Comparing Laboratory Blast Simulators and Exploring Influence on Helmet Test and Evaluation

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Abstract. Preventing warfighter exposure to primary blast waves (BW) is important to mitigate injuries. Experimentally recreating BW is necessary for test and evaluation (T&E) of head protection systems (HPS) [1,2]. Advantages of laboratory blast simulators (LBS) over live-fire blast testing include reliability, repeatability, safety, and cost. However, there exists a paucity of cross-comparisons between different LBSs [3]. The goal of this study is to investigate if different LBSs can achieve comparable T&E results for the purposes of HPS performance by targeting the same peak incident overpressure at the test subject location. Two target peak incident overpressure conditions were tested with four different LBSs. Differences in these LBSs include geometry and shockwave generation method (diaphragm or gas-detonation) and each LBS was characterised with the same pressure sensor array. A head surrogate was added to understand differences between LBSs when evaluating HPSs. Measured incident peak overpressures across LBSs neared the nominal target; however, statistical differences were observed in a portion of sensor locations when cross-comparing LBSs. Positive phase duration and impulse varied significantly across LBSs. Achieving matching peak incident pressure and positive phase impulse simultaneously was not reconciled due to the need for costly permanent changes to the LBSs. A scaling methodology to predict the effect of two different helmets at an LBS based on results at another LBS was explored, but was not able to overcome differences. It was found that the differences in the generated shockwave characteristics by the LBSs, not differences in helmet design, drove discrepancies in helmet evaluation. While no agreed-upon injury risk curves (IRCs) currently exist for blast-induced traumatic brain injury (bTBI), standardised test metrics would help motivate the different research teams to generate similar shockwaves from different LBSs to achieve reproducible test results to assess HPSs.

1. INTRODUCTION

Blast injuries are a concern for the warfighter, and the study of blast-induced traumatic brain injury (bTBI) is becoming increasingly important to the design and evaluation of head protection systems (HPS) [1,2]. Live-fire blast events using high energy explosive materials and high-fidelity measurement systems are essential to evaluate HPS performance; however, there are many challenges associated with live-fire blast testing including repeatability, reproducibility, cost, safety, skilled personnel and environmental control. Laboratory testing has historically been able to create complex loading events in a repeatable and reproducible way that is well suited for HPS testing. Therefore, the ability to replicate realistic blast overpressure conditions in the laboratory through the use of laboratory blast simulators (LBS) is of great interest to support efficient and effective testing and evaluation of HPSs.

Several organizations have conducted LBS testing to evaluate the performance of HPSs using different LBS designs, instrumentation, and data analysis methods [2,3,4]. While these studies have done much to characterise the individual LBS, little work has been done comparing different LBSs using near-identical data collection methods or test articles. Studies comparing various LBSs have been limited due to the complex nature of shockwaves as well as challenges associated with coordination across different institutions. There is a desire for a standardised test methodology to assess blast overpressure attenuation performance of HPSs, and the feasibility of comparing test results across different LBSs is unknown. In an effort to investigate if different LBSs can achieve comparable HPS test results, experiments were conducted to determine if HPS testing could be conducted with consistent inputs (e.g. consistent shockwave metrics) and consistent outputs (e.g. HPS blast attenuating performance metrics) across four disperate LBSs.

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2. METHODS

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) led this effort to evaluate LBSs at four different partner institutions; JHU/APL [2,4,5], Aberdeen Test Center (ATC), Virginia Polytechnic Institute and State University (VT) [6], and Walter Reed Army Institute of Research (WRAIR) [7]. Table 1 summarises key differences in the LBS design, shockwave generation, and shockwave expansion.

Table 1. LBS Design Metrics

	JHU/APL	**ATC**	**VT**	**WRAIR**
Cross-sectional dimensions	91 x 91cm	71 x 71cm	119 ×122cm	60 x 60cm
Driver gas used for this study	Air	Helium	Oxyacetylene	Air
Shockwave generation method	Diaphragm-rupture	Diaphragm-rupture	Ignition- gas combustion	Diaphragm-rupture
Driven chamber expansion direction	Horizontal only	Horizontal and vertical	Horizontal only	Horizontal only
Design paradigm	Advanced Blast Simulator [8]	Shock Tube	Advanced Blast Simulator [8]	Advanced Blast Simulator [8]

In the first phase of the study, tests were conducted with indentical experimental and analytical methods in order to characterize effects of different LBS designs and assess the consistency of the shockwaves generated at two different pressure conditions, as outlined in Table 2. This approach enables a direct comparison of shockwave variations across LBSs to inform future test standardization. Each LBS was tuned to produce peak incident pressures of 69 and 103 kPa measured at the center of the LBS. These two pressure values were chosen because each LBS in the study was already capable of achieving these conditions and because the conditions were deemed relevant to blast dosages where HPSs could potentially make a difference in health outcomes as these levels are below the threshold for lung injury [9]. Limited repeats were conducted at VT at 69 kPa due to the original test plan prioritizing an alternative test condition.

A custom designed array of pressure sensors was mounted to the test region of each LBS and used to quantify the shockwave characteristics of these four LBSs. Tests at JHU/APL and VT were conducted using the nine-probe-array configuration, as shown in Figure 1, whereas the five-probe-array in Figure 1 (outlined in the red box) was used at ATC and WRAIR due to the smaller cross-sectional areas of these LBSs. The probe-array consists of free-standing aerodynamic pitot-static probes [10] held in place by aerodynamic rigid stands of specified lengths. Pitot-static probes measure incident and stagnation pressure time-histories by utilizing two perpendicular pressure sensors. The stands were mounted to steel plates on the floor and ceiling of the LBSs. A coordinate measurement machine (ROMER Absolute 7535, Hexagon Metrology) was used to check sensor locations after installation. Endevco (END) 8530C-100 (piezoresistive) and PCB Piezotronics 113B27/113B21 (piezoelectric) sensors were utilised in different pitot-static probe locations in the custom pressure sensor array. Tests were executed in sets of 5, which was informed by a design of experiments to increase testing efficiency and to reduce the effects of confounding variables such as test day, time, humidity, and temperature. If an LBS misfire, data loss, or other anomaly was detected on the test day, the shot condition was repeated. However, if the issue was not identified within the test period, the test was not repeated. Pressure measurements from the sensors were sampled at 1MHz and then filtered using a 40 kHz low-pass Butterworth filter.

In the second phase of the study, the Wireless Blast Anthropomorphic Test Device (WBATD) Headform (Figure 2) [11] was used, in lieu of the pressure probe array, to assess the consistency of the headform response and HPS performance metrics across different LBSs. The WBATD intracranial pressure (ICP) measurements were the primary metrics assessed in both barehead and helmeted configurations. Two different combat helmet systems were used (Helmet A and Helmet B). The WBATD Headform was mounted to a Hybrid-III neck in the forward-facing orientation in the test region of the LBSs [4]. A pitot probe was also positioned in the inner bottom left of the LBS for the headform characterization tests at JHU/APL, and in the inner bottom left and inner top left at WRAIR. Due to resource constraints, WBATD tests were only conducted at JHU/APL and WRAIR, which were downselected from the four LBSs due to similarities in their design and performance. Tests were performed as outlined in Table 3.

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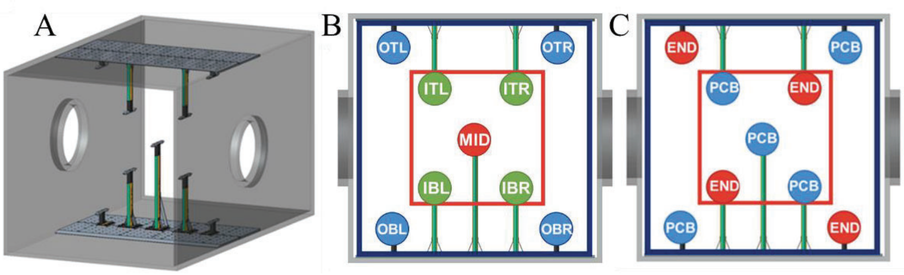

Figure 1. Nine Probe-Array Configuration (A), Pressure Sensor Naming Convention (I/O – Inner/Outer, T/B – Top/Bottom, L/R – Left/Right, and MID – Middle) (B) and Pressure Sensor Layout (C), five probe array configuration indicated by red box

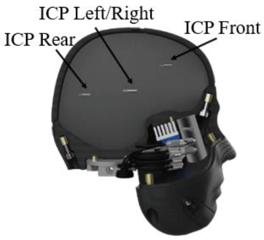

Figure 2. CAD Rendering of WBATD Headform showing the ICP sensor locations. The ICP Left and ICP Right sensors are symmetrical with respect to the mid-sagittal plane

Table 2. Probe-Array Test Matrix

Target Incident Pressure (kPa)	JHU/APL	ATC	VT	WRAIR
69	15	15	4	15
103	25	23	25	25

Table 3. Headform Test Matrix

Target Incident Pressure (kPa)	HPS Configuration	JHU/APL	ATC	VT	WRAIR
69	Barehead	5	0	0	5
103	Barehead	5	0	0	5
69	Helmet A	5	0	0	5
103	Helmet A	5	0	0	5
69	Helmet B	5	0	0	5
103	Helmet B	5	0	0	5

These experimental methods allow for a quantitative evaluation of features of the shockwaves generated in each LBS and establish a baseline for use in the development of LBS helmet testing standards. Additionally, for the first time, the same experimental (i.e sensor type, placement, headform surrogate) and analytical (i.e. data processing and feature extraction) methods were used across these disparate LBSs, enabling direct comparison and a better understanding of the differences between the shock waves simulated by each system.

3. RESULTS

The time history plots in Figure 3 and Figure 4 demonstrate the propagation of the shockwave across the middle probe of the probe-array at the two test conditions. The middle probe was selected as a representative sensing location as it is the farthest from walls and corners (and associated predicted reflections) of the tube. Side-facing sensors were selected as they measure incident overpressure, which the laboratories in this study utilise to drive their nominal pressure conditions. The comparison corridors for each LBS represent the average time history trace plus or minus one standard deviation. Each

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laboratory demonstrates a Friedlander wave shape, with a sharp rise to the peak overpressure and a decay into a negative phase before the pressure returns to zero.

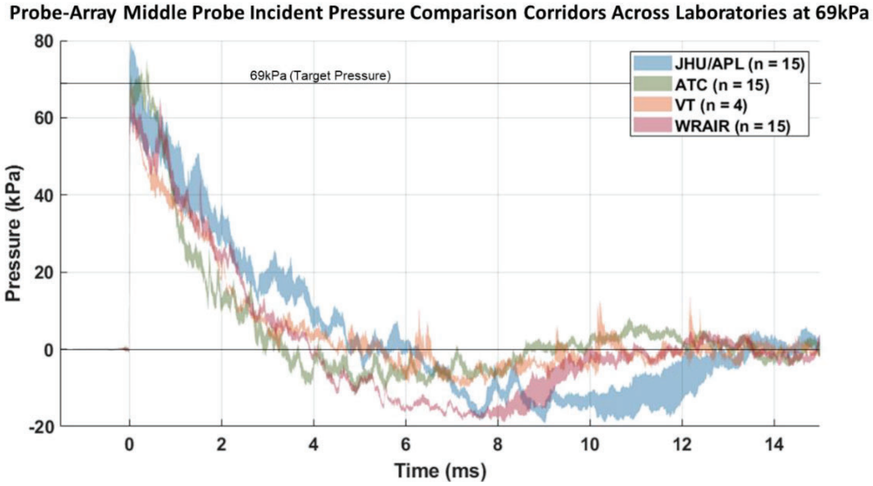

Figure 3. Probe-array Overpressure Comparison Corridors for JHU/APL, ATC, VT, and WRAIR, 69-kPa Nominal Target Overpressure Condition, Middle Probe, Side-Facing Sensor

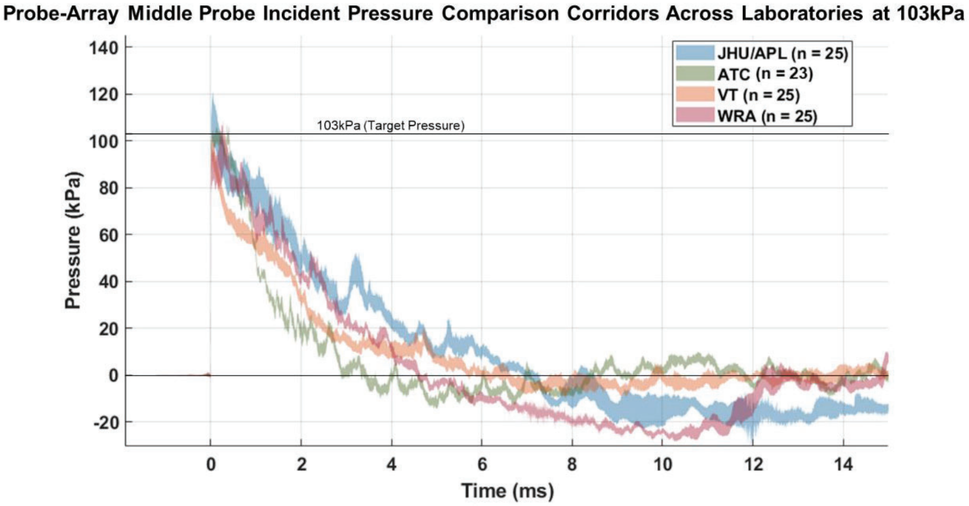

Figure 4. Probe-array Overpressure Comparison Corridors for JHU/APL, ATC, VT, and WRAIR, 103-kPa Nominal Target Overpressure Condition, Middle Probe, Side-Facing Sensor

Peak overpressure, positive phase duration, and positive phase pressure impulse features were extracted from the 40 kHz filtered pressure sensor time histories of the side-facing sensors in the pitot probe-array (Figure 5). Peak pressure was defined as the signal's maximum value. The start of the positive phase duration (or time of arrival) was defined by over-filtering (10 kHz low-pass Butterworth filter) the signal and determining the time point at which the signal reached 10% of the peak value. The end of the duration was the time point at which the over-filtered signal crosses zero for the first time after the time of arrival. The pressure impulse was then computed by integrating the 40 kHz filtered pressure time history across the positive phase duration. Cases in which the automated featured extraction did not capture the actual peak as a result of some anomaly in the data were corrected manually and the duration and pressure impulse were then recalculated.

Peak incident pressure measurements were used to evaluate the repeatability of a given LBS, the shockwave uniformity of a given LBS, and the ability of each LBS to achieve the target peak incident pressure conidtion. Of the four LBSs evaluated, ATC had the most repeatable peak incident pressure measurements, with a mean coefficient of variation (CV) of 3% across sensor locations and across test

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conditions. JHU/APL's LBS had the least repeatable peak incident pressure, with mean CVs across sensor locations of 13% at 69 kPa and 9% at 103 kPa. ATC's LBS was the least uniform, with a large difference in peak incident pressure between the middle probe and the peripheral probes (25 kPa mean difference at the 69kPa test condition and 39 kPa mean difference at the 103kPa test condition). The JHU/APL, VT, and WRAIR shockwaves were generally more uniform in comparison. All four LBSs achieved mean middle probe peak incident pressure measurements within 10% of the target values.

The positive phase duration and impulse varied greatly between the four LBSs. Positive phase impulse is affected by both the magnitude and duration of the pressure wave. Since the peak pressure was targeted to be the same in the test conditions across the different laboratories, positive-phase duration was the main driver of impulse differences between the different LBSs. As shown in Figure 5, JHU/APL had the longest duration shockwaves and, as a result, it had the higest pressure impulse values across all sensor locations and test conditions. In contrast, ATC had the shortest duration shockwaves and lowest pressure impulse values across all sensor locations and test conditions. The exception to this trend is the VT LBS, which ranks the second highest for duration but third highest for impulse. The differing wave shape generated by VT drives this phenomenon, primarily due to VT's shockwave generation method which utilizes a gas detonation system, unlike JHU/APL, WRAIR, and ATC.

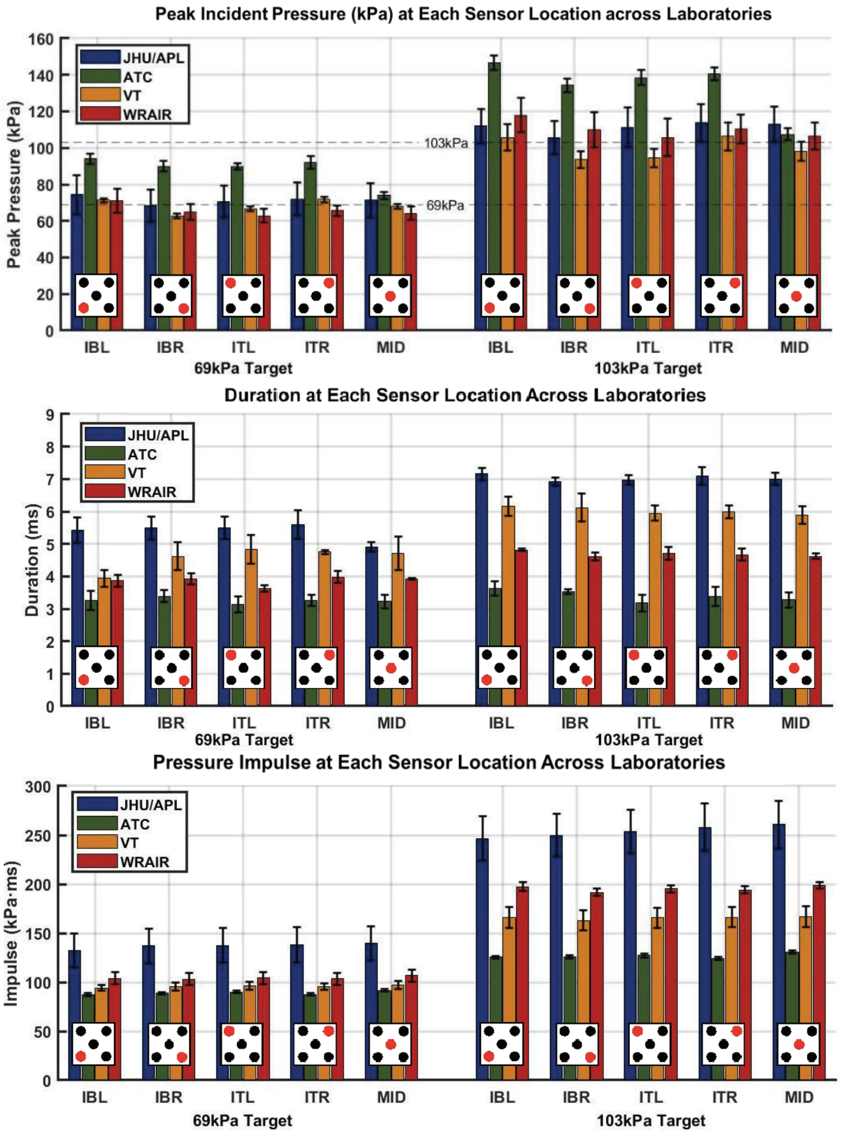

Figure 5. Probe-array Incident Pressure Metrics Comparison Across Sensor Locations for JHU/APL, ATC, VT, and WRAIR

Analysis of Variance (ANOVA) tests were conducted with both stagnation and incident peak pressures to determine if there were statistical differences between the LBSs. A Tukey's honestly significant difference (HSD) procedure, with alpha (**α**) set to 0.05, was conducted to determine which specific groups were statistically different from one another. To control for family-wise error rate, a Bonferroni p-value correction (*m*) was implemented. The null hypothesis is the peak incident pressure is statistically the same across laboratories. If the null hypothesis was not rejected, the box is grey. If the null hypothesis was rejected and the lab listed first had a greater metric than the lab listed second, the box is orange. If the lab listed second had a greater metric than the lab listed first, the box is green. The VT 69-kPa condition was not included due to only 4 repeats completed, noted in black.

Figure 6 and Table 4 show the results of the ANOVA tests. In the 69-kPa condition, JHU/APL, ATC, and WRAIR were found to be statistically similar at the middle pressure probe. At three of the four inner probes, JHU/APL and WRAIR were statistically similar. As expected, ATC's inner probe measurements were statistically different than JHU/APL and WRAIR. At 103-kPa, no laboratories were statistically similar across all five sensors. At the middle sensor, the null hypothesis was only rejected when comparing ATC and VT's peak incident pressures (Table 4).

🟧 Statistically significant, group A > group B
🟩 Statistically significant, group B > group A
⬜ Not statistically significant
⬛ Not included due to limited repeats

Figure 6. ANOVA and Tukey's HSD Table Legend

Table 4. Wave Metric ANOVA Tukey's HSD Results

	Incident Overpressure Filtered Peak (69-kPa)					
IBL	🟩	⬛	⬜	⬛	🟧	⬛
IBR	🟩	⬛	⬜	⬛	🟧	⬛
ITL	🟩	⬛	🟧	⬛	🟧	⬛
ITR	🟩	⬛	⬜	⬛	🟧	⬛
MID	⬜	⬛	⬜	⬛	⬜	⬛
	Incident Overpressure Filtered Peak (103-kPa)					
IBL	🟩	🟧	⬜	🟧	🟧	🟩
IBR	🟩	⬜	⬜	🟧	🟧	⬜
ITL	🟩	🟧	🟧	🟧	🟧	⬜
ITR	🟩	🟧	⬜	🟧	🟧	⬜
MID	🟧	🟧	🟧	⬜	🟧	🟧
	APL vs. ATC	APL vs. VT	APL vs. WRAIR	ATC vs. VT	ATC vs. WRAIR	VT vs. WRAIR

The second phase of the study (Table 3) was conducted to assess the effect of different LBSs and different helmets on the WBATD headform's intracranial pressure (ICP) measurements. JHU/APL and WRAIR LBSs were selected for the study due to the similarity in their design, other than cross-sectional area, and the statistical similarity observed at seven of ten peak incident pressure readings across all probes. The WBATD headform ICP peak pressure measurements and presure impulse measurements are shown in Figure 7 and Figure 8, respectively. For the peak ICPs, JHU/APL was greater than WRAIR at seven of the eight test conditions and sensor locations, with the lone exception being the right sensor at 69kPa. For comparison, the mean difference across the four sensors in peak ICP while targeting 69kPa was 16 kPa, and while targeting 103kPa was 8 kPa. The mean difference in the pressure probe peak pressure measurements was 7 kPA at the middle sensor while targeting both 69kPa and 103kPa.. For the positive impulse of the ICPs, JHU/APL was greater than WRAIR at all test conditions and sensor locations. This is driven by the higher positive phase duration and impulse at the JHU/APL LBS. The mean difference across the four sensors in impulse was 26 kPa*ms at 69kPa and 35 kPa*ms at 103kPa, whereas the mean difference in the pressure probe measurements was kPA*ms at the middle sensor was 32 kPA*ms for 69kPa and 62 kPA*ms for 103kPa.

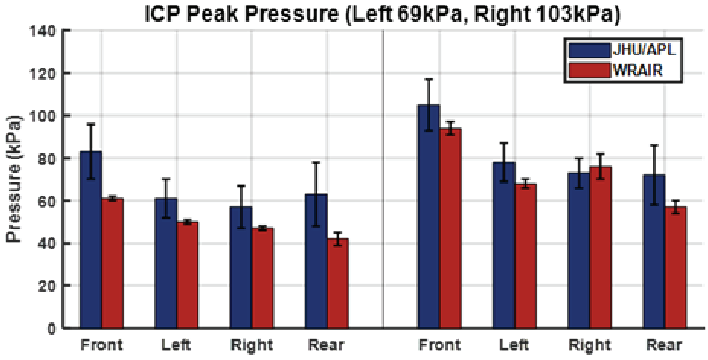

Figure 7. WBATD Peak ICP at 69kPa (left) and 103kPa (right) target peak incident pressure test condition for Barehead at JHU/APL and WRAIR

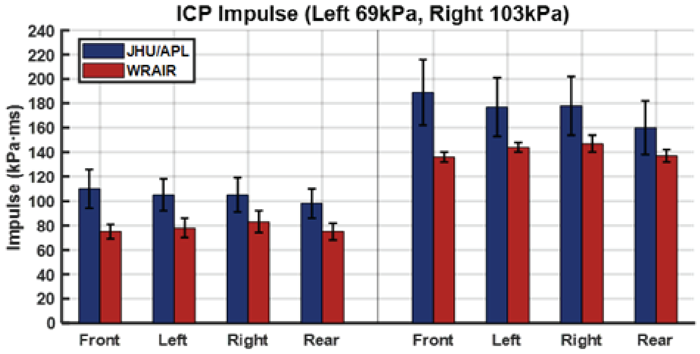

Figure 8. WBATD ICP Impulse at 69kPa (left) and 103kPa (right) target incident pressure test condition for Barehead at JHU/APL and WRAIR.

The helmeted headform conditions exhibited varying responses across the JHU/APL LBS and the WRAIR LBS. To separate the effects of different HPSs, a scaling methodology was applied. Specifically, the mean ICP metrics in the helmeted conditions were normalise against (divided by) the corresponding mean ICP metric measured on a bare headform under the same conditions. A two-tailed independent t-test with alpha (**α**) set to 0.05 was conducted to determine if the normalised ICP measurements were statistically different between the two helmets. The null hypothesis is the normalised ICP measurements is statistically the same across Helmet A and Helmet B. If the null hypothesis was not rejected, the box is grey. If the null hypothesis was rejected and Helmet A outperformed (i.e. resulted in lower normalised ICP measurements than) Helmet B, the box is orange. If the null hypothesis was rejected and Helmet B outperformed Helmet A, the box is green (Figure 9). In the 69-kPa condition, Helmet B showed better performance in six of the eight normalised ICP metrics using the JHU/APL LBS, while Helmet A showed better performance in seven of the eight normalised ICP metrics using the WRAIR LBS. Evaluated at 103-kPa nominal dose, the performance is split with seven of the eight normalised ICP metrics across laboratories not having statistically significant differences using the JHU/APL LBS. Four of the eight normalised ICP metrics are statistically different at WRAIR, with Helmet A having better performance at the left and right normalised peak metrics but Helmet B having better normalised performance at both rear metrics (Table 5).

🟧	Statistically significant, Helmet A Metric Performance > Helmet B Metric Performance
🟩	Statistically significant, Helmet B Metric Performance > Helmet A Metric Performance
⬜	Not statistically significant

Figure 9. Helmet Comparison T-test Legend

Table 5. Helmet Comparison T-test Results

		Front Peak	Left Peak	Right Peak	Rear Peak	Front Imp	Left Imp	Right Imp	Rear Imp
69 kPa	JHU/APL	🟩	▨	▨	🟩	🟩	🟩	🟩	🟩
	WRAIR	🟧	🟧	🟧	🟧	🟧	▨	🟧	🟧
103 kPa	JHU/APL	▨	🟧	▨	▨	▨	▨	▨	▨
	WRAIR	▨	🟧	🟧	🟩	▨	▨	▨	🟩
		Helmet A ICP Metric Performance vs. Helmet B ICP Metric Performance							

4. DISCUSSION

4.1 Shockwave Characterization with Probe-Array and Headform

In an attempt to standardise across different LBSs, the purpose of the study was to determine if response characteristics of four disperate LBSs could be considered similar enough for consistent evaluation of HPSs. It is evident from the results that each LBS can achieve defined target peak overpressures at the centre sensor location despite the unique geometry and shockwave generation characteristics of each system. While each institution had demonstrated this prior to the current study, different data collection methods and shockwave initiation methods show a clear affect to the creation of this peak pressure as shown by the variation in responses across the tube. Furthermore, it was found that positive phase duration and positive phase impulse varied significantly across laboratories, as shown in Figure 5.

The ANOVA tests comparing peak incident pressure measurements across laboratories showed that while each laboratory was close to the target peak incident overpressure at the middle of the test region, statistical differences are prevalent between the different systems. This study made clear that standardised experimental and analytical methods must be used to properly characterise lab-generated shockwaves to compare their similarity, and comparing response at a single point in these systems is insufficient. Additionally, multiple features of the lab-generated shockwave must be considered when evaluating the similarity of LBSs. As shown later by the differences in headform response, targeting a single feature such as peak incident pressure is not sufficient for comparing systems. LBSs in this study acheived specific peak overpressures, but key differences in duration (and to a lesser extent, wave shape) drove differences in impulse. In the future, multiple metrics must be reported in research publications as well as test standards to fully communicate the simulated blast exposure achieved by LBSs.

Repeatability is an essential determinant for the utility of a test device. At both WRAIR and JHU/APL, the WBATD bare headform response was repeatable, with peak pressure and impulse metrics having standard deviations similar to those of the probe-array sensor metrics, indicating that shot-to-shot variability in the WBATD response was driven in large part by shot-to-shot variability in the LBSs. Based on these results, if it is determined that ICP is correlated with blast injury, the WBATD or similar headform composed of ICP sensors could be a useful test equipment for standardized HPS testing. Significant challenges arose during this effort when assessing helmet performance between LBSs based on ICP metrics. These challenges are not yet well understood.

4.2 Observed Helmet Performance

A successful scaling methodology could allow for the comparison of helmet performance from one LBS to another where the blast overpressure signature or the headform response are different. Additionally, a valid scaling methodology would demonstrate evidence that the differences observed in pressure metrics or helmet performance between LBSs were due to predictable physical phenomenon. A hypothetical ideal scaling methodology would look something like "HPS tend to show 20% greater blast attenuation at 'Lab B' compared with 'Lab A' due to the positive phase impulse of the shockwave generated at 'Lab B' being 10% greater than that of 'Lab A'. For a standardised test methodology utilised across multiple LBSs to be useful, the results must forecast— either directly or through a transfer function— how HPSs would perform at 'Lab B' given only performance data measured at 'Lab A'.

Of the LBSs investigated in this effort, WRAIR and JHU/APL had the most a similar design, with the driving difference being the larger cross-sectional area at JHU/APL. JHU/APL and WRAIR also had statistically similar nominal peak incident pressures when targeting 69-kPa and 103-kPa at seven of the ten possible sensor locations. However, JHU/APL had longer duration and higher impulse. In addition, all the data has used incident pressure as a basis for analysis, it is yet unclear the role of stagnation pressure in affecting these variables. When assessing pressure transmission to the helmeted WBATD brain surrogate across WRAIR and JHU/APL using ICP sensor measurements, convoluting factors between LBS characteristics and helmet performance became apparent. No trends that could be leveraged for a scaling methodology were observed across LBSs or blast doses. The underlying physics of the headform, brain simulant, and sensor response are complex and not yet well understood. The differences in the LBS design metrics (Table 1) were more significant relative to the differences in ICP metric performance of Helmet A and Helmet B. This demonstrates that simply defining a target peak incident overpressure is not sufficient in defining standard testing conditions for consistent evaluation of HPSs across LBS that differ in nominal test conditions to the degree of the LBSs in this study.

4.3 Limitations and Future Work

Many wave characteristics (e.g., stagnation overpressure metrics, negative phase waveform metrics) are not currently captured by this shockwave characterization and may be an important component to describing the shockwaves at each lab. The significance of wave non-uniformity (differing wave metrics across the plane of the test region) or wave non-planarity (differing time of arrival across the plane of the test region) on headform response and HPS performance is not yet understood and requires further investigation. In addition, the difference in stagnation pressure to account for the effect of "blast wind" on these variables needs to be taken into account. Future work for test standardization may necessitate developing requirements for an acceptable level of wave uniformity and planarity. A future investigation could conduct statistical tests to compare the outer probe shockwave features to the middle probe shockwave features to better assess the uniformity of the shockwaves. Time of arrival analysis across the probe locations would allow for a better understanding of the planarity across LBSs. This study utilised two different sensing modalities—piezoelectric and piezoresistive pressure transducers—installed in the probes. While the data collected presents an opportunity to further understand different sensing modalities for blast pressure measurements, this study has not looked at differences between these sensors, and data from both sensor types are currently being treated as interchangeable and comparable.

A key limitation is the scale of the headform test series. Larger sample sizes across more LBSs with additional test conditions could provide further evidence that simply defining a target peak incident overpressure is not sufficient in defining standard test conditions for consistent evaluation of HPSs. Helmet A and Helmet B were not designed for blast attenuation. Tested in the forward orientation, they have relatively small blast attenuation effect sizes when compared to other HPS conditions (e.g., rear orientation, helmet with visor), as they do not directly interfere the blast wave prior to it impacting the face of the headform. It may be the case that HPSs exhibiting a larger effect size would show clearer trends agnostic of the LBS. A future study could test additional headform orientations or configurations with larger effect sizes to better determine scalability or comparison of helmet performance between labs. Furthermore, normalizing headform data was considered to address shot-to-shot variance, but differences in pitot probe measurements during headform testing stemmed from reflections off of the test article rather than blast overpressure variations. Further studies could optimize probe placement or explore alternative measurement methods to improve shot-to-shot normalization of headform data.

At this time, tuning two LBSs to better match both peak pressure and impulse is a significant challenge. An encouraging study demonstrated the ability of tuning both peak pressure and positive phase impulse, however, this methodology of tuning would require permanent modifications to the LBS, and these modifications may negatively affect wave uniformity and planarity [12]. It is also unclear to what extent a LBS shockwave needs to perform similarly to a live-fire wave to provide operationally relevant simulations of blast in the context of HPS performance. Complimentary live-fire testing would provide insight in deconvoluting the effect of the helmet and the LBS. A future effort could aim to tune a LBS to closely match different live-fire test conditions, and then directly compare live fire and LBS HPS results.

A 2D computational fluid dynamics (CFD) model was completed to asses LBS and test article size influence on overpressure loading [13]. Building upon that study, 3D CFD models of LBSs using realistic headform and HPS geometries could assist in deconvoluting variables influencing 'helmet effects' observed in this study, while also offering the opportunity to be validated experimentally. These higher fidelity models could also help differentiate shockwave loading effects purely from geometric differences and effects from difference in the wave generated. This may provide valuable information regarding a future tuning effort, or development of future LBSs.

Without clear metrics for standardised testing in LBSs, there has been less motivation to fully explore extensive modifications to tune LBSs. This problem is exacerbated by the current lack of blast injury risk curves (IRCs). Blast IRCs would inform and motivate efforts to tune multiple LBSs to a point where they are similar enough to be used in conjunction with one another. Some key performance issues, such as the lengthy blast duration generated by JHU/APL's LBS, or the non-uniform wave generated at ATC, could be the focus of future tuning efforts; however, without IRCs it is unclear how important these differences are in the context of the evaluation of HPSs regarding blast injury. The data collected in this effort could be revisited after the development of an IRC and provide meaningful context for future blast standardization methods. This data could also influence the design of future LBSs, head surrogates, and HPSs as it is the first investigation of its kind comparing probe-array pitot probe data and headform characterization data across a variety of LBSs.

5. CONCLUSIONS

The first phase of this study demonstrated that the four disparate LBSs varied drastically in duration, impulse, and other characteristics despite having simlar peak pressure values. Measures of repeatability, reproducibility, and shockwave planarity varied between the different LBSs. Headform and helmet testing with the two more similar LBSs resulted in consistent results within a LBS but inconsistent results between LBSs, and no trends could be leveraged to develop a scaling method to compare test results between LBSs. Simply defining a target peak overpressure is not sufficient in defining standard test conditions across different LBSs. Tuning the disparate LBSs to match in more than one metric was challenging and not explored fully due to resource constraints. While this study does not rule out the feasibility of using a combination of tuning and scaling techniques to enable HPS testing across LBSs, it does provide evidence of many challenges with that approach. This study also does not challenge the ability of LBSs to be used for standardized HPS testing, especially if a single LBS or very similar LBS designs are used. One major outcome of this study is the development of a reproducible test method and pressure probe array that can be used as a standarized method to characterize different LBSs and to compare the characteristic responses of other LBS to those of the four LBSs evaluated in this study.

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