The effectiveness of PPE on blast overpressure propagation in a nonhuman primate

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Abstract. Injuries from explosive devices continue to be a major concern in military and civilian populations and personal protective equipment (PPE) could help reduce these injuries. However, the standards set by the National Institute of Justice as part of the acquisition process for explosive ordinance disposal (EOD) PPE only test the integrity and not the protectiveness of the suit. At present, there are no protection requirements against blast overpressure (BOP) for bomb suits; there are also no standardized guidelines or test methodologies to study the effectiveness or protectiveness of the EOD bomb suits and other PPE against primary BOP. The current testing strategies include surrogate testing (e.g. hybrid III), which are not validated for BOP. The objectives of this study are to determine the effectiveness of PPE based on BOP biomechanics using a custom-built EOD-PPE fabricated to fit the nonhuman primate. Two intracranial pressure (ICP) sensors (ventricle and epidural) and a thoracic pressure (ITP) sensor were placed in anesthetized animals. Animals with and without PPE were exposed to the same range of BOP levels. The presence of the vest did not affect the peak pressure in the thoracic region, but the helmet seemed to decrease peak pressures in the intracranial region. The vest did not reduce the impulse in the thoracic region, but the helmet did reduce impulse in the intracranial region. The presence of the helmet did increase the rise time of the pressure wave in the cranial region; this effect was not similarly reflected in the thoracic region. Future work conducting a similar comprehensive assessment with other species including postmortem human surrogates (PMHS) that may help define scaling laws across species. This will produce better correlations between blast parameters and injury risk, enabling the creation of guidelines for testing the effectiveness of PPE.

1. INTRODUCTION

Protecting military personnel from the devastating effects of explosions, particularly those encountered by Explosive Ordnance Disposal (EOD) specialists, remains a critical challenge. While substantial progress has been made in developing personal protective equipment (PPE) to mitigate injuries from shrapnel, fragments, and blunt force trauma, a significant gap persists in safeguarding against blast overpressure (BOP). This invisible threat poses a unique challenge, as it can induce severe, often lethal, internal injuries even when external damage is minimal. At present, there are no appropriate guidelines and test methodologies to study the effectiveness of the EOD bomb suits and other PPE against BOP [1].

Current testing standards for EOD suits and other PPE predominantly focus on maintaining structural integrity against blast events, neglecting the complex biomechanical responses of the human body to BOP. The requirements from the Maneuverability Center of Excellence to develop lighter PPE to meet the demands of the Warfighter in future multi-domain operations 2028 (MDO) includes the EOD suit, helmet and vest. This suit has been designed to protect against injuries from projectiles, shrapnel, debris and blunt object impact, but not BOP. This oversight stems from a lack of standardized testing protocols and validated injury criteria specific to BOP exposure. Consequently, the true efficacy of existing PPE to mitigate BOP-induced injuries remains largely unknown, hindering the development of next-generation PPE.

Several factors contribute to this knowledge gap. Major factors are the lack of understanding of BOP injury mechanism (e.g. contribution of peak, impulse or rise time to injury), how BOP parameters correlate to injury, and how well current PPE protects against them. This knowledge gap makes it difficult to quantify the protective capacity of PPE and establish safety standards for Service Members. Current surrogate models used to assess BOP effects, such as the Hybrid III crash test dummy, are ill-suited for replicating the intricate biomechanical interactions between blast waves and the human body. Another factor is conducting research using improper simulated blast waves which have pressure profiles that differ significantly from the "free-field" explosions experienced by personnel in the field. This discrepancy in blast wave characteristics further limits the translatability of current research findings to real-world scenarios.

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There have been attempts to develop more sophisticated testing methods such as using human surrogate dummies (e.g. Human Surrogate Torso Model (HSTM)), which can measure internal pressures in response to blast exposure [2]. However, these models lack validation against human biomechanics data, making it even more difficult to translate response from the HSTM to human injury. Furthermore, a lack of standardized test methodology and injury risk criteria for BOP make it challenging to compare the effectiveness of different PPE designs and develop material-based countermeasures. Addressing these limitations requires a multi-pronged approach that includes developing more biofidelic test models, validating non-surrogate models, and establishing well-defined injury criteria based on the biomechanical forces associated with BOP.

To create proper methodologies to evaluate PPE protectiveness against BOP exposure will require three steps: 1) establish biomechanical responses to blast in multiple experimental animal models; 2) develop the correlation of these biomechanical responses to injury; and 3) develop transfer functions based on biomechanics to scale the findings from animals to humans and establish injury risk thresholds. The research described this paper is part of the first step, to compare the effect of PPE on BOP parameters in the non-human primate (NHP) (pre-clinical) animal model. A custom PPE was designed and made to fit the NHP in similar fashion to the EOD suit. All animals were instrumented with pressure catheters in the head and thoracic region of the body. Ultimately, this research will pave the way for designing and fielding next-generation PPE capable of providing comprehensive protection against the full spectrum of blast-related threats faced by military personnel.

2. METHODS

A total of nine Rhesus macaques were used for this study. There were two females and seven males that averaged 9.80±0.97 years old, weighing 9.29±0.70 kg. Paired housed animals were separated prior to the start of the study in side-by-side cages with their paired cage mate.

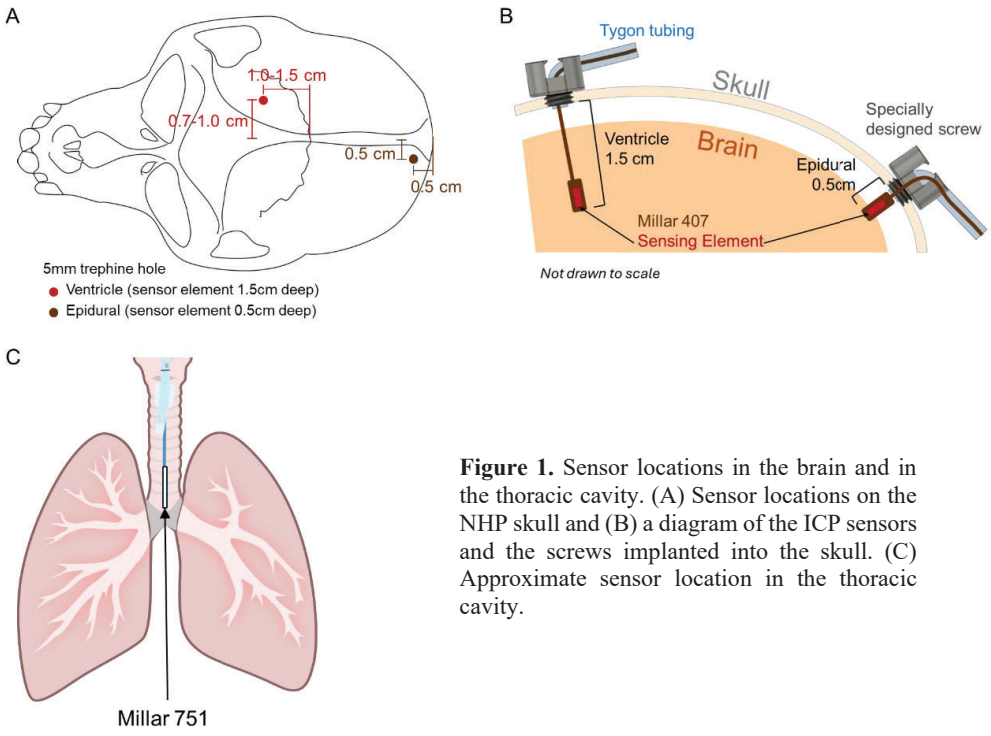

Figure 1. Sensor locations in the brain and in the thoracic cavity. (A) Sensor locations on the NHP skull and (B) a diagram of the ICP sensors and the screws implanted into the skull. (C) Approximate sensor location in the thoracic cavity.

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2.1 Surgical procedure.

Non-survival surgery was performed to implant pressure sensors in the brain and thoracic cavity. Animals were fasted for ≥12 hours prior to surgery and fully sedated with anesthesia throughout the surgery and data collection. Routine monitoring included indirect blood pressure, heart rate, respiration rate, end-tidal CO2, pulse oximetry, and body core temperature to ensure all animals were appropriately sedated.

2.2 Pressure sensor implantation

After shaving the fur, a local anesthetic (bupivacaine 0.5%) was administered to the incision site. The animals were placed in ventral recumbency, and an incision was made in the scalp. Trephines (5mm diameter) were used to drill two holes at the following locations, ventricle and epidural (Figure 1A). The coordinates for the ventricle sensors were 1-1.5 cm rostral, 0.7-1 cm lateral to bregma; epidural coordinates were 0.5cm rostral and lateral to lambda, opposite to the ventricle sensor. A specially designed screw secured the ventricle and epidural sensors (Figure 1B) to the skull. The ventricle sensor (Millar SPR-407 catheter, 1.5F body size) was placed in the lateral ventricle at 1.5cm deep; the epidural sensor (Millar SPR-407 catheter) was placed in the occipital lobe at 0.5cm deep. A third pressure sensor (Millar SPR-751S, 5F body size) was inserted into the esophagus and advanced approximately 22 cm into thoracic cavity and taped to the endotracheal tube (Figure 1C). The 751 Millar had two sensing elements (thoracic and distal), measuring 2.5 cm apart, with the distal caudal to the thoracic sensor. Anesthesia was maintained for the duration of the blast procedure until euthanasia.

2.3 Blast exposure

Animals were secured in an upright seated position within the Advanced Blast Simulator (ABS; ORA Inc., Marion, NC), which comprises of a 5.8 m long system with a driver chamber, divergent transition section, and a 61-cm² diameter test section (Figure 2). Compressed air was used to rupture acetate membranes (Graphix Inc, Ohio) or Valmex® membranes (Low and Bonar, Martinsville, Inc., Martinsville, VA) of varying thicknesses to generate blast waves with peak incident pressure levels of 32, 68, 104, or 145 kPa and associated impulses of 46, 117, 219, or 282 kPa•sec, respectively. The incident pressures chosen spanned the range produced by the ABS. This range of pressures has also been used in other animal species to study the BOP propagation through the brain and body; using the same ranges will enable direct comparison across species.

Figure 2. Advanced blast simulator (ABS)

A pitot probe (Stumptown Research and Development, Marion, NC) measured peak reflective, stagnation and incident pressures near the animal. Nine Rhesus macaques underwent multiple blast exposures, yielding ≥9 data points per pressure group. Data was acquired using a TMX-18 system (Astronova Inc., West Warwick, RI) at a sample rate of 800,000 Hz. Following data collection, animals

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were euthanized according to the 2020 AVMA Guidelines for the Euthanasia of Animals using an intravenous injectable barbiturate.

2.4 Data analysis

Pressure profiles were analyzed using MATLAB (R2020a, Natick, MA). Pressure-time histories were analyzed for peak pressure, rise time, positive duration and impulse. The peak pressure was defined as the peak that is present after the initial rise of the shock, not accounting for the reflective peaks. Rise time is defined as the first time point where the pressure exceeds 2 kPa. Positive duration was defined from the beginning of the rise time to the next time the pressure trace crossed zero (zero crossing). Finally, impulse was defined as the integral of pressure (area under the curve of the positive phase) across the positive duration. Negative phase data was collected but not reported for this paper. All Millar sensors were filtered with a 4^{th} order Butterworth filter with a 10,000Hz cutoff frequency. This filter was selected to remove the presence of cable whip and other high frequency noise events while keeping intact the majority of the signal. Analysis was performed as described above in all sensors: pitot, ventricle, epidural, thoracic, and distal.

The data were then imported into JASP (Version 0.19.3) where all required assumptions were assessed before completing the analysis. The Shapiro-Wilks test was implemented to test for multivariate normality. Multivariate outliers were examined with the Cook's Distance. Linearity and homoscedasticity of each of the predictor variables was assumed and analyzed through the residuals plot of the fitted data. Independence of residuals was analyzed through the Durbin-Watson test between observations and finally, the assumption of multicollinearity was also analyzed. Q-Q plots tested the data for normality and analysis of covariance (ANCOVA) tested for significant interaction between variables. When p value is less than 0.05, comparison in the data is considered statistically significant.

2.5 Personal Protective Equipment (PPE)

The custom-tailored body armour was constructed using the same or similar materials that are used in the MedEng EOD-8 bomb suit, which is widely fielded across military and law enforcement organizations. The PPE was tailored to fit the average sized NHP for this study. The suit only included the ballistic materials and a cover fabric. The other external accessories used on a typical bomb suit were not replicated. Every attempt was made to use identical ballistic materials if available. If substitutions were necessary, similar materials at the same areal density were used. The helmet was constructed using Tensylon HA 120 for the outer shell, Spectra Shield 4232 for the mandible, and an 18 mm thick Plexiglass visor. The outer shell material used for the suit was a TenCate Defender M fabric. The soft armor for the torso, arms, and legs were constructed using Twaron Style 1028 with the same layering as is used in the EOD-8. The rigid plates in the center neck, upper torso, groin, and thighs were constructed using Spectra Shield 4232 at the same areal density as the equivalent items in the bomb suit. The armour plates were shaped and sized to fit the NHP body in a manner to provide equivalent coverage as provided by the full-sized bomb suit. A Skydex attenuation panel was removed from an existing bomb suit torso plate and trimmed and mounted to the NHP torso plate.

3. RESULTS

The pressure-time histories for the incident, intracranial (ventricle and epidural), and intrathoracic (thoracic and distal) pressures were analyzed for the effect of PPE on the following blast parameters: peak pressure, impulse, rise time, and positive duration.

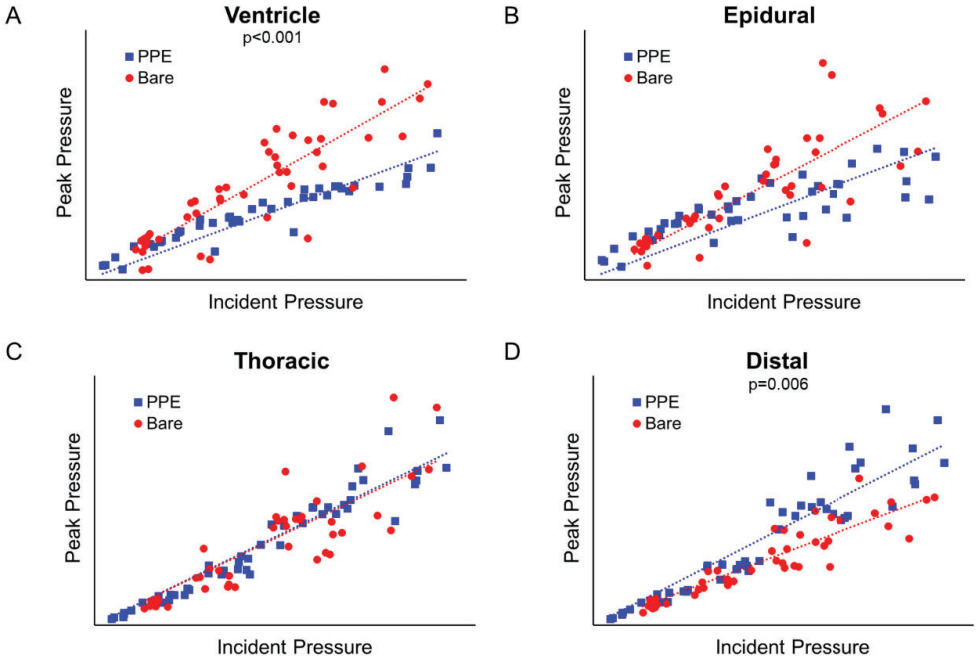

Figure 3. Comparison of the peak pressure data between PPE and bare configuration in Millar sensors showed significant changes in some of the sensors. (A) Ventricle ($p<0.001$) but not (B) epidural saw significant differences. (C) Thoracic was not significantly different but (D) distal ($p = 0.006$) did show significant differences.

3.1 PPE effect on peak pressures

A comparison of pressure data between the Millar and incident sensors showed that PPE produced differing effects between the brain and the thoracic region (Figure 3). The helmet significantly changed the peak pressures in the ventricle ($p<0.001$) (Figure 3A) but not the epidural. In contrast, the PPE had no effect on the thoracic sensor (Figure 1C) but significantly ($p < 0.01$) changed the peak pressures at the distal sensor (Figure 3D) suggesting that the PPE possibly amplified the transmission of pressure into the thoracic region.

3.2 PPE effect on impulse

The effect of PPE on impulse is illustrated in Figure 4. The PPE configuration saw lower impulse in the head, though this decrease is only significant ($p<0.001$) for the ventricle sensor (Figure 4A, B). Similar to the epidural, the presence of protection did not affect impulse in the intrathoracic region (Figure 4C, D).

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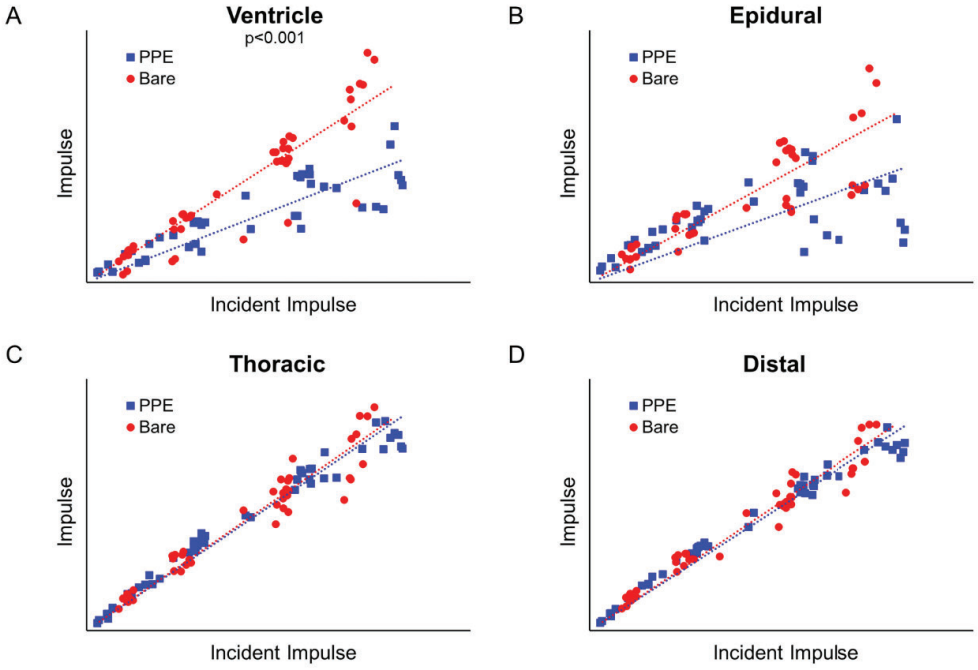

Figure 4. Comparison of the positive pressure impulse data between PPE and bare configurations showed only the (A) ventricle sensor ($p<0.001$) had significant differences. The pressures measured with the (B) epidural, (C) thoracic, (D) and distal sensors were not significantly altered by the presence of PPE.

3.3 PPE effect on rise time

The presence of the PPE was found to significantly impact the rise time at all four sensor locations (Figure 5). In the thoracic region, PPE seem to have opposing effects on the rise time. The thoracic rise time ($p<0.001$) increased with PPE and whereas it decreased for the distal sensor ($p=0.005$). Note, the ANCOVA only tested for statistical changes but not for statistical increases or decreases. For the sensors in the head, both ventricle ($p<0.001$) and epidural ($p<0.001$) locations yielded similar behavior; the rise times were significantly different when the PPE was worn versus when it was not worn. As there were no significant differences in the rise time of the incident pressures across all kPa's tested, the intracavity rise times were graphed in box and whisker plots to better display the group differences between PPE and bare configurations.

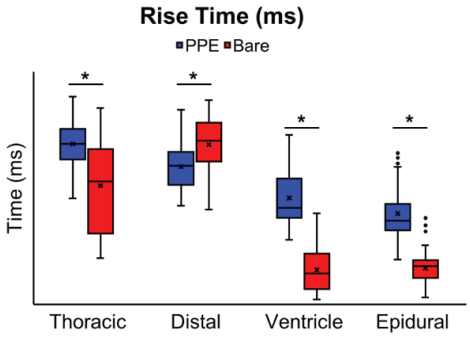

Figure 5. PPE had a significant effect on rise time on each of the four sensor locations: thoracic ($p<0.001$), distal ($p=0.005$), ventricle ($p<0.001$), and epidural ($p<0.001$).

3.4 PPE effect on positive duration

Figure 6 compares the effect of PPE on positive duration for each of the four sensor locations. The only sensor location that was significantly altered by the PPE was the distal sensor ($p<0.001$) (Figure 6D). The PPE did not affect the positive duration in the other three sensor locations. These findings suggest that the presence of PPE somewhat affects the duration of the positive pressure phase, although the exact nature of this relationship requires further investigation.

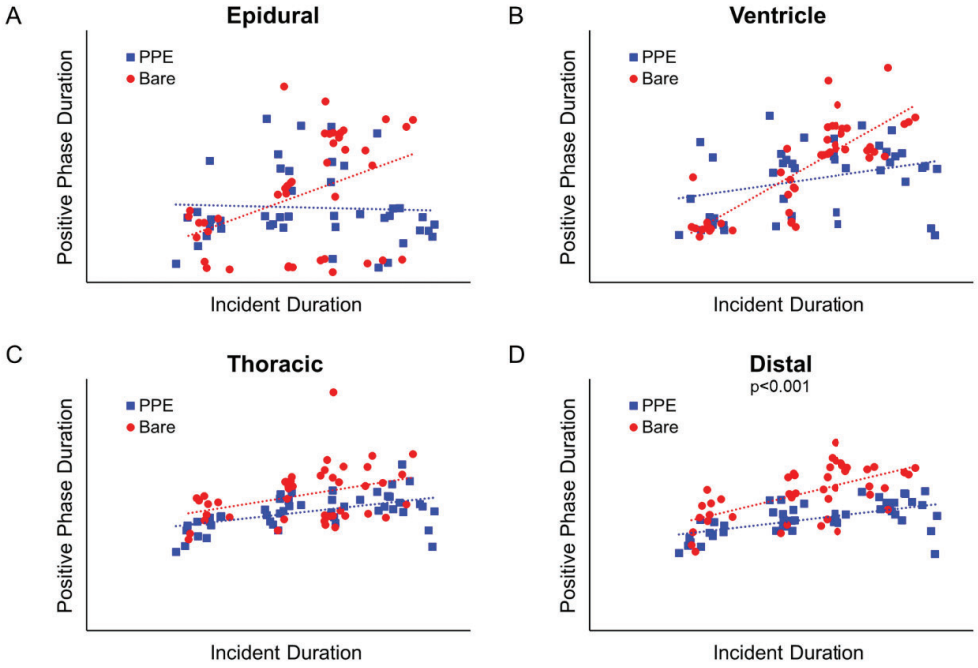

Figure 6. Comparison of the positive durations between PPE and bare configurations at the four sensor location: (A) ventricle, (B) epidural, (C) thoracic, (D) distal locations ($p<0.001$). The PPE seemed to have an impact on pressures only at the distal sensor location.

4. DISCUSSIONS

The current study investigated the biomechanical responses from BOP loading with and without the presence of PPE on intracranial (ventricle and epidural) and thoracic (thoracic and distal) pressures in a non-human primate model. Overall, the results show that the helmet significantly reduced the peak pressure and impulse in the ventricle region of the brain. This reduction in impulse was primarily due to a reduction of peak pressure but not due to a reduction in positive duration. In the thoracic region, the distal sensor saw an increase in peak pressures but a decrease in positive duration when the PPE was worn. This may explain why the calculated positive impulse saw no change with PPE. The rise time of the intracranial pressure in the brain for the bare configuration was found to be shorter than in the thoracic region, implying that thoracic surge is not the mechanism of intracranial pressure transmission in the cranium. The PPE significantly altered the rise time of for all four pressure sensors suggesting that the shockwave properties of the BOP were altered.

A number of research articles that have published studies on the biomechanical response to BOP in multiple species such as rodent [3, 3, 5], swine [6, 7], and other animals [8, 9]. The findings in this study are generally consistent with previous studies, showing increasing intracranial and intrathoracic pressures with increasing BOP levels. The intracavity rise times are also increased compared to the incident pressure rise times (data not shown). Some studies have reported higher intracranial pressure than the exposed incident pressure, a finding that was not observed in this study and could be due to a difference in species.

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When comparing the biomechanical performance of PPE, only a handful of studies exist. Some studies used animal models to study the effectiveness of body worn PPE [10, 11], others used physical anthropomorphic test dummies (ATD) [12, 13]. ATDs [14, 15, 16, 17] or computational modeling [18, 19] can be used to study the biomechanical responses of helmet and eye protection but does not allow for an injury response comparison. One of the significant limitations of these data from ATDs and computational models are lack of validation from experimental data. This research is unique in that a custom-made, scaled-down PPE made from the similar materials used for human PPE to protect both head and body was created to fit the NHPs. Data from this study could be used to compare to PMHS tests with PPE, validate and verify computational modeling results, and develop transfer function to define injury risk criteria.

Previous studies have shown that body worn PPE can have varying effects on intrathoracic pressures from BOP exposure. For example, Philips et al. 1988 [9] found that a cloth ballistic vest increased intrathoracic pressures and mortality in sheep. Young et al. 1985 [20] found that protective vests (e.g. ballistic vest, ceramic vests, field jacket) generally did not affect intrathoracic pressures compared to wearing fatigues for living humans standing in front of a shock tube, exposed to 18.6 kPa overpressure, with one exception. The ballistic vests they tested increased the intrathoracic pressures compared to wearing fatigues alone.

Research with more modern ballistic vests (hard and soft) were overall found to reduce peak pressure when used on instrumented testing rigs [21]. Sekine et al 2021 [11] showed that swine wearing ballistic vests observed no mortality at the 3-hour survival time point whereas the control group (that did not wear ballistic armor) saw a mortality rate of 55%. In contrast to the more recent studies, the findings in this research are more similar to the Young et al 1985 [20] study where they found most PPE, except the ballistic vest, had little effect on ITP compared to fatigues. The custom NHP PPE did not significantly alter most of BOP parameters analyzed (peak pressure, impulse, and positive duration) for the thoracic sensor. It is interesting to note that the PPE affected the distal sensor readings significantly compared to the thoracic, despite only being 2.5cm apart. This suggest that placement of the sensors in the thoracic region is important, due to potential complex interactions in the chest cavity. Studies with survival NHPs will need to be conducted to compare the injury response between PPE and bare conditions.

Similar to past research, the NHP helmet in this study was effective in reducing the peak pressures in the brain. Azar et al. 2020 [14] found that a tactical ballistic helmet with a visor combination reduced peak pressures in a surrogate headform. Dionne et al, 2018 [15] used a Hybrid III model to test the efficacy of an EOD suit exposed to blast. However, their analysis focused solely on using acceleration as a metric, as opposed to looking at reduction in BOP propagation. While some studies have shown increased pressure under the standard issue helmet, the data from this is more relevant to the helmets that have visors, similar to EOD helmets and could be a contributing factor in the reduction of pressure inside the cranium.

There are several limitations to this study. The first is that only pressure was measured. The difference in outcome between the thoracic and distal sensors demonstrate how PPE may affect BOP parameters. This suggests it would be valuable to include accelerometers and or strain gages to determine if body worn PPE could affect chest wall velocity. Another limitation is the size of the animal model with respect to the size of the ABS used. It is estimated that approximately 45% of the cross-sectional area of the ABS was occupied by the specimen, and more if the specimen was in the suit. As the cross-sectional area of the ABS is increasingly occluded, the dynamic pressure can increase, resulting in reflections [22]. The exact level of acceptable occlusion to minimize reflections is experiment dependent. Furthermore, free flight studies in the ABS showed the drag forces did not create sustained accelerations with larger objects compared to smaller diameters objects [23]. This suggests the maximum allowed blockage in the ABS permitted to accurately assess the impact on the flow conditions is not clear.

5. CONCLUSIONS

The results of this study provide valuable insights into the effects of PPE against BOP exposure and will shed light on the primary mechanisms underlying blast injury. Furthermore, these findings can be leveraged to validate various non-experimental models such as surrogates and computational models of the brain and body. Comparing the results from NHP with post-mortem human subjects (PMHS), will enable the development of scaling factors to facilitate interspecies comparisons. Direct comparisons between rodent and swine ICP data to humans are confounded by differences in head size, shape, skull thickness, and other physiological differences. Correlating the outcome from survival animals with and without PPE to the blast parameters in this paper, can inform the development of an injury risk curve as well as provide greater insight on the primary mechanism of blast injury. Altogether, these efforts will

potentially guide designs of more effective protective measures and enhance our understanding of blast physics and its effects on people.

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Disclaimer

Material has been reviewed by the Walter Reed Army Institute of Research. There is no objection to its presentation and/or publication. The opinions or assertions contained herein are the private views of the author, and are not to be construed as official, or as reflecting true views of the Department of the Army or the Department of Defense. Research was conducted under an IACUC-approved animal use protocol in an AAALAC International - accredited facility with a Public Health Services Animal Welfare Assurance and in compliance with the Animal Welfare Act and other federal statutes and regulations relating to laboratory animals.

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