Evaluation of military helmets and roof padding on head injury potential from vertical impacts

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ABSTRACT
Objective: Soldiers in military vehicles subjected to underbelly blasts can sustain traumatic head and neck injuries due to a head impact with the roof. The severity of head and neck trauma can be influenced by the amount of head clearance available to the occupant as well as factors such as wearing a military helmet or the presence of padding on the interior roof. The aim of the current study was to examine the interaction between a Hybrid III headform, the helmet system, and the interior roof of the vehicle under vertical loading.

Methods: Using a head impact machine and a Hybrid III headform, tests were conducted on a rigid steel plate in a number of different configurations and velocities to assess helmet shell and padding performance, to evaluate different vehicle roof padding materials, and to determine the relative injury mitigating contributions of both the helmet and the roof padding. The resultant translational head acceleration was measured and the head injury criterion (HIC) was calculated for each impact.

Results: For impacts with a helmeted headform hitting the steel plate only, which represented a common scenario in an underbelly blast event, velocities of $\frac{2264}{6}$ m/s resulted in HIC values below the FMVSS 201U threshold of 1,000, and a velocity of 7 m/s resulted in HIC values well over the threshold. Roof padding was found to reduce the peak translational head acceleration and the HIC, with rigid IMPAXX foams performing better than semirigid ethylene vinyl acetate (EVA) foam. However, the head injury potential was reduced considerably more by wearing a helmet than by the addition of roof padding.

Conclusions: The results of this study provide initial quantitative findings that provide a better understanding of helmet–roof interactions in vertical impacts and the contributions of the military helmet and roof padding to mitigating head injury potential. Findings from this study will be used to inform further testing with the future aim of developing a new minimum head clearance standard for occupants of light armored vehicles.

Introduction

Soldiers in military vehicles subjected to an underbelly (UB) blast event can sustain traumatic head and neck injuries due to head impact with the vehicle roof. This can occur by at least four different mechanisms: (1) the vehicle is involved in a rollover, (2) the vehicle has suspension seats and the straps loosen as a result of the blast, (3) the soldier is unbelted and hits the roof through their own inertia, and (4) the soldier is restrained but the extensive upward hull deformation results in an impact with the roof. In the hull deformation case, which is the focus of the current study, once the seat has stroked (the occupant has stopped moving vertically down as the energy absorption from the seat has been exhausted), the occupant then moves vertically upwards with the seat due to the deforming floorpan. This may then result in a head impact, as shown in Figure 1, where a straight-spine Hybrid III (HIII) is being tested in a UB live-fire blast event.

In this case, the likelihood of a head impact with the roof will depend on factors such as the blast magnitude, the proximity of the solider to the blast, the effectiveness of the energy-absorbing seat system, and the head clearance available (which will depend on the vehicle roof height and the seated height of the soldier). Head and neck injury potential will be determined not only by these factors but also by wearing a military helmet, the type and condition of the helmet, and the impact surface.

Increasing the amount of head clearance available to the occupant will reduce the likelihood of a head impact and, should a head impact occur, result in less severe head and neck injuries. However, the amount of vertical space available for soldiers in military vehicles can be constrained by a multitude of vehicle design and injury mitigation considerations such as the need to limit the overall height of the vehicle for operative reasons (Cimpoeru et al. 2015), space for equipment stowage, and the need for a well-designed energy-absorbing seat system to mitigate thoracolumbar spinal trauma. As these factors restrict the amount of vertical space available to the occupant, in some military vehicles, the soldier’s head can be quite close to, or even be touching, the roof.

Although there are automotive standards specifying the maximum amount of roof intrusion allowed in civilian passenger vehicles due to rollover (i.e., 127 mm; NHTSA 1995), thus...
Figure 1. Live-fire UB blast testing with a straight-spine HIII. Extensive vehicle hull and floorpan deformation resulted in a head impact where both head and neck injury criteria were considerably over the relevant injury thresholds: (a) pretest, (b) during the head impact, and (c) evidence of a crown head strike as shown by witness marks on helmet.

Upper Interior Head Impact Protection (NHTSA 1998) is used to assess occupant injury potential from head impacts with the upper interior of the vehicle (e.g., the roof, headliner, side rails, and the A- and B-pillars). For this standard, tests are conducted with a free motion headform (FMH) at 24 km/h (6.67 m/s) or, for locations where a curtain airbag may deploy, 19 km/h (5.28 m/s). The FMH data are used to calculate the HIC(d), a modified head injury criterion that must not exceed 1,000 and compensates for the effects that the inertia of the body would have on the motion of the head. Although automotive tests and standards are not designed to test injury potential in military scenarios, at present they are used as there are few alternatives.

Thus, the aim of the current study was to use an FMH to examine the interaction between the helmet system and the interior roof of the vehicle due to vertical impacts with the roof such as those seen in UB blast scenarios. This included testing different types of roof padding for injury mitigation, finding the effect of not wearing a military helmet, and determining the head velocities for which a vertical roof impact is likely to exceed the FMVSS 201U threshold and thus be predicted to result in a serious head injury. It was anticipated that the data from this study would provide initial quantitative findings that could be used to understand the helmet–roof interactions in vertical impacts, and also provide data that can later be used to extend the Test Series to examine both head and neck injury potential in UB blast events, with the future aim of developing a new minimum head clearance standard for occupants of light armored vehicles.

Material and methods

Testing apparatus

An FMH machine, which is designed for FMVSS 201U assessments, was used to perform vertical impact tests on a rigid steel plate bolted to the ground. The steel plate was 840 mm in both length and width and 15 mm in thickness. The FMH machine was modified to conduct vertical impacts and the FMH headform, which is designed for impacts to the forehead and thus has a flat facial region, was replaced with a 50th percentile HIII headform, denoted HIII FMH in the current study (Figure 2). Nine MSI 64-2000-10-360-LD, 2,000 g accelerometers in a 3-2-2-2 arrangement (to form a 9-accelerometer package) were installed in the headform for data acquisition, although only the three sensors at the center of gravity were used in the current study. The data were sampled at a rate of 20 kHz using a TDAS Pro 32 DR0024 channel data rack (DTS, Seal Beach, CA). The tests were then performed according to the FMVSS 201U standard, which involves accelerating the headform vertically upwards using the impactor machine and then releasing it at a prespecified velocity 25 mm from the target. The target was either the steel plate only or the roof padding coupon adhered to the steel plate. Tests were conducted both with and without a military helmet: the previously in-service Australian Defence Force aramid helmet, the RBH 303 AU, (Rabintex Industries Ltd, Israel), size medium, with ¾-in. Team Wendy ZAP pads. The standard-issue helmet has a harness with the original equipment manufacturer’s ring suspension: the suspension was removed and the helmet retrofitted with the pads (according to the manufacturer’s instructions) as this helmet and
pad combination is commonly used by soldiers. For each test, the helmets were fit and fastened to the headform by one person, a technician who had been trained to fit the helmets correctly according to the manufacturer’s instructions, and using advice from an ergonomist specializing in fitting helmets. All tests were conducted at ambient temperature (∼23°C).

For each impact, the maximum resultant translational acceleration ($a_T$) at the center of gravity of the headform was measured and the HIC($d$) calculated according to Eqs. (1)–(2):

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

(1)

$$\text{HIC}(d) = 0.75446 \times \text{HIC}_{36} + 166.4,$$  

(2)

where the head acceleration values were filtered using CFC 1000 and the HIC$_{36}$ calculated for Eq. (2). Although HIC$_{15}$ is more suitable for shorter-duration impacts, given the short impact duration in the current study, HIC$_{36} = \text{HIC}_{15}$ as $t_2 - t_1 < 15$ ms for all shots. Where relevant, the NHTSA expanded Prasad/Mertz equations (NHTSA 1997) were used to estimate the predicted injury severity sustained according to the Maximum Abbreviated Injury Scale (MAIS) value (Association for the Advancement of Automotive Medicine 2008).

In order to determine how many tests could be performed with the same helmet and helmet padding, repeated tests were initially conducted. The methodology and text matrix for these tests is presented in Table A1 (see online supplement).

**Roof padding analysis**

Two different types of foams were tested in order to determine their potential effectiveness on brain injury mitigation under impact. IMPAXX (Dow Chemical Co., Midland, MI) is an extruded polystyrene, rigid, closed-cell, plastically deforming, energy-absorbing foam, designed for automotive applications. Ethylene vinyl acetate (EVA), sourced from Pao Leisure Pty Ltd. (Milperra, Australia), is also a closed-cell foam but is semirigid and viscoelastic. Both IMPAXX and EVA have been integrated into civilian passenger vehicles in headliners, pillar trims, and headrests and as the two materials have different compressive properties, they were chosen for the current study.

IMPAXX foam is available in three densities: IMPAXX 300, IMPAXX 500, and IMPAXX 700, where the number designation correlates to the approximate compressive strength of each product in kilopascals. EVA foam is manufactured to a specific density depending on the intended use: in the current study, EVA 75.0 was used. Although the compressive strength was not provided by the manufacturer, tests by a different manufacturer (Ultralon Foam Group, Christchurch, New Zealand) demonstrated that the compressive strength of EVA 75.0 was 70 kPa (noting that this value is approximate, as each grade of foam has a density tolerance range). Foam densities were selected based on their potential to have the best energy-absorbing response under the impact energy range used in the tests. Although a thick roof foam with a low density would be expected to offer the greatest protection to occupants, the thickness of any foam retrofitted into a military vehicle needs to be minimized due to the limited vertical space available but be considerable enough to not densify (i.e., bottom out) under impact. Using a nominal thickness of 15 mm (approximately the maximum that can be accommodated in a light armored vehicle) and after examining the available stress–strain data available for each foam, IMPAXX 300 ($\rho = 38.5$ kg/m$^3$), IMPAXX 500 ($\rho = 40.4$ kg/m$^3$), and EVA 75.0 ($\rho = 75.0$ kg/m$^3$) were chosen for testing. As IMPAXX and EVA foams were not readily available in exactly the same thickness; 15 mm was used for the IMPAXX foams and 12 mm for the EVA. Thus, although the results could be compared, they were not directly comparable.

The roof padding coupons were cut to a standard size of approximately $220 \times 200$ mm and then adhered to the steel plate. Impacts were performed at 6 and 7 m/s as it has been observed from blast testing that these velocities are indicative...
of an occupant over or near the blast who may sustain a hard head impact. Data from Defence Science and Technology (DST) Group show that velocities near the seat range from ~3.5 to 12.1 m/s, which is consistent with seat accelerometer data from the literature where seat velocities of 4.0 to 10.2 m/s and 5.6 to 12.4 m/s have been used to simulate UB blast events using cadaver and HIII sled tests respectively (Bailey et al. 2015). For an occupant over the blast, a representative velocity curve from the seat from DST Group data had a peak acceleration of ~7.7 m/s (Figure 2), whereas another representative curve in the literature had a peak velocity of ~ 9 m/s (Bailey et al. 2014), although this is considered to be quite high (Bailey et al. 2015): for HIII and cadaver tests, seatpan velocities above 7 m/s are considered to be high, and seatpan velocities below 7 m/s are considered to be low (Bailey et al. 2015). Thus, the current study mainly focused on impact velocities of 7 m/s, but as the results from the repeated impact tests (Figure A2, see online supplement) demonstrated that 6 and 7 m/s velocities resulted in an HIC(d) near or over the FMVSS 201U threshold of 1000, the 6 m/s velocity was also of interest.

For each of the three types of roof foam, three impacts were performed at two different velocities; thus, there were a total of 18 impacts (Table 1, Test Series 1) with the headform wearing a military helmet for all 18 impacts. After each test, both the test coupons and the helmet pads were replaced, as the repeated impact tests demonstrated that the helmet padding should be replaced after each impact at these velocities (refer to Appendix, online supplement).

### Injury mitigating effects of different helmet and roof padding combinations

In order to examine head injury potential due to the interaction between the helmet system and the interior impacting surface of the vehicle, impacts were conducted in four different configurations: these included tests with and without the helmet in addition to impacts with the roof padding and with the steel plate only (Table 1, Test Series 2). Tests were performed at 7 m/s as this velocity best represents hard impacts in an UB blast event, and IMPAXX 500 foam was used as the results of the roof padding analysis demonstrated it had the best injury-mitigating capabilities at 7 m/s. When used, the roof padding was replaced after each impact, and the helmet padding was replaced after each test according to the results of the repeated impact testing (Figure A2, see online supplement). The \( \alpha_T \) and HIC(\( d \)) values were determined for each test.

### Statistical analysis

Due to the small sample size for each impact condition, \( t \)-tests were not conducted; instead, the effect size was calculated to evaluate the magnitude of the difference in the \( \alpha_T \) and HIC(\( d \)) values between different impact conditions. This was performed by calculating Cohen's \( d \) (Cohen 1992), where \( d = (M_1 - M_2)/SD_{pooled} \), \( M_1 - M_2 \) is the difference between the group means (\( M \)) and \( SD_{pooled} = \sqrt{[(SD_1^2 + SD_2^2)/2] \). Effect sizes were classified as small (\( d = 0.2 \)), medium (\( d = 0.5 \)), large (\( d = 0.8 \)), or very large (\( d \geq 1.3 \)). Effect sizes were calculated using Microsoft Excel 2010.

### Results

An example of a 7 m/s test is shown in Figure 3. When the impact velocity was 7 m/s, the HIII FMH hit the impacting surface (either the steel plate or foam padding) at 65 ms, whereas the deceleration curve (shown as an acceleration in Figure 3) peaked later (at 70 ms in the example shown) depending on the damping effect of the helmet and/or roof foam. For all impact velocities, the piston stopped accelerating at 60 ms, at which time the headform was released at the specified velocity.

### Roof padding analysis

The \( \alpha_T \) and HIC(\( d \)) results at 6 and 7 m/s for the three foams and the steel plate only are shown in Table 2, Test Series 1. Comparison of the 6 m/s data for the three foams and steel plate revealed that the IMPAXX 300 had a lower average \( \alpha_T \) and HIC(\( d \)) than the other two foams (very large effect size with \( d > 1.4 \) for all tests).

At an impact velocity of 7 m/s, the average \( \alpha_T \) for the IMPAXX 300 and IMPAXX 500 foams was the same (small effect size, \( d = 0.2 \)), whereas the average HIC(\( d \)) was lower for the IMPAXX 500 than the IMPAXX 300 (medium effect size, \( d = 0.5 \)). Although the IMPAXX 500 was slightly better than the IMPAXX 300 at 7 m/s, both foams resulted in considerably lower \( \alpha_T \) and HIC(\( d \)) values than the tests on the steel plate only with very large effect sizes (1.9 < \( d < 5.4 \)). Although the \( \alpha_T \) and HIC(\( d \)) values were lower for the EVA tests than for the steel plate–only tests, with large (\( d = 0.9 \)) and medium (\( d = 0.7 \)) effect sizes for the \( \alpha_T \) and HIC(\( d \)) values, respectively, these effect sizes were not as large as those between the IMPAXX and steel plate–only tests.

The results indicate that at an impact velocity of 6 m/s, the best performing foam was the IMPAXX 300, whereas at 7 m/s, the IMPAXX 500 performed marginally better than the IMPAXX 300. The EVA provided less energy attenuation than either of the IMPAXX foams at both 6 and 7 m/s. However, the EVA test coupons were thinner than the IMPAXX coupons (12 and 15 mm, respectively), which most likely contributed to its poorer performance.

### Table 1. Test matrix for impacts with different foams (Test Series 1) and tests with different helmet/roof padding combinations (Test Series 2).

| Test Series no. | Impact velocity (m/s) | Helmet   | Impacting surface | No. of tests |
|-----------------|-----------------------|----------|-------------------|--------------|
| 1-1             | 6                     | Y        | IMPAXX 300        | 3            |
| 1-2             | 6                     | Y        | IMPAXX 500        | 3            |
| 1-3             | 6                     | Y        | EVA               | 3            |
| 1-4             | 7                     | Y        | IMPAXX 300        | 3            |
| 1-5             | 7                     | Y        | IMPAXX 500        | 3            |
| 1-6             | 7                     | Y        | EVA               | 3            |
| Total           |                       |          |                   | 18           |
| 2-1             | 7                     | Y        | IMPAXX 500        | 3            |
| 2-2             | 7                     | Y        | Steel plate       | 3            |
| 2-3             | 7                     | N        | IMPAXX 500        | 3            |
| 2-4             | 7                     | N        | Steel plate       | 3            |
| Total           |                       |          |                   | 12           |

\(^{a}\)Tests 1-5 and 2-1 are the same.
and at 6 m/s, an MAIS 2 injury was predicted to be most likely (~39–41% probability). Hence, for helmeted hard impacts, the roof padding did not considerably reduce the predicted head injury potential.

The acceleration–time traces at 7 m/s (Figure 4a) demonstrate the immediate and uniform damping effects of the IMPAXX foams, which produce smooth traces for the duration of the impact. The EVA trace, however, is characterized by two peaks, which is similar to the traces measured for the impacts to the steel plate only. A similar pattern was observed for the 6 m/s traces (Figure 4b).

**Injury mitigating effects of different helmet and roof padding combinations**

The results for the different military helmet and roof padding combinations (Table 2) demonstrate that although the roof foam was beneficial in reducing both the $a_T$ and HIC($d$), the protective effect of the helmet was far greater than the roof foam. For impacts between the unhelmeted headform and the steel plate only, the average HIC($d$) was 13,651 (MAIS 6; fatal: outside the meaningful HIC range). When the roof foam is used, the average HIC($d$) was substantially lower (2,577), although the most likely outcome would still be an MAIS 6 injury (~90% likelihood). However, when the helmet was worn, even when no roof foam was present, the average HIC($d$) was low enough (1,277) to result in a most likely injury severity of only MAIS 3 (~41% likelihood). When both helmet and foam were present, the average HIC($d$) = 1,126; thus, although lower in value than the helmet but no-foam case, the injury potential is the same (~41% likelihood of an MAIS 3 injury). The effect size between conditions was very large for all tests (2.6 < $d$ < 150.7 for both $a_T$ and HIC($d$) values). These results demonstrate that although energy mitigation can be achieved by the use of roof foam, the effect of wearing a helmet reduces injury potential far more than the reduction in injury potential from roof padding.

The acceleration–time traces (Figure 4c) demonstrate the injury mitigating effect of the helmet and roof paddings. The no-helmet/no foam traces are characterized by a short-duration triangular pulses with peak magnitudes >1,000 g, and the addition of roof foam extends the duration of the impact, resulting in a lower $a_T$ (~400 g). In addition, the immediate energy mitigation response of the IMPAXX foam results in an initial loading rate that is considerably slower than the loading rate to the steel plate only; however, the gradient later increases steeply, potentially indicating the point that the foam has bottomed out under

![Figure 3](image-url) Exemplar high-speed footage corresponding to the acceleration–time plot. Note that the sampling rate of the camera was one frame per millisecond; thus, the absolute peak acceleration (202.3 g at 70.20 ms) was not captured by the high-speed photography. The figure shows the first impact in the second series of 7 m/s repeated impact tests.

Despite the differences in $a_T$ and HIC($d$) values for the various impact surfaces, for the same velocity, the injury predictions were similar for each case: at 7 m/s, the most likely predicted outcome was an MAIS 3 injury (~41% probability)

| Helmet | Roof padding | Test no. | $a_T$ (g) | HIC($d$) | MAIS$^a$ |
|--------|--------------|---------|----------|----------|--------|
| Y      | IMPAXX 300   | 1-1     | 134 (3.4) | 777 (19.7) | MAIS 2 |
| Y      | IMPAXX 300   | 1-2     | 141 (2.4) | 829 (32.6) | MAIS 2 |
| Y      | IMPAXX 300   | 1-3     | 168 (3.7) | 867 (19.5) | MAIS 2 |
| Y      | EVA 75.0     | 2-1     | 182 (3.3) | 1,147 (51.7) | MAIS 3 |
| Y      | None         | 2-2     | 214 (11.2) | 1,126 (23.1) | MAIS 3 |
| N      | IMPAXX 300   | 2-3     | 422 (16.8) | 2,577 (161.1) | MAIS 6 |
| N      | None         | 2-4     | 1,162 (21.0) | 13,651 (84.0) | MAIS 6 |

$^a$Predicted/most likely MAIS of head injury due to impact according to NHTSA expanded Prasad/Mertz equations (NHTSA 1997).
Figure 4. The Hill head \( \alpha_{\text{V}} \) vs. time graphs for all impacts at (a) 7 m/s for the 3 different foams, (b) 6 m/s for the 3 different foams, and (c) 7 m/s for the Test Series to evaluate the helmet and roof foam contributions to injury mitigation.

In the current study, three roof padding foams were assessed for their capability to mitigate head injuries. The EVA was shown to be less effective than the two IMPAXX foams, potentially due to the different mechanisms by which energy is absorbed by each type of foam. For IMPAXX, energy absorption occurs through plastic buckling of the cell walls within the foam, whereas energy absorption in EVA foam is achieved through viscoelastic compression of the cell walls; thus, unlike the IMPAXX, EVA generally re-forms to its original thickness when the load is removed (compressive resilience of EVA 75.0 \( \leq \) 56%). Although the viscoelastic behavior of EVA may be a practical advantage if there is a need to use the material for more than one impact, the IMPAXX foams were shown to be more effective than EVA at attenuating the impact energy for the impact velocities assessed in this study.

The performance of the IMPAXX 300 and 500 foams did not differ greatly at either impact velocity tested; however, due to the greater compressive strength of IMPAXX 500, this foam is probably a better choice for the interior roof as the thickness could possibly be reduced without compromising performance. Further studies to evaluate the potential for IMPAXX as a retrofit solution may be best achieved using a finite element parametric analysis to optimize the foam parameters such as thickness and density.

Although IMPAXX performed better than EVA in this study, other foams are also used in the automotive industry and may be of practical use in military vehicles; for example, expanded polypropylene (EPP), expanded polystyrene, and cork (Coelho et al. 2011; Kleiven 2007). Anderson and colleagues (2002) tested nine different padding materials, including EPP, in order to develop a headband for motor vehicle occupants for head injury mitigation. They found that rigid foams that crushed during impact and those with a columnar structure provided better protection than other materials, which was consistent with the results of the current study. Although Anderson (2002) and colleagues chose EPP over other similar materials due to EPP’s durability and ease of manufacture, IMPAXX foam has been shown to exhibit more efficient energy absorption than EPP when the density of both materials are similar (Slik et al. 2006); however, as these data are from the IMPAXX manufacturer, they require independent verification.

The data in the current study show that, in the event of a high-velocity head–roof impact, the most likely outcome for a soldier not wearing a military helmet in a typical UB blast event is a fatality, regardless of the presence of roof foam.
Although the helmeted impacts to the IMPAXX roof padding resulted in the lowest average $a_T$ and HIC($d$) values, the contribution of the roof padding to injury mitigation is minimal. With vertical space at a premium in many military vehicles, these results indicate that wearing a helmet is a better option than retrofitting a vehicle with roof padding. Although not wearing a helmet increases the head clearance available in the vehicle and possibly offers enhanced comfort for the combatant, the greater injury potential when not wearing a helmet is substantial and the use of roof padding alone does not sufficiently mitigate this risk. Thus, the results of the current study support the requirement for soldiers to wear their helmet at all times in military vehicles when in a high-threat environment (i.e., when there is a risk of a landmine attack). Roof padding may be a secondary option if a helmet cannot be worn for logistical or operational reasons; however, although roof padding reduces the likelihood of head injuries, it has been demonstrated that it can also exacerbate the potential for, and severity of, neck injuries (Nightingale et al. 1997). For example, previous research has shown that although the presence of foam, which increases surface friction, can protect against head injuries, it can also constrain the movement of the head during the impact, therefore generating large compressive loads in the neck as the torso continues to move. An interesting outcome of the current research is that the results may have implications for determining head injury potential in military vehicles in situations other than a UB blast event. For example, in a previous study, computer simulations of head impacts that occurred due to incidents in military vehicles used for transport demonstrated that head injuries are most likely to occur in the 5–7 m/s head velocity range (Dorn and Carr 1998). Thus, further testing in this velocity range would seem pertinent for future work.

Neck injury potential was not assessed in the current study as the aim was to understand the interaction between the helmet and the roof for different roof padding surfaces and impact velocities, which required a large number of tests. Although head and neck injury may occur in conjunction in UB blast events, the studies discussed above indicate that head injury may be the dominant injury mode when the head hits a relatively low-friction surface such as an unpadded military vehicle roof. These issues need to be quantified in a further study, including investigating the effect of a full-body anthropomorphic test device, which may alter the kinematics of the impact.

One limitation of this study is that helmet-mounted equipment that combatants often wear, such as night vision goggles and combat ID devices, were not considered; however, it is unlikely that these items would alter the structural integrity or performance of the helmet shell. Additionally, only one type of helmet was tested. It is possible that a bump helmet, which has limited ballistic protection, may offer sufficient protection from blunt vertical impacts in the vehicle while reducing the mass burden on the wearer.

At present, there is no military standard to specify the minimum head clearance required to mitigate the risk of head and/or neck trauma due to UB blast loading. Furthermore, in live-fire tests of military vehicles, a straight-spine 50th percentile HIII, usually an FAA HIII, is used to determine head and neck injury potential: the FAA HIII has a sitting height of 907 mm, which represents approximately the 20th percentile Australian Army male combatant sitting height (Edwards et al. 2014). Thus, it is likely that the probability of a head impact and subsequent head and neck injuries is currently being underestimated in live-fire UB blast tests.

Using the results of the current study as a guide, future work will involve sled or other tests to ascertain the combined head and neck injury potential under specific impact velocities. In addition, tests will be conducted with the neck in different positions (i.e., in flexion and extension), as previous cadaveric tests have shown that the position of the neck affects the frequency and severity of neck injuries (Nightingale et al. 2015). It is anticipated that this work will lead to the future development of head clearance standards for occupants of light armored vehicles.

In the current study, vertical head impacts replicating UB blast loading were performed in order to evaluate the performance of both the helmet and various roof padding materials in mitigating head injury potential. Repeated tests demonstrated that the helmet shell could be used for up to 12 sequential impacts for velocities up to 7 m/s, but the helmet padding should be replaced for impact velocities greater than 3 m/s due to padding degradation. Vertical impacts at velocities ≤ 6 m/s resulted in HIC values below the FMSS threshold, whereas vertical impacts at 7 m/s or greater, which include those typical of an UB blast scenario, resulted in HIC($d$) and $a_T$ values that exceed the reference threshold values and thus are likely to cause serious head injuries.

The two IMPAXX foams tested demonstrated better performance than the EVA at both 6 and 7 m/s. However, wearing a helmet was found to be far more important for injury mitigation than the presence of roof padding. Although roof padding may be beneficial in some cases—for example, if the soldier is unable to wear a helmet for operative reasons—the results of this study suggest that a helmet should always be worn inside the vehicle to protect against potential head injury due to UB blast loading.

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