Comparison of Pressure Attenuation Performance of Bomb Suit Designs during Free-Field Blasts using an Advanced Human Surrogate

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Abstract. Assessing blast overpressure attenuation and mechanical response of the body are important for evaluating protection of bomb suits. However, there is limited information and no standard test methodology for overpressure attenuation of existing suits. Additionally, existing literature has primarily used an automotive test device (50th percentile male Hybrid III, or HIII) with added surface pressure sensors, which limits our understanding of pressure experienced by internal organs of interest. Thus, the objective of this study was to investigate overpressure attenuation and the mechanical response of the body for current bomb suits using an advanced human surrogate.

Nine free-field blasts were performed using a 4.5kg spherical C4 charge positioned at mid-sternum height (1.37m) with a 1.83m standoff. The surrogate tested was a combination of a HIII head, a surrogate neck, an advanced human surrogate torso, and HIII legs. The torso was constructed from biosimulant materials representing a skeletal system, organs, flesh, and skin. Pressure sensors were embedded in major organs and on the skin surface. An accelerometer and a custom displacement sensor were mounted to the sternum. For each test, the surrogate was dressed with one of four bomb suit designs and rigidly mounted to a steel fixture at the waist to maintain a front-facing, standing position.

Reference pressures were similar across tests. Sternum acceleration and velocity differed between suits, but sternum compression remained relatively similar. Peak pressures varied across suits, with a significantly higher lung pressure with suit B than suit A. Peak surface pressures were significantly different from internal pressures. These findings suggest the suits tested provide varying levels of protection. However, further work is needed to relate these biomechanical metrics to risk of injury. This study supports previous results showing that internal pressure differs from surface pressure, indicating the benefits of using advanced surrogates in assessing bomb suit performance.

1. INTRODUCTION

Design of bomb suits to support an explosive ordnance disposal (EOD) technician during improvised explosive device (IED) defeat missions requires a complex balance of protection and performance. The bomb suit must protect against the imminent threats of blast overpressure, fragmentation, and ballistic impacts, while also allowing the EOD technician the range of motion, visibility, and dexterity needed to complete the mission. This complex design space has led to multiple test methodologies [1-3] and associated standards to verify that bomb suits meet the needs of EOD technicians. However, an official test methodology for blast overpressure attenuation performance of bomb suits does not exist.

One challenge in developing standards for assessing bomb suit blast attenuation performance is linking test methodologies to risk of primary blast-induced injuries. Current test methodologies commonly use an automotive anthropometric test device (i.e. a 50th percentile male Hybrid III) that has pressure sensors added to its outer surface to assess blast attenuation performance of a bomb suit [1-3]. While this provides a reasonable assessment for a relative comparison across bomb suit designs, there is limited data correlating this test methodology to risk of primary blast injuries. Additionally, this modified Hybrid III only provides an assessment of pressure experienced at the surface of the test device. This limits our understanding of the pressure experienced by internal organs of interest, such as the lungs, which has previously been associated with a degree of pulmonary contusion in an ovine model [4].

In previous work, an advanced surrogate system of the human torso, referred to as the Human Surrogate Torso Model (HSTM), was developed to assess blast overpressure attenuation performance of personal protective equipment [5,6]. This surrogate system was designed to measure a range of biomechanical metrics that are potentially linked to risk of blast-induced injury, including surface torso pressure, internal organ pressure, and skeletal kinematics. In working towards a robust standard test

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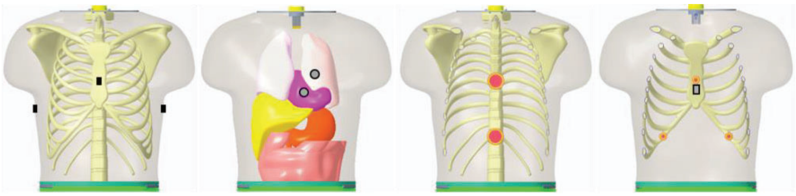
methodology, an advanced surrogate system that incorporates a wider array of sensing modalities may provide a more complete understanding of blast attenuation performance of bomb suits. Thus, the objectives of this study were (1) to evaluate the feasibility of using an advanced surrogate system to assess blast overpressure attenuation of bomb suits and (2) to perform a baseline assessment of the blast attenuation performance of current bomb suit designs with this advanced surrogate system.

2. METHODS

2.1 Advanced Blast Surrogate System

The Human Surrogate Torso Model (HSTM) was developed in prior efforts as a physical test device to assess the response of the human torso to high-rate (i.e. blast and ballistic) loading with varying personal protective equipment configurations [5,6]. The HSTM is representative of the human torso's form factor, structure, and material response, and enables repeatable dynamic measurements both on the surface and inside the torso (Figure 1). The HSTM is constructed with biosimulant materials representing a skeletal structure, major organs, mediastinum, flesh, and skin. Previous versions of this surrogate were application specific and, thus, the organs represented and the types of sensors used within the HSTM differed depending on the injuries of greatest concern. The organs represented in this version of the HSTM consisted of the left and right lungs, heart, liver, stomach, and intestinal mass. The heart, liver, stomach, and intestines are fabricated from the same silicone-based material, which was previously selected based on matched-pair testing to human tissues [7-10]. For the lungs, glass microspheres were spun cast into the silicone-based material to reduce its density and bulk modulus to better match an air-filled human lung than the standard silicone material [7,9]. Pressure sensors were embedded in the left lung and heart (EPIH, TE Connectivity, Schaffhausen, Switzerland), as well as on the skin surface (Model F, Honeywell, Charlotte, North Carolina). The placement of the four skin surface sensors was selected to be comparable to the sensor placement of a Blast Test Device (i.e. front, left, right, and back), a system that is commonly used to assess reference pressure during live-fire blast events. An accelerometer (7270A, Endevco, Sunnyvale, California) and a custom displacement sensor were mounted to the sternum.


Front View Location of surface pressure sensors shown – Mounted to skin (posterior sensor not shown)

Front View Location of internal pressure sensors shown

Front View EMF coils shown – Mounted to vertebrae sectioned for clarity

Back View EMF coils (red) and accelerometer (gray) shown – Backside of sternum sectioned for clarity

Figure 1. Sensing modalities within the HSTM consist of: (1) four external surface pressure sensors, (2) two internal pressures sensors embedded in the left lung and heart, (3) two EMF emitter coils mounted on the spine, (4) one accelerometer on the sternum and three EMF receiver coils with one mounted on the sternum and two mounted on the junction of left and right ribs 7 and 8. Together, the EMF emitter and receiver coils allow for measurement of the displacement of the skeletal system.

Previous tests utilised the HSTM independent of other components of the body to study the isolated response of the torso to blast overpressure. However, to allow for proper fit of the bomb suits tested in this study, a custom neck was designed and built to attach a Hybrid III head to the HSTM. The design of the neck was constrained by the existing HSTM connector, which is located on the top plate of the HSTM. This required the neck to be offset from the top of the HSTM to allow room for the connector. The neck component consisted of three layers, including an aluminium baseplate to attach to the top of the HSTM, a layer of silicone, and an aluminium top plate to attach to the Hybrid III head (Figure 2). This neck was then mounted to the top of the HSTM using aluminium standoffs. This allowed for physiological positioning of the Hybrid III head relative to the HSTM and proper fit of the tested bomb suit helmets.

In order to allow the bomb suits to fit on the surrogate system as specified by the manufacturer, the baseplate of the HSTM was also modified to allow for attachment to a standing Hybrid III pelvis and legs. Custom components were designed and fabricated to attach to currently existing threaded mounts within the Hybrid III pelvis. This combined surrogate system was then rigidly mounted at the waist to a steel blast test stand with the HSTM mounted to the top of the stand and the Hybrid III pelvis mounted to the bottom (Figure 3). Use of the blast test stand with the HSTM and Hybrid III pelvis allowed for the bomb suit trousers to be worn as specified by the manufacturer, with the straps of the trousers tightly fitting over the shoulders of the HSTM. Additionally, this test stand allowed the surrogate system to maintain a front-facing, standing posture during tests.

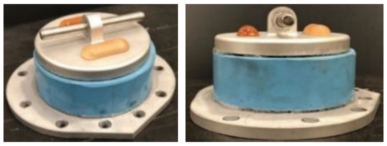


Figure 2. Custom neck used to connect the Hybrid III head to the HSTM. This silicone neck was mounted to the top of the HSTM using standoff mounts to allow for room for the sensor connector.

Figure 3. Surrogate system mounted to the steel blast test stand. The stand included a plate to mount the HSTM and the Hybrid III pelvis and a head support to prevent excessive torso hyperextension.

2.2 Bomb Suit Tests

The bomb suit test series consisted of 2 calibration tests followed by 9 assessment tests. The calibration tests were used to determine the correct standoff for the assessment tests. Prior to the calibration tests, it was determined that a 4.54 kg spherical charge of C4 suspended from 1.37 m would be used for each blast test. The charge height was selected to prevent the Mach stem from passing through the HSTM. The charge weight was optimised based on the predicted blast overpressure and estimated size of the fireball. The Conventional Weapons Effects (ConWep) software [11] was used to determine that this charge weight would produce a blast overpressure at a 1.52 m standoff that is comparable to the overpressure achieved with the current National Institute of Justice (NIJ) standard for bomb suit blast integrity testing (0.567 kg C4 at 0.6 m standoff) [12]. Thus, the target standoff was set at 1.52 m. However, during the calibration tests it was discovered that the fireball was larger than anticipated. This led the final standoff to be set at 1.83 m, given that this distance resulted in an acceptable blast overpressure and minimised the risk of damage to the surrogate system when protected by the EOD suits.

Four bomb suit designs were used in this test series (referred to as suits A, B, C, and D) with each suit design tested a different number of times (n = 4, 3, 1, and 1, respectively). The number of tests for each design was set based on availability of suits for testing. The primary functional differences across these bomb suit designs were variations in the frontal thoracic layup (Figure 4). Suit D had a frontal thoracic layup that consisted of a hard armour plate over a soft armour package with a thin layer of foam present between the soft armour and the torso. The other three suits (A, B, and C) had a frontal thoracic layup that consisted of at least two rigid ballistic plates separated by thin foam, a soft armour package, and a layer of thick foam between the soft armour and the torso. This layup provided a substantial additional layer of foam between the ballistic protection and the torso, in comparison to Suit D.

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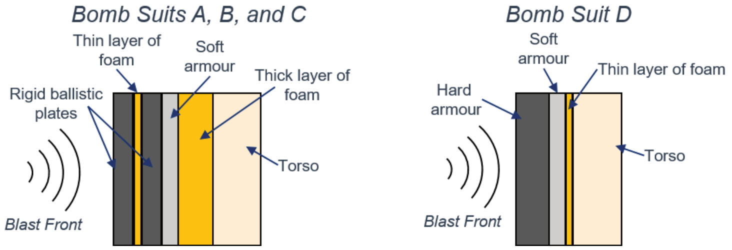

Figure 4. Schematic of the frontal thoracic layup of the bomb suit designs tested in this study. This drawing is not to scale and, thus, does not reflect exact relative thicknesses.

Each blast test included the surrogate system and two reference pressure systems. Reference pressure systems consisted of a pitot-static probe (Model 113A36/061A50, PCB Piezotronics. Depew, NY) and a blast test device (BTD) [13]. The pitot-static probe allowed for measurement of both the stagnation pressure and static overpressure. The BTD included four pressure sensors that were mounted flush to the front, left, right, and rear surfaces and allowed for an assessment of the stagnation and static overpressure that an unprotected individual would experience.

The test devices were positioned such that a reference point on each device was at the charge height of 1.37 m and at a 1.83 m standoff relative to the centre of the spherical charge. Reference points consisted of the front surface pressure sensor on the HSTM and the BTD and the side pressure sensor on the pitot-static probes. To ensure consistent standoff, the distance from the charge suspension line to the reference point on each test device was measured and adjusted as needed prior to each test. Once standoff was achieved, the HSTM was dressed with the bomb suit.

Cables for the test devices was routed from the blast pad into a steel blast shelter, which housed all data acquisition systems. For the HSTM, cables were first run from the surrogate into a set of buffer boards. These buffer boards provided signal conditioning and amplification needed for the sensors within the HSTM. The buffer boards were housed in aluminium boxes that provided blast protection and isolation from vibrations. Cables were then run from the buffer boards into the blast shelter, where it interfaced with the data acquisition systems. Where reasonable, cables were wrapped with Kevlar fabric to provide further protection from fragmentation during tests.

2.3 Data Processing

All data were recorded in the J211 coordinate system [14] and filtered using previously established protocols for free-field blast testing (**Error! Reference source not found.**). HSTM sternum velocity was then computed using numerical integration of the filtered sternum acceleration. Relevant metrics of interest were then computed for the HSTM and the reference pressure systems (**Error! Reference source not found.**). Sternum viscous criterion was computed using sternum displacement and accelerometer-derived velocity (Equation 1, [15]).

$$VC = \frac{y(t)\dot{y}(t)}{D}, \tag{1}$$

where $y(t)$ and $\dot{y}(t)$ are the sternum displacement and velocity, respectively, and D is the chest depth. The peak viscous criterion was then computed for each test. This metric has been shown to relate to the risk of severe chest injury (i.e. Abbreviated Injury Score ≥ 4) during moderate velocity, long duration blunt impacts (e.g. pendulum impacts), with the injury threshold typically set at a viscous criterion of 1.0 m/s [15]. However, this threshold has not been validated for blast induced chest injuries.

Table 1. Sampling frequency and filtering scheme used for each signal collected in this study.

Signal	Sampling Frequency (kHz)	Filtering Scheme
Pitot-static probe Pressure	400	40 kHz low-pass hardware filter
BTD Pressure	400	40 kHz low-pass hardware filter
HSTM Pressure	1000	60 Hz, 20-pole band-stop filter and 10 kHz, 20-pole low-pass filter
HSTM Sternum Displacement	1000	CFC60 filter [14]
HSTM Sternum Acceleration	1000	60 Hz, 20-pole band-stop filter and a 30 Hz high-pass, 10 kHz low-pass, 20-pole band-pass filter

Table 2. Metrics computed from the HSTM response and the reference pressure systems.

Metric	Definition
Peak Pressure	Maximum positive pressure
Start of Pressure Pulse	Time at which the pressure reached 10% of the peak value prior to the peak
End of Pressure Pulse	Time at which the pressure first dropped to 10% of the peak value following the peak
Pulse Duration	Length of time between the peak start and end
Pressure Positive Phase Impulse	Integral of pressure with respect to time from the pulse start to end
Peak Sternum Kinematics (Acceleration, Velocity, and Displacement)	Minimum value of signal, which corresponded with the maximum compressive sternum kinematics

2.4 Statistical Analysis

Peak stagnation pressure, static overpressure, and rear pressure were sorted based on suit design worn by the HSTM for each test. Unpaired t-tests with a Bonferroni-Holm correction for multiple comparisons were then used to assess differences in peak reference pressure experienced by each suit design. For suit designs tested multiple times, an unpaired t-test with a Bonferroni-Holm correction for multiple comparisons was performed for each of the computed metrics (i.e. peaks, pulse durations, pressure positive phase impulses, and viscous criterion) to determine statistically significant differences in blast attenuation performance across bomb suit designs. Significance was set at $p < 0.05$ for all comparisons.

3. RESULTS

3.1 Reference Pressures

Peak stagnation and static overpressure were not statistically different across all tests (Table 3). Additionally, peak reference pressures when separated by suit design worn by HSTM were also comparable (Figure 5). This indicates that the blast pressure dose experienced by each suit was similar and, thus, allowed for a valid comparison across suit designs.

The BTD peak stagnation pressure measured with the front pressure sensor was substantially higher than the peak stagnation pressure measured with the pitot-static probe (Table 4). However, the BTD left and right peak pressures were comparable to the static overpressure measured with the pitot-static probes.

Table 3. Peak reference pressures (mean ± standard deviation) across all nine tests. Table includes peak unfiltered and filtered pressures measured with the pitot-static probe.

	Stagnation Pressure (MPa)	Static Overpressure (MPa)
Unfiltered Pitot-Static Probe	5.66 ± 0.61	1.03 ± 0.090
Filtered Pitot-Static Probe	4.05 ± 0.26	0.862 ± 0.056

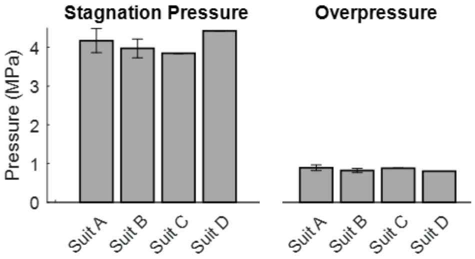

Figure 5. Bar plots show peak stagnation pressure and static overpressure (mean ± standard deviation) measured with the pitot-static probe for each suit. No significant differences were observed across suits, indicating that each suit experienced comparable blast pressure doses across each test.

Table 4. Peak pressure (mean ± standard deviation) measured with the front, left, and right pressure sensors of the BTD across all tests.

	Front (MPa)	Left (MPa)	Right (MPa)
BTD Peak Pressure	5.01 ± 0.60	0.903 ± 0.21	0.814 ± 0.25

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3.2. Bomb Suit Performance

The HSTM sternum kinematics differed significantly across bomb suit designs. Sternum accelerations that occurred with suit D were substantially different from the accelerations with suits A, B, and C (Figure 6). Peak sternum accelerations were greater for suit D than suits A, B, and C and significantly greater for suit B than suit A (Figure 7, p = 0.049). This relationship remained consistent for sternum velocity with a greater peak velocity observed for suit B than suit A (p = 0.006). However, there were no significant differences observed in sternum displacement across bomb suit designs (Figure 6 and Figure 7).

Previously, a sternum viscous criterion threshold of 1.0 m/s has been defined as the cut-off for the risk of severe chest injury. In this study, the peak viscous criterion were well beneath this previously defined threshold for all suit designs (**Error! Reference source not found.**Figure 8). However, there was a significant difference in peak viscous criterion between suit A and B (p = 0.03).

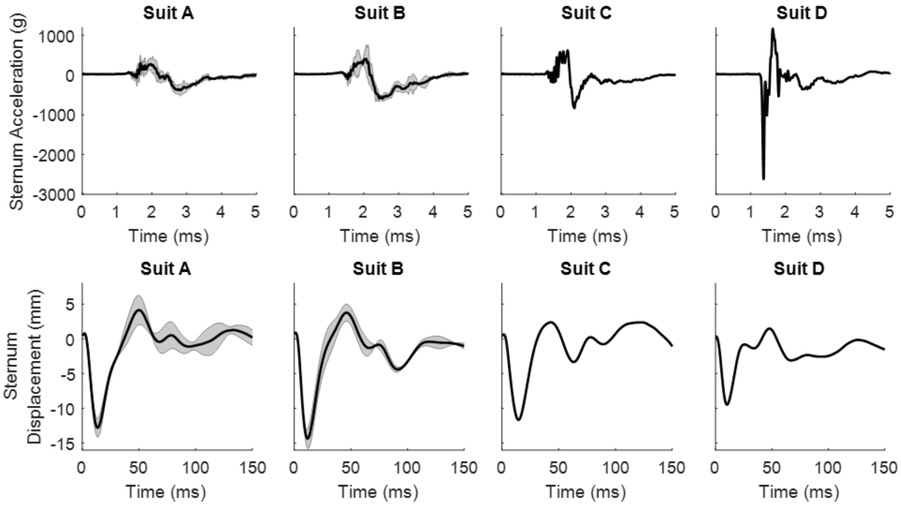

Figure 6. Plots show sternum acceleration (top) and displacement (bottom) for each suit measured across all tests (mean ± standard deviation). For suit designs tested once, the time history shown is for the single test. Negative values indicate the sternum moving towards the spine.

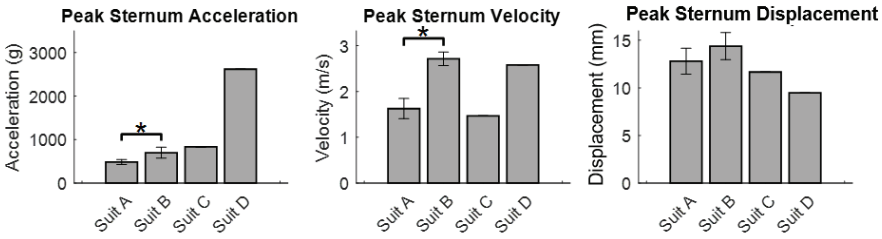

Figure 7. Bar plots show the peak sternum acceleration (left), velocity (middle), and displacement (right) across all tests for each suit design. * indicates a significant difference across suit designs peak.

Figure 8. Peak torso viscous criterion (mean ± standard deviation) for each suit design. * indicates a significantly different peak viscous criterion between suit design.

Surface pressures measured with the HSTM also differed substantially across bomb suit designs (**Error! Reference source not found.**). Each of the bomb suit designs resulted in a significant pressure attenuation relative to the unprotected configuration, based on a comparison of the BTD front pressure to the HSTM front surface pressure across each test (**Error! Reference source not found.**). However, this pressure attenuation performance varied across suit designs with a greater peak front pressure for suit D than suits A, B, and C. Additionally, suits C and D exhibited greater peak left surface pressures than suits A and B and suit D exhibited a greater peak right surface pressure than the other suits (**Error! Reference source not found.**).

Lung and heart pressures measured with the HSTM followed a similar trend to the front surface pressure. Greater peak lung pressures occurred with suit D than suits A, B, and C and significantly greater peak lung pressures occurred with suit B than suit A ($p = 0.03$). No significant differences were observed in peak heart pressure. Significant differences were also observed between the surface and internal pressures measured with the HSTM (**Error! Reference source not found.**). Across all tests, the peak lung pressure was significantly greater than the front surface pressure, while the peak heart pressure was significantly lower than the front surface pressure ($p < 0.001$ and $p = 0.007$, respectively).

No significant differences were observed in the pressure positive phase impulse for the front surface, lung, and heart across the bomb suit designs (Figure 12). It is important to note that the threshold for injury based on these metrics has not been defined for an armoured configuration. Therefore, it is unclear how the magnitude of the pressure impulse relates to risk of injury across suit designs.

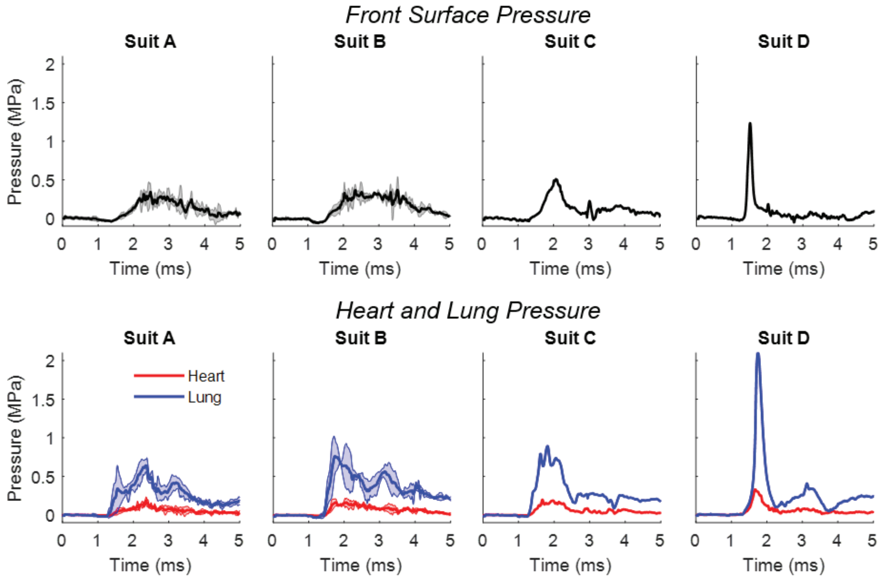

Figure 9. Time histories of front surface pressure (top) and heart and lung pressure (bottom) for each suit measured across all tests (mean ± standard deviation). For suit designs tested once, the time history is shown for the single test.

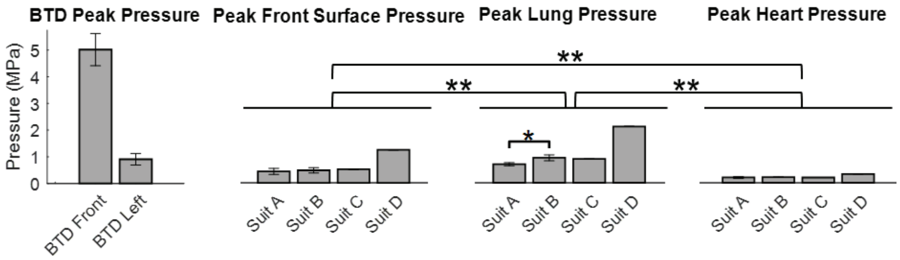

Figure 10. Bar plots show peak BTD, front surface, lung, and heart pressures (mean ± standard deviation) measured across all tests for each suit design. * indicates a significantly different peak metric across suit design. ** indicates a significantly different pressure across locations.

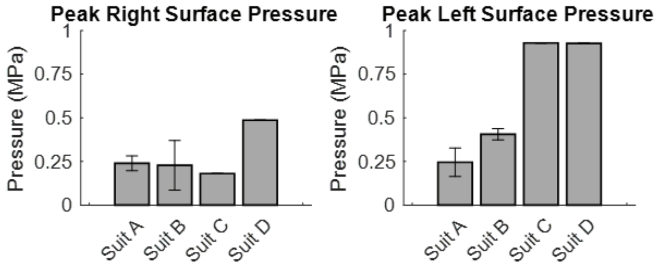

Figure 11. Bar plots show peak right and left surface pressures (mean ± standard deviation) measured across all tests for each suit design. No significant differences were observed for these pressure metrics.

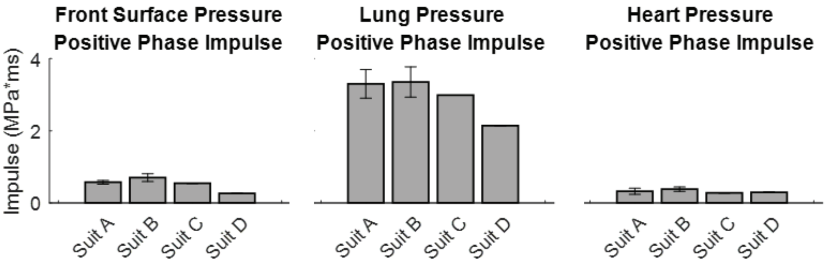

Figure 12. Bar plots show front surface (left), lung (middle), and heart (right) primary pressure impulse (mean ± standard deviation) for each suit design. No significant differences were observed.

4. DISCUSSIONS AND CONCLUSIONS

This study sought to evaluate the feasibility of using an advanced surrogate system to assess blast overpressure attenuation of bomb suits and to perform a baseline assessment of current bomb suit designs. The findings of this study indicate the HSTM provides a repeatable assessment of bomb suit performance, given the relatively low variability measured within a given bomb suit design. This is similar to previous assessments of the repeatability of the HSTM during ballistic impacts [16]. Additionally, this study suggests that the test methodology used can detect relative differences in bomb suit blast attenuation performance. It was observed that suit D exhibited the greatest sternum accelerations, but similar sternum velocities, and displacements when comparing to the other suit designs (**Error! Reference source not found.**). Additionally, suit D resulted in the greatest surface and internal pressures experienced by the HSTM, but also exhibited the shortest peak pressure duration (**Error! Reference source not found.**). These findings suggest a potential difference in protection from blast-induced injuries across the bomb suit designs. However, future work is needed to directly link these metrics to risk of injury.

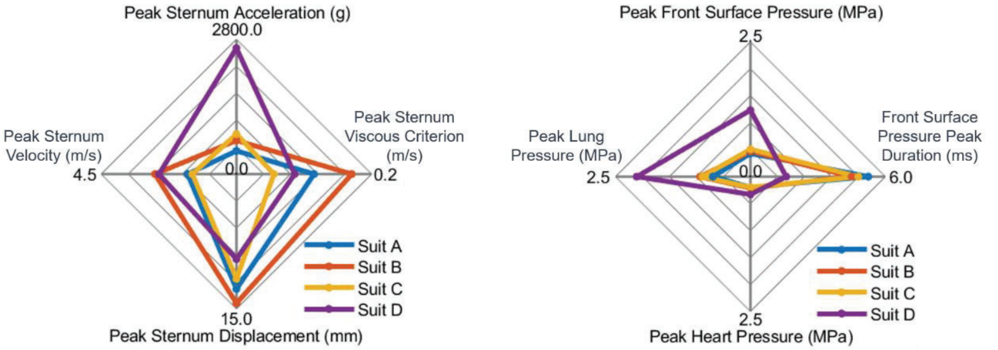

Figure 13. (Left) Plot shows the average peak sternum acceleration, velocity, displacement, and viscous criterion for each suit design. (Right) Plot shows the average peak front surface, lung, and heart pressure and the average front surface pressure duration for each suit design.

The second aim of this study was to assess the use of an advanced blast test surrogate for comparing bomb suit performance. In this test series, the HSTM exhibited excellent repeatability across the same suit design and good robustness with no sensors damaged. The HSTM also measured a significant difference between surface and internal pressures. This suggests that it may be important to use an advanced surrogate system, with the ability to measure pressure experienced by organs of interest, when assessing blast attenuation performance of bomb suits. The benefit of this blast surrogate was further supported by the differences observed in the measured lung and heart pressures. This finding indicates that the HSTM may be useful in detecting relative differences in injury to the internal organs.

Differences in suit performance were potentially influenced by the frontal thoracic layup of each suit design. As previously discussed, suit D was designed with only a thin layer of foam present between the hard armour plate and the surface of the HSTM. Suits A, B, and C were designed with a much thicker layer of foam between the ballistic protection and the HSTM surface. The results of this study suggest that this additional layer of foam is critical for improving the blast attenuation performance of a given suit design and mitigating the pressure applied to the surface of the body and to internal organs. Previous studies have shown that addition of a foam layer between a hard armour plate and the torso, resulting in an impedance to transmitted blast stress waves, can significantly reduce the risk of lung injury in an animal model [17-20]. The results of this study support these previous findings and provide a first step in identifying metrics that may be useful in detecting lung injury.

As previously mentioned, measurements made with the HSTM in an armoured configuration have not been directly linked to risk of blast-induced injury. However, previous work has compared the peak lung pressures measured with the HSTM when wearing hard armour plates to lung injury scores assessed in an ovine model [4]. In this previous study, blast testing was performed in a relatively small room with rigid walls using both an armoured HSTM and an armoured ovine model. The HSTM and ovine testing did not occur at the same time, but the testing configurations and charge weights were matched between the studies. In this test series, the ovine lung injury scored at an average of 31.9 based on a modified version of the Blast Injury Scoring System [21,22] (i.e. moderate lung injury) and the HSTM measured an average peak lung pressure of 0.625 MPa with a charge weight of 1.25 kg. In the current study, the peak lung pressures measured with the HSTM were greater than 0.625 MPa for each bomb suit design. While this may indicate a risk of lung injury for the bomb suits tested, it is important to note that attempts in this previous study to use the HSTM lung pressure to directly predict lung injury score were inconclusive. This may indicate that peak pressure alone is unable to predict lung injury and that further investigation is needed to determine a better injury prediction metric. Additionally, it is unknown how ovine lung injury scores relate to lung injury risk in humans, which limits the translation of these findings to the EOD technician.

While use of the HSTM and the associated test methodology allowed for a comparison across bomb suit designs, some limitations were noted in this study. The primary limitation of the test methodology is the mounting fixture used for the surrogate system. In the current design, the bottom of the HSTM and the top of the Hybrid III pelvis were rigidly mounted to a steel blast support system. While this mounting technique provided a stable support and helped limit variability across tests, it also resulted in an approximation of the worst-case scenario in regards to mechanical loading experienced by the skeletal system and internal organs of the surrogate. This approach was necessary due to the cables required for the HSTM. However, recent updates in miniaturised data acquisition systems have allowed for the potential to develop a wireless HSTM. Moving to a wireless surrogate will allow for modifications to this mounting design that result in a more realistic motion of the surrogate and a more accurate assessment of the blast attenuation performance across bomb suits. However, any updates to the test methods will need to maintain a high level of repeatability across tests to allow for an accurate comparison of suit designs. The primary limitation with the HSTM is the current inability to directly link the response of this surrogate system to human injury. Currently, the HSTM is best utilised in comparative assessments of different loading conditions or different armour systems, as was performed in this study. While there is some data linking the HSTM pressure response to risk of lung injury in an ovine model, future experiments are needed to develop a method to predict risk of blast-induced injury for humans with this advanced surrogate. The primary limitation in comparing performance across bomb suit designs was the limited sample size, which prevented a robust statistical comparison of some of the results. This was primarily due to difficulty in obtaining multiple bomb suits for each of the designs. However, the limited number of bomb suits did not detract from demonstrating the feasibility of using the HSTM with this new test methodology. In future studies that are primarily focused on comparing bomb suit designs, performing at least three tests with a given suit design is recommended.

In conclusion, this study achieved the proposed objectives of developing a bomb suit test methodology using an advanced blast surrogate and demonstrating its use for comparing across suit designs. The first key finding of this study was that the advanced blast surrogate allowed for a repeatable and reliable framework for bomb suit assessment and provided more information related to the human body response than previous test methodologies. The second key finding was that suits with thicker layers of foam between the hard armour and the torso exhibited lower peak sternum accelerations and lower peak surface and internal pressures, as compared to the suit with a thin layer of foam. These results suggest potential differences in the injury mitigation performance of the tested bomb suits, but future work is needed to understand the types of injuries that may have occurred in these free-field blast tests.

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