Helmet Blast Attenuation Performance

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Abstract. The Blast Overpressure Simulation System (BOSS), an advanced blast simulator, and the Human Surrogate Headform Model (HSHM), an instrumented test device, developed at the Johns Hopkins University Applied Physics Laboratory were previously used to establish requirements for a standardized blast test methodology for headborne protective equipment. This methodology was used herein to test and evaluate the blast attenuating performance of eight currently fielded and historic helmet systems. Specifically, tests were designed to examine the effects of helmet geometry, material, and suspension system (e.g. pad vs. sling). The HSHM was mounted on a Hybrid III neck, outfitted with each helmet system, and exposed to a blast overpressure pulse inside the BOSS using a face-on configuration. Overpressure was measured along the walls of the BOSS as well as on the surface of the headform at 18 locations. Data from an accelerometer and angular rate sensor inside the headform, combined with high speed video of each event, was recorded to quantify the kinematic response of the head/neck. Characteristic shock wave metrics including peak overpressure magnitude, positive phase duration, and positive phase impulse were calculated for each sensor location for every test, and used for a comparative analysis across helmet systems. Of the helmet variables examined, changing the suspension system resulted in the greatest differences in response. Helmet geometry was also a large driver in recorded differences, while helmet shell material showed the weakest contribution to differentiating between helmet systems. This test series demonstrated the ability of the previously-developed test methodology to characterize and distinguish between helmets when considering differences in geometry, material, and suspension system. Recommended future work to examine alternate orientations will elucidate a greater understanding and sensitivity of these effects on overall helmet blast attenuating performance.

1. INTRODUCTION

Currently, there is no standard test method or criteria for evaluating the blast attenuating performance of headborne personal protective equipment (PPE). Prior work conducted by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) and the U.S. Army Combat Capabilities Development Command (CCDC) Soldier Center resulted in the development of a robust laboratory test methodology for evaluating headborne PPE in blast overpressure conditions[1]. The primary focus of the prior work was developing and validating highly repeatable laboratory equipment (e.g. shock tube and instrumented headform) and analytical methods to induce a planar shock wave and assess the kinetic and kinematic response of the head. The purpose of the current study is to use this methodology to assess the blast attenuating performance and examine the effects of various design elements of 8 combat helmet systems that had a variety of shell geometries, shell materials, and suspension system types.

2. METHODS

All blast tests were conducted using the Blast Overpressure Simulation System (BOSS) (Figure 1) located at JHU/APL and the Basic Human Surrogate Headform (HSHM/B) (Figure 2), as described in [1]. Briefly, the headform was mounted on a Hybrid III neck, placed within the test region of the 91 cm x 91 cm BOSS, and exposed to a shock wave created using an acetate plastic membrane and compressed air gas. The HSHM/B has 18 surface pressure measurement locations as well as an internal triaxial accelerometer and angular rate sensor.

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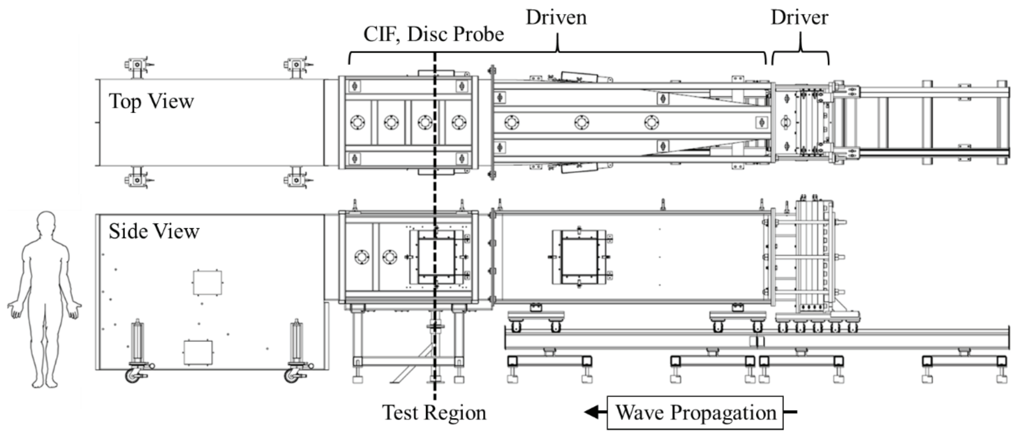

Figure 1. Blast Overpressure Simulation System (BOSS). Note that the CIF and Disc Probe sensors align with the dotted line and are located inside the BOSS; on the wall and in the flow, respectively.

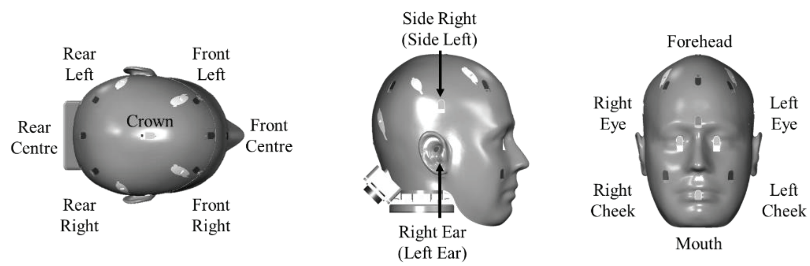

Figure 2. Basic Human Surrogate Headform Model (HSHM/B) with each sensor location labelled.

All tests in the current study were conducted with a forward-facing orientation to simulate an eye-level blast; however a subset of the helmets tested had previously been evaluated in 3 other orientations (side, rear, and inclined). Table 1 shows the test matrix. Each helmet system was tested at least 10 times.

Table 1. Test matrix of eight helmet systems.

Identifier	Shell Geometry	Shell Material	Suspension System	Fielded Status	Sample Size
No Helmet	-	-	-	-	24
A1P	A	1	Pad	Fielded	11
A1S	A	1	Sling	No*	10
B1P	B	1	Pad	No*	10
B1S	B	1	Sling	Historic	10, 3**
B2S	B	2	Sling	No	10, 3**
C3S	C	3	Sling	Historic	10
D1H	D	1	Honeycomb	Historic	10
E4P	E	4	Pad	Fielded	14

*These two configurations are not outfitted as fielded; rather, the fielded suspension systems were swapped between the shell geometries specifically to examine the effect of suspension system in the alternate shell geometry.
**The additional three tests were conducted with an updated fitting protocol for the helmet on the headform.

This study assessed the performance of eight helmet configurations consisting of combat helmets from multiple countries and from multiple generations. There were 5 unique helmet shell designs; geometry A corresponded to a tactical cut, B corresponded to a full cut, C corresponded to a historic cut,

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D corresponded to a single-size full cut, and E corresponded to a high cut helmet. Geometries B, C, and D have a brim on the front of the helmet. Geometry E has a high cut around the ear; all other geometries cover the ear. Helmet shells were constructed of 1) aramid, 2) sheet moulded compound (SMC) consisting of fiberglass-reinforced thermoset plastic, 3) steel, and 4) ultra-high molecular weight polyethylene (UHMWPE). Note, the SMC helmet was not a fielded helmet design, but included in this study to assess the effects of material for a given shell shape and suspension system combinations. Suspension systems ranged from polyurethane foam pads (P) to fabric slings (S) and plastic honeycomb (H) designs. Non-standard suspension system configurations were tested to assess the effect of suspension system for a given shell geometry and material. A1S represents a tactical cut helmet retrofitted with a sling suspension system from a full cut helmet, and B1P represents a full cut helmet retrofitted with a pad suspension system from a tactical cut helmet. Table 2 shows midsagittal view (via computed tomography) of each of the helmets outfitting on the headform.

3. RESULTS

The metric of peak overpressure showed the greatest sensitivity to changes in helmet systems. There was less variation in positive phase duration and positive phase impulse compared to peak overpressure measurements. While positive phase duration and positive phase impulse were analysed, the following presentation of results focused on pressure versus time data traces and peak overpressure measurements.

3.1 Evaluation of Input Conditions

It is of utmost importance that any test methodology intended to evaluate performance is repeatable. Examining the sensor responses of the BOSS sensors (downstream and around the test object) is one way to examine the repeatability and reproducibility of the input conditions over a test series.

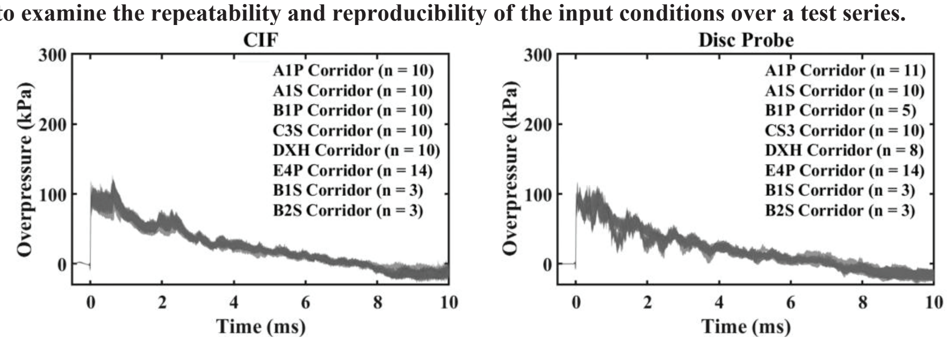

Figure 3 shows the response corridors for the Disc Probe and the CIF pressure sensor locations within the BOSS (Figure 1). The Disc Probe measures static overpressure and is located alongside the headform in the fluid flow. The CIF pressure sensor also measures static overpressure, but is located flush with the inner top surface of the BOSS. These two sensors have been selected to assess the repeatability of the system. Other sensors downstream of the headform can also be used, and show a similar result as the Disc Probe and CIF sensors. Note that in these images, all of the corridors, which represent average ± 1 standard deviation of each test configuration, are plotted simultaneously, and that a dark colour indicates an overlapping region. The lack of drastic differences in these corridors indicates repeatability. The tests shown in these and the following figures were randomized and conducted over the course of three months; the tight corridors therefore also indicate reproducibility over time. The figure legends are included to show the number of tests included within each corridor.

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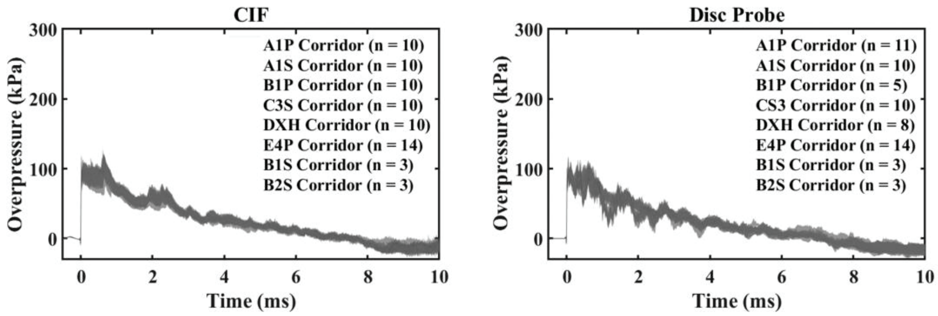

Figure 3. Response corridors at two locations in the BOSS for all test conditions, overlaid.

3.2 Effect of Geometry

In order to isolate and assess the effect of helmet shell geometry on blast attenuating performance, an identical 7-pad suspension system and identical fabric sling suspension system were installed and tested in two different aramid helmet shells, one with a tactical cut and one with a full cut. The effect of geometry was assessed through two comparisons: A1P v. B1P, and A1S v. B1S (A1P and B1S represent fielded configurations). The results can be more broadly interpreted and applied in common helmet designs by evaluating the effect of helmet shell geometry with both pad and sling suspension systems, rather than one or the other. Peak overpressures for the headform sensors are shown in

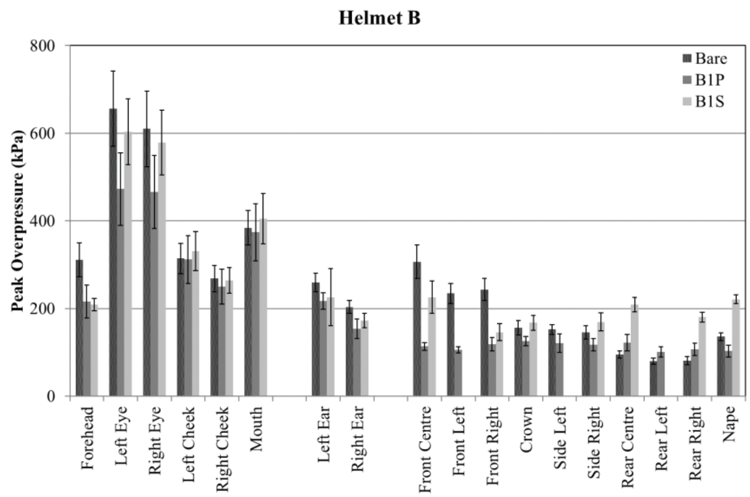

Figure 4, and corridor (average ± 1 standard deviation) responses for select headform sensors are shown in Figure 5. Peak pressures were generally similar for the two helmet geometries, except for at the forehead and eye pressure sensors, where geometry B (full cut, with brim) generally had lower peak pressures that geometry A (tactical cut, no brim). Corridor responses showed some differences in the shape of the pressure versus time response between the two helmet shapes.

3.3 Effect of Suspension System

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The effect of suspension system (pad versus sling) was assessed through two comparisons: A1P v. A1S, and B1P v. B1S. Peak overpressures for the headform sensors are shown in

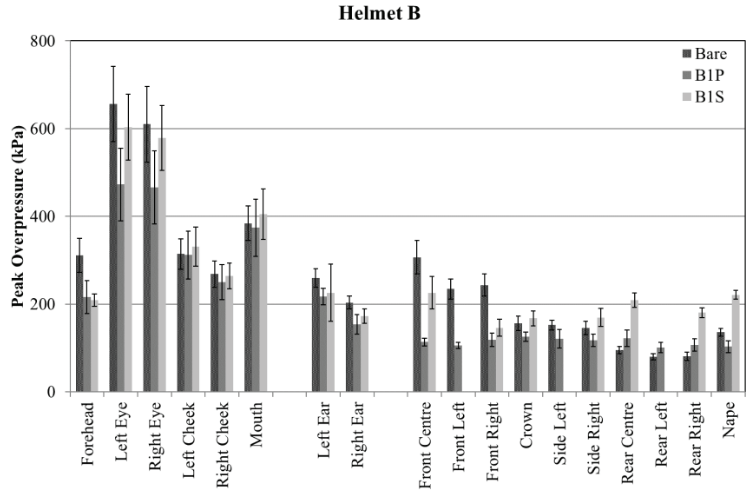
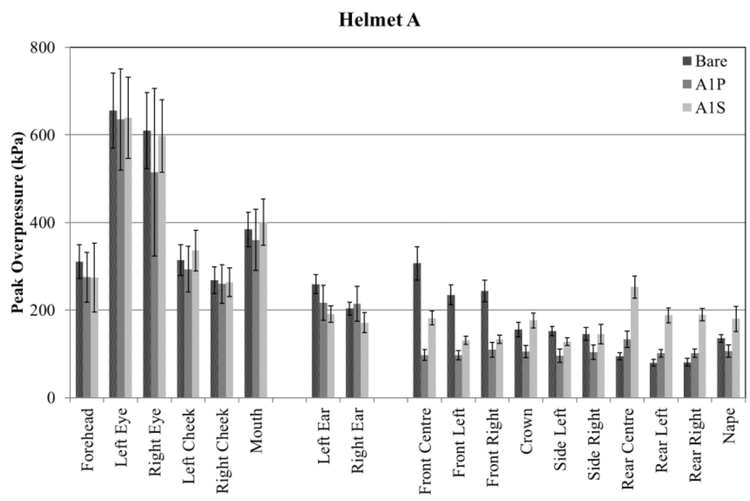


Figure 4.



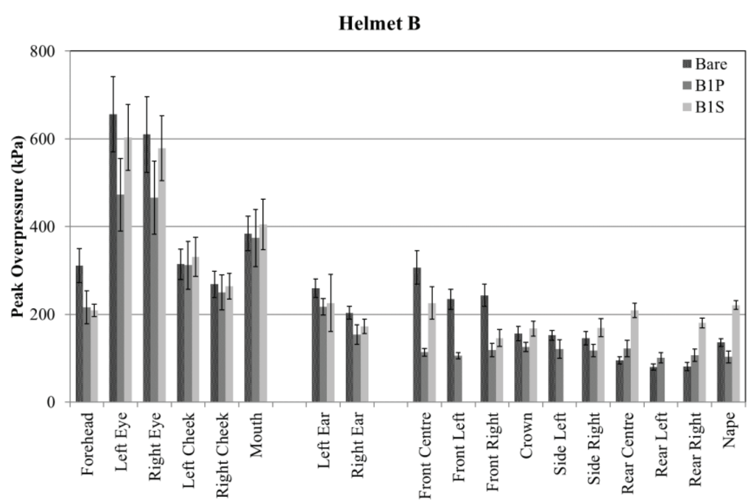


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Figure 4. Peak overpressure measured on the headform for two helmet systems outfitted with either a pad (P) or sling (S) suspension system. Sensor locations are grouped by face (left), ear (centre), and underneath helmet (right) in the bar charts.

Corridor (average ± 1 standard deviation) responses for select headform sensors are shown in Figure 5. Figure 5 also shows the effect of helmet fit for the B1S helmet system. When the helmet systems were initially CT-scanned, the B1S and B2S helmets were fitting closer to the head than the other helmets; the suspension systems were adjusted to provide a more consistent fit, and re-tested as such. While little or no difference was observed in the facial and ear pressure sensors between pad and sling tests, pressure sensors underneath the helmet generally showed lower peak pressures for the pad suspension system and corridor responses were characteristically different between pad and sling.

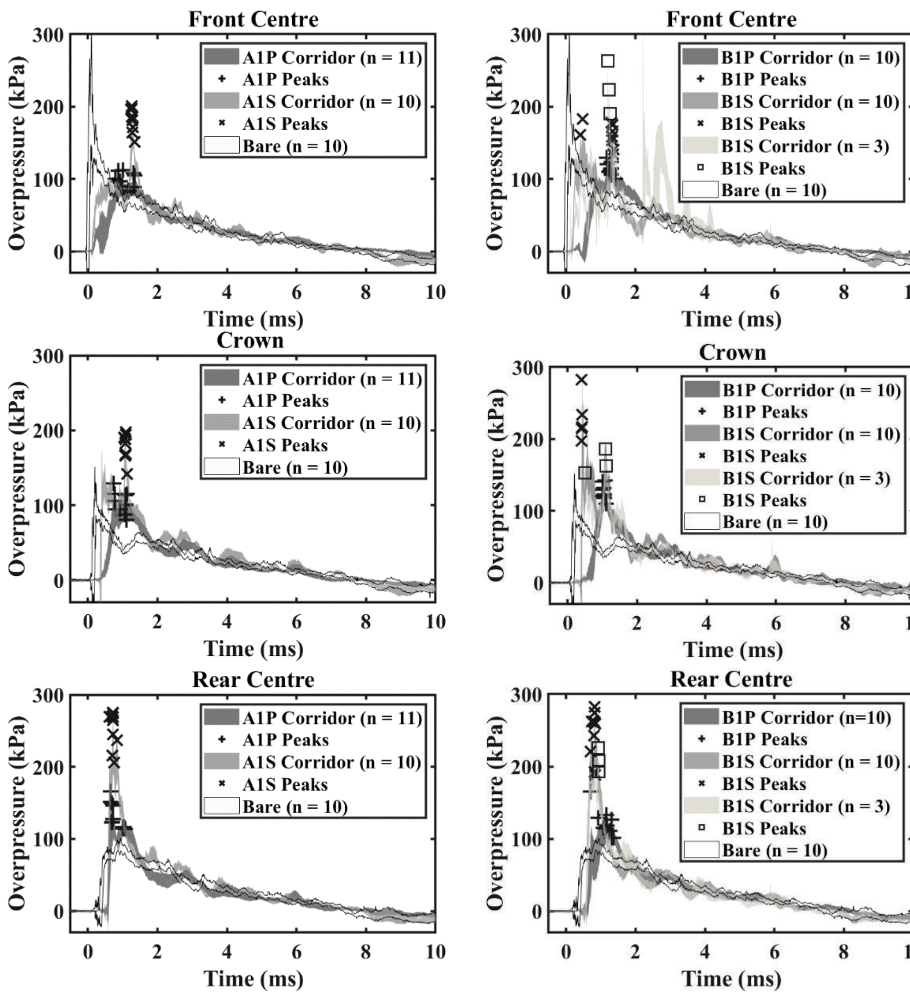

Figure 5. Overpressure corridors for select sensor locations for two helmet systems outfitted with either a pad (P) or sling (S) suspension system. Peak overpressure values for individual tests are marked with a '+', 'x', or '□'. Bare headform corridors included for comparison.

3.4 Effect of Material

The effect of material was assessed through one comparison: B1S v. B2S. Figure 6 illustrates the effect of material for a select number of sensors on the headform. Some slight differences can be observed between the B1S (Aramid) and B2S (plastic) helmets.

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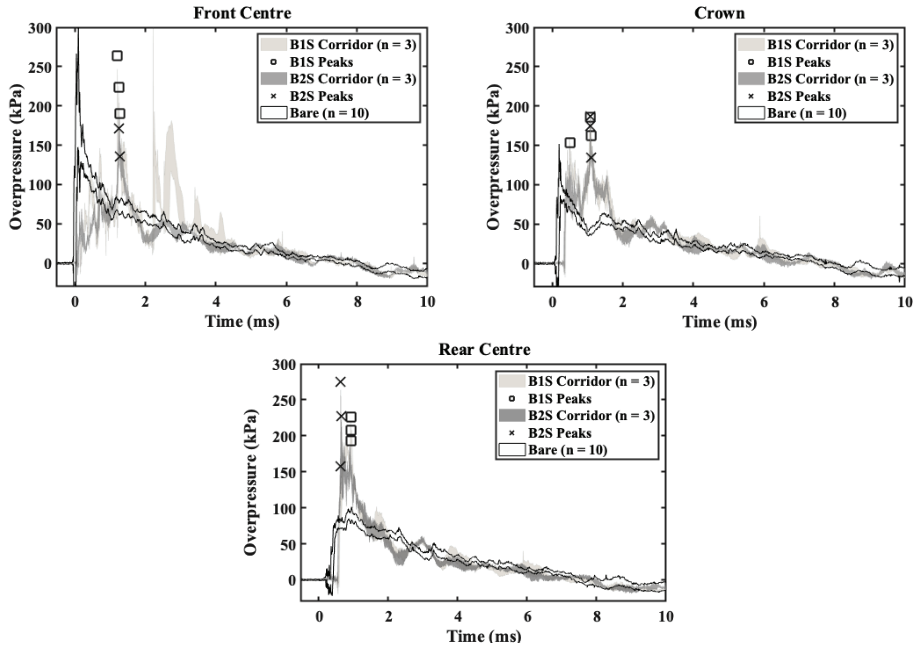

Figure 6. Overpressure corridors for select sensor locations for two helmet systems that have the same geometry and suspension system. Peak overpressure values for individual tests are marked with an 'x' or '□'. (Left) updated helmet fit; (right) original helmet fit.

3.5 Fielded v. Historic

The currently fielded helmets were compared to the historic helmets. Figure 7 shows the peak overpressures measured across the headform for the historic (B1S, C3S, DXH) versus currently fielded (A1P, E4P) helmets. Data from a bare headform are also included for reference. Figure 8 shows the corridor responses of the Front Centre Pad sensor location. Some differences can be observed between the two groups of helmets.

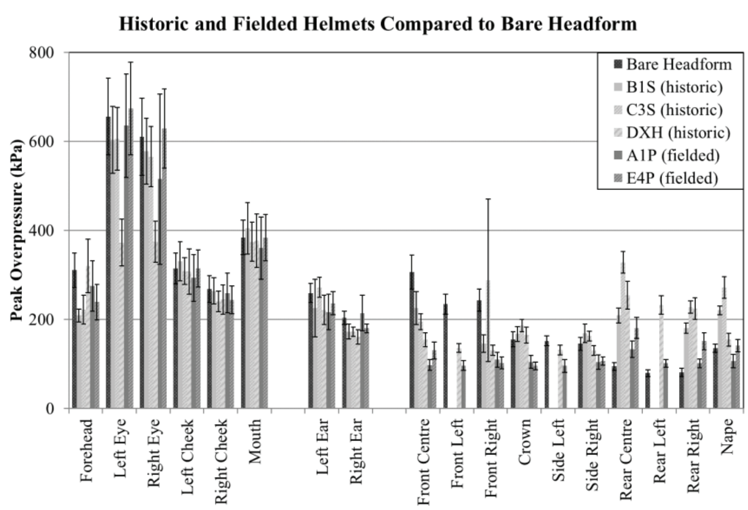

Figure 7. Peak overpressure measured on the headform for two historic helmet systems (B1S, C3S, DXH) and three fielded helmet systems (A1P, E4P), compared to a bare headform.

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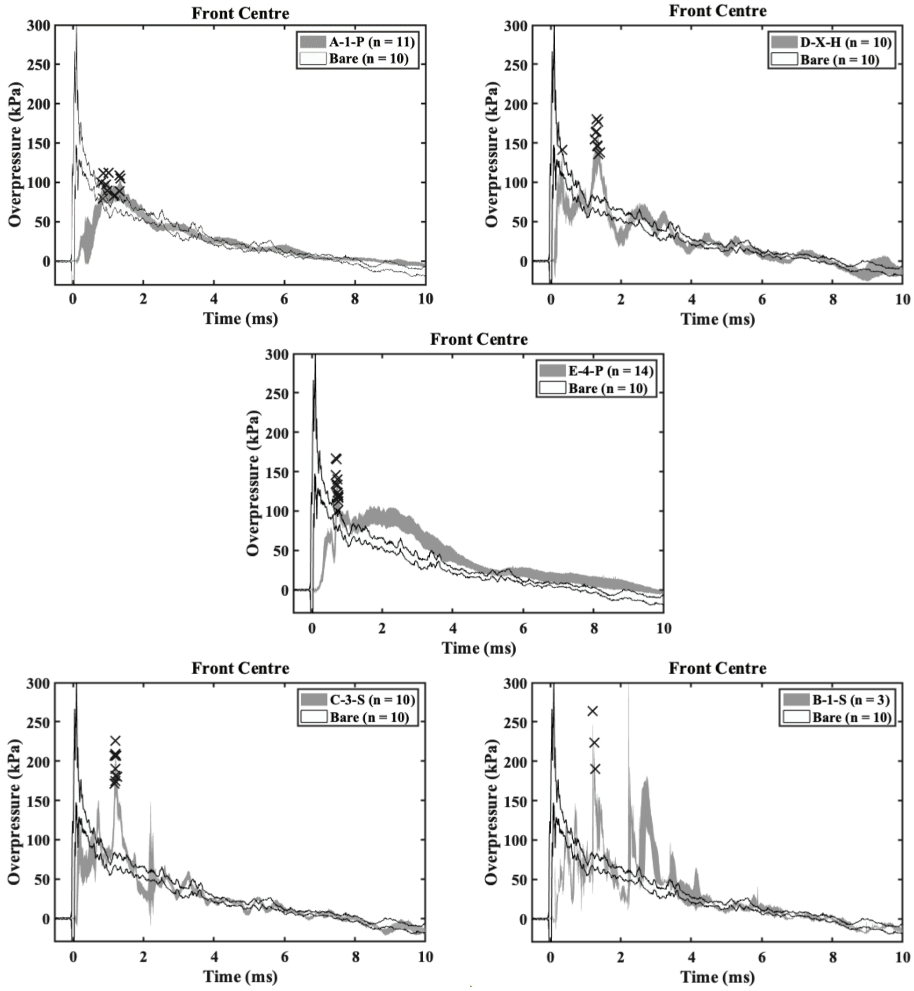

Figure 8. Overpressure corridors for a single sensor location for five historic or fielded helmet systems. Peak overpressure values for individual tests are marked with an ‘x’.

4. DISCUSSION AND CONCLUSIONS

4.1 Effects of Geometry, Material, and Suspension System

The suspension system used showed the greatest difference across the helmets tested. A pad suspension system utilizes a series of foam pads that can be attached to the inside the helmet shell (often with Velcro); a sling suspension system utilizes a separate inner lining that suspends the helmet shell above the wearer’s head. Either suspension system allows for standoff between the wearer’s head and the helmet shell. Where the pad system directly contacts the wearer’s head, a sling suspension allows air to pass through the space between the head and the helmet shell. This air gap in the standoff space presents an opening for the shock wave to propagate, and could be a factor in generally greater peak pressure readings observed for the sling versus pad suspension system.

Although there are manufacturer suggestions for the location of the pads within the helmet, an individual may choose to place the pads in slightly different locations. Similarly, a wearer can adjust the straps of the sling suspension system to provide an individualized fit beyond the manufacturer’s suggestions. All of the helmets tested in this series followed manufacturer suggestions for the pad or sling suspension systems based on the size of the HSHM/B headform.

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Generally similar trends exist across Helmet A (tactical cut) and Helmet B (full cut) compared to the bare headform; however, Helmet B shows a marked difference at the Forehead and Eye sensors compared to Helmet A, likely due to the addition of the brim on the front of Helmet B. Local geometry of the helmet and its proximity to facial structures have shown a variety of results. For example, the addition of a brim on the front of the helmet, compared to a brimless helmet, showed a marked difference (decrease) in the pressure measured at the eye.

While helmet shell materials can affect pressure propagation, the differences observed in this study between Aramid and SMC were small compared to the effects of suspension system and geometry. It is possible other helmet shell materials, including layering of various materials with significant impedance mismatch, could potentially have a greater effect on reducing pressure propagation than measured herein. Future work to specifically examine this could prove or disprove this, as the results of the current study show minimal differences due to helmet shell material.

4.2 Fielded v. Historic

Historic and currently fielded helmets showed different responses; however the differences vary by sensor location and are not consistent for all currently fielded versus all historic helmets. While assessing the evolution of combat helmets and their blast attenuating performance may be interesting, evaluating individual helmet designs on their merits may be more beneficial to informing helmet improvements.

4.3 Evaluation of the Test Methodology

The fact that various helmets illustrated markedly different responses, even in a single orientation, indicates that the test methodology used in this study was able to distinguish between different helmets, especially with respect to peak overpressure measurement. Additionally, the test methodology has proven to be robust, repeatable, and reproducible over several years of operation and over a thousand tests. The shock wave profile generated in the BOSS has been shown to be operationally relevant [2]. While this study was limited to testing in a single orientation, forward facing the blast, the system is capable of and has been used extensively to test other operationally relevant orientations such as rearward, side, and inclined [1].

Prior work developed a formal methodology detailing the required test equipment as well as specific step-by-step instructions to conduct and analyse tests. This methodology was used for the tests described herein and could serve as the basis for a future standardized helmet blast test protocol. In order to implement this methodology more globally, slight modifications or adaptations of the methodology would be needed to address differences between individual shock tubes and Advanced Blast Simulators (like the BOSS); however, the specific test equipment used to conduct the tests herein (e.g., the HSHM/B) could be used for a direct comparison of performance across specific test equipment to ensure matched results. Once matched results are confirmed, equipment-specific modifications or adaptations can be included in the standardized methodology to account for testing at different facilities.

4.3.1 Standardising Helmet Fit in Methodology

While testing helmets with different shapes and suspension systems, the need for standardising the specific placement of the helmet on the headform became apparent. Initial tests conducted to develop the methodology used helmet systems that were relatively similar in shape [1]. However; evolving helmet designs may lead to drastically different shell and suspension system designs, complicating the direct comparison across different helmets.

While external measurements of helmet symmetry and brim height with respect to landmarks on the headform are typically used during helmet testing, this study utilized an additional tool to assess and help properly adjust helmet fit. Computed tomography (CT) scans were taken of the headform outfitted with each helmet as it would be placed during testing (Table 2). While the standoff distance between the headform and the shell of the helmet is fairly fixed for helmets with pad suspension systems, for the helmets with sling suspension systems, the standoff could easily be adjusted and significantly altered by tightening or loosening the straps and/or bands. In addition to informing helmet fitting procedures, the CT scan data provided insight into factors, such as standoff and locations of pads, straps, and other materials near each headform pressure sensor, that may have affected the test results.

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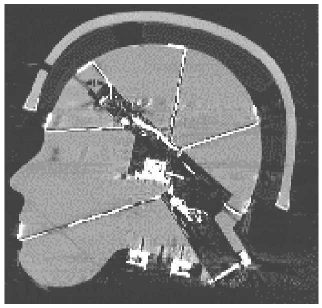
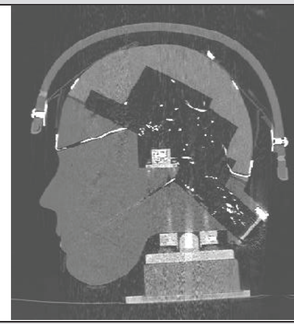
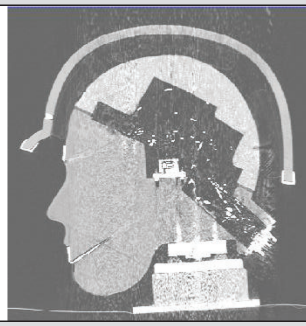
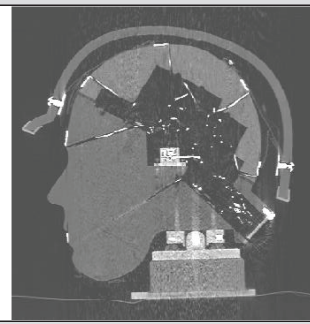
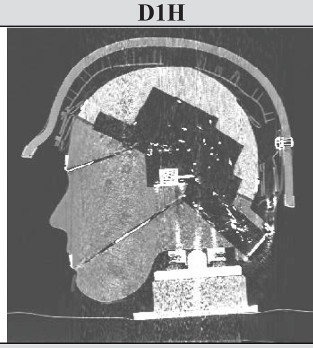
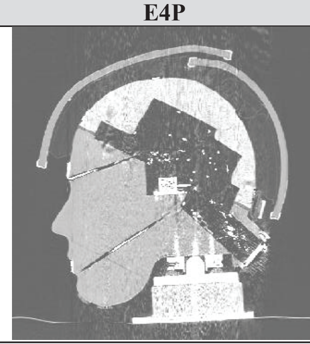
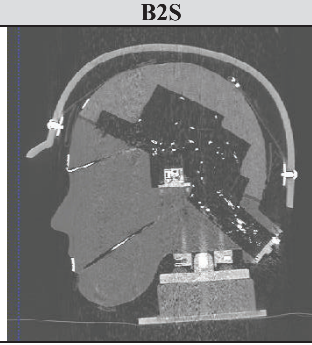
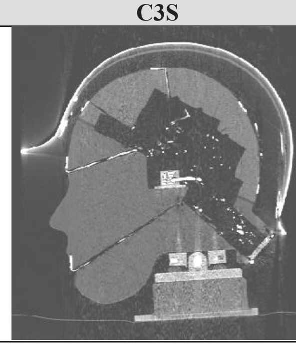
Table 2. Midsagittal slice from CT scans of the helmets outfitted on the HSHM/B. All tests were conducted using a Hybrid III neck; CT scans utilized a shorter neck that fit within the bore of the CT.

A1P	A1S
	
B1P	**B1S**
	
D1H	**E4P**
	
B2S	**C3S**
	

4.4 Limitations and Future Work

The current study demonstrates a test methodology that is able to discriminate differences in helmet design (geometry, material, suspension system), especially in the magnitude and time of peak overpressure measured at various locations around the headform. Depending on sensor location, the

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addition of the helmet could increase or decrease the peak overpressure magnitude. Due to the current limitations of injury research, the utility of the current work is limited to comparative analysis. Future advancements to establish injury correlations would enable the current methodology to be used for an injury-based blast helmet requirement. Although lower pressure may be 'better' than higher pressure, there are no quantitative metrics at this time that can be used to identify injury risk. Similarly, the magnitude of the increase or decrease in pressure observed in the sensors in the current study may not be great enough to distinguish between the sensitivity of a protective system to actually 'protect'. Further work to connect field, laboratory, and clinical outcomes is needed to make this further assessment.

The HSHM/B used for this methodology included 18 surface pressure measurement locations. As the design of helmet systems evolves over time, the equipment used to test, evaluate, and compare headborne protective equipment should enable a fair assessment for designs that are drastically different. This study illustrated a marked difference in the response between a pad and a sling suspension system at the sensor locations examined. All of the HSHM/B pressure sensors covered by the helmet were located underneath a helmet pad for the A1P and B1P test configuration, except for the Side Left Pad and the Side Right Pad sensors. The location of a pad near or directly over a pressure sensor will affect the response; ensuring modularity of the test equipment used will be critical to providing an un-biased comparison that is less prone to manipulation. Increasing the number, location (e.g., especially between pads or other suspension design components), and modularity of the sensors on a piece of test equipment can be a useful first step to this end [3]. Furthermore, sensors placed inside the headform (i.e., brain) could inform how the shock wave transmits through the skull. JHU/APL developed a headform that includes four intracranial pressure sensors for this purpose. This headform is referred to as the HSHM/E (enhanced), and has a reduced number of sensors on the surface of the headform to account for the additional sensors in the brain. The HSHM/B was used in the current study in order to capture more measurements around the surface of the headform for the variety of helmets tested. Future tests repeated with the HSHM/E will yield additional knowledge of the shock wave transmission.

It should be noted that helmet performance can be drastically affected by the fit or placement of the helmet, as illustrated with the B1S and B2S tests. Although the tests in this series standardized the fit of the helmet on the headform, it is possible that an individual user may make minor modifications beyond the manufacturer's recommendations in order to obtain a more comfortable fit. It is possible these slight changes might affect the performance of the helmet. It is critical, therefore, to examine the effects of minor differences in fit; a computational model may provide valuable insight to minor variations in helmet fit more quickly than experimental testing. Results from a computational sensitivity study could inform a down-selected set of subsequent experimental tests for validation.

Lastly, all of the tests reported in this paper were conducted with a single orientation, facing the blast. Previous work showed notable differences in responses at various orientations, especially for side-on exposures to a blast [1]. A comprehensive comparative evaluation of helmet performance should therefore include tests with multiple orientations in order to elucidate orientation-specific results.

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