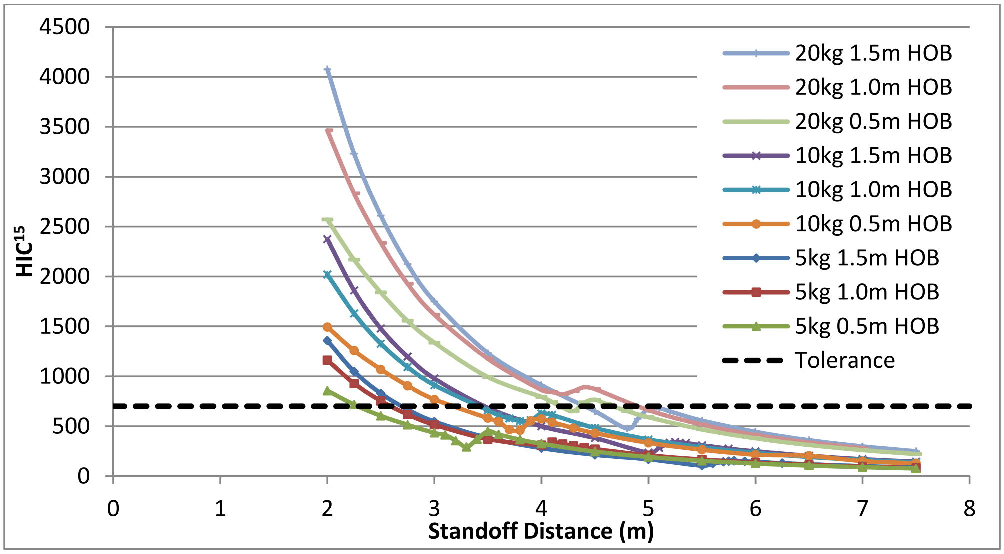


Figure 9 – HIC$_{15}$ versus standoff distance, for all explosive sizes and HOB.

4.4 Discussion & Limitations

For the close proximity blast scenarios investigated, there was a rapid acceleration of the head over approximately 1ms resulting from interaction with the blast wave. Increasing the standoff distance resulted in a reduction in peak acceleration until the Mach stem effect reached the height of the GEBOD head, which then caused an increase in acceleration. The Mach stem effect instantaneously increased the applied pressures when the triple point height reached the head height, leading to an increase in acceleration and expanding the potential injury zone surrounding a charge.

The trajectory of the triple point depends on the explosive size and HOB, with lower HOB resulting in earlier interaction of the head with the Mach stem since the incident wave reflection off the ground occurs earlier in time. The peak acceleration values for a lower HOB are smaller (for the same ground standoff) due to the increase in true distance from the head center of gravity to the charge center.

For a given HOB, the explosive size and standoff distance are the pertinent variables determining peak resultant head acceleration and thus resultant HIC$_{15}$ values in a blast scenario (Figure 10).

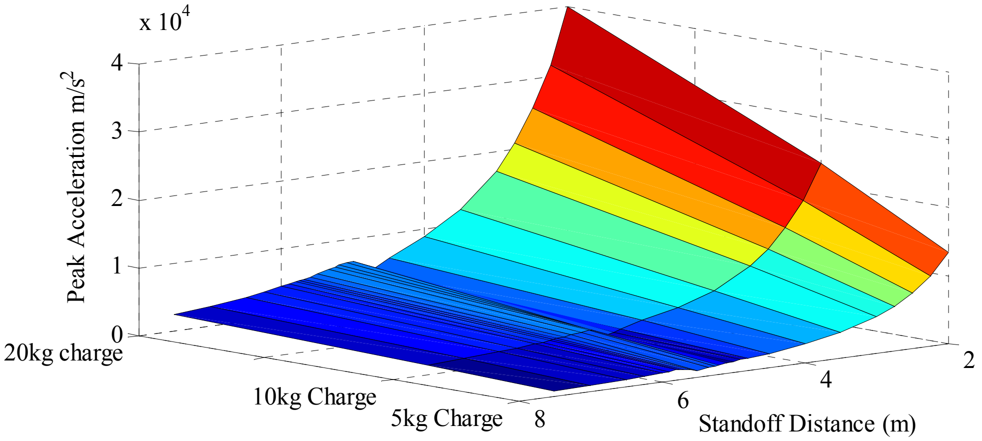


Figure 10 - 3D plot of Peak Acceleration versus Standoff for all three charges at 1.5m HOB.

In close proximity blast scenarios, rapid acceleration of the head along with other factors such as fragmentation and fireball impingement greatly increase the possibility of injury in an explosive event. This has not been considered in the current study and is the focus of a follow-on study. Tertiary (whole body displacement) and quaternary (other effects) blast injuries were not considered in the current study. This study investigated the global head kinematics resulting from direct interaction with a blast wave. The local tissue response and potential injury mapping of the motion described was not discussed, but is being addressed using detailed head models in a parallel study.

5. CONCLUSIONS

Improvised explosive devices have become more prevalent in modern conflicts and the ability to mitigate their effects is of significant importance. This study examined the resultant head kinematics of a multi-body model (GEBOD) exposed to various blast loading scenarios. The effects of the large accelerative loading were investigated using the HIC_{15} injury metric to determine potential injury resulting from blast events.

The explosive pressure wave was applied to the GEBOD model using enhanced blast capabilities implemented in LS-Dyna. This method models most major characteristics of a blast wave including overpressures and Mach stem effects by applying a rapid increase in pressure, temperature and density. The applied pressures resulted in a rapid acceleration in close proximity to the charge where the HIC_{15} tolerance level was exceeded for all explosive sizes tested. The peak resultant acceleration decreased with increasing standoff distance until the interaction of the Mach stem triple point and the GEBOD head. This was due to the Mach stem effect increasing the pressure applied to the head and thus increasing the accelerative force. For the lower HOB simulations, the Mach stem effect occurred at a reduced standoff distance, due to the incident wave reflecting off the ground earlier.

As expected, the predicted accelerations and head injury criteria decreased with increased standoff distance and the presence of a Mach stem resulting from an elevated charge has been found to increase the potential injury zone surrounding an explosive charge compared to a free field blast.

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