Behind Helmet Blunt Trauma Due to Ballistic Mandible Protectors

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Abstract. Ballistic mandible protectors (BMPs) have recently been integrated with combat helmets to protect the face from primarily blunt and ballistic threats. Advancements in armour materials, design, and fabrication have enabled some BMP to stop small arms rounds from penetrating. In preventing penetration, armour backface can deform and strike the wearer causing injury, termed behind helmet blunt trauma (BHBT). It is of great interest to assess the risk of BHBT involving BMP. In this study, live ammunition striking an ultra-high molecular weight polyethylene BMP was used to create BHBT loading. Four postmortem human surrogate (PMHS) tests were conducted at ballistic conditions near muzzle velocity, using one BMP per PMHS. Two anatomical impact locations were tested; directly over the maxilla intersecting the mid-sagittal plane and over the mandible oblique from the mid-sagittal plane. X-rays and computed tomography scans were acquired before and after the test and were used in aiding characterization of the BHBT injury. An anatomical dissection, facilitated by a board-certified forensic pathologist, was conducted to physically evaluate the characteristics and severity of the injuries identified in the medical imaging. Backface armour deformation of the BMP was found to be substantial. The distance from the inner surface of the BMP and the face was greater (≈45 mm) for the maxilla shot versus the mandible shot (≈25 mm). Injuries observed in the maxilla impact location included lacerations of the upper and lower lips, teeth avulsions and fractures, and maxilla, hard palate, and additional facial bone fractures. Injuries observed in the off-centre mandible impact location included upper lip, lower lip, and tongue lacerations, teeth avulsions and fractures, and comminuted maxilla and mandible fractures. BHBT injuries from BMP provided better outcomes than penetrating injuries at the same locations. These BHBT injuries are thought to be potentially survivable as determined by a forensic pathologist, justifying the use of BMP.

1. INTRODUCTION

Combat helmets represent a multifaceted tool available to the warfighter. The helmets' primary function is to protect the wearer from various threats including protection from blunt loading from falls and large objects, protection from threats that could penetrate the helmet, such as ballistic rounds and fragmentation, as well as protection from the helmet system deforming and striking the wearer from non-penetrating events (Behind Helmet Blunt Trauma or BHBT). BHBT is a more recently developing threat that is not well understood and is the focus of recent research [1], [2]. While this research and knowledge in characterizing the risk associated with these helmet systems is helpful, there is no generalizable injury risk function yet to be used for new BHBT scenarios. As new form factors and subcomponents are designed and incorporated in helmet systems, there is a need to characterise the risk to the wearer of those new systems. Ballistic mandible protectors (BMPs) have recently been integrated with combat helmets to protect the face. Advancements in armour materials, design, and fabrication have enabled some BMP to stop small arms rounds from penetrating. There is an unknown risk to the wearer from BHBT from the backface of these BMPs.

BMPs primarily protect the face, which consists of soft tissue supported by skeletal structures. The upper facial bones support the eyes, nose and sinuses. The maxilla, mandible and associated teeth support structures of the mouth including the cheeks, tongue, gums and lips. Existing research in injury biomechanics examines facial injuries resulting from blunt trauma [3], [4]. These include test methodologies specifically developed to understand and correlate the loads to different structures and injuries to the face [5]. However, the high rate and focal nature of injuries induced by BHBT loading to the skull and face are distinct from typical blunt head trauma observed in the general population [6], [7]. For this reason, there is a need to understand the BHBT loading from BMP and resulting induced injuries. Postmortem human surrogate (PMHS) testing has been used in literature to correlate BHBT loading to injury [7], [8], [9]. In order to start to characterise the unique nature of BHBT loading from BMP involved events, this study presents the results from PMHS testing using live ammunition striking

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BMP and inducing BHBT. The results of this study can help inform future performance standards, necessary medical readiness if these systems are used, and future armour design.

2. METHODS

2.1 Projectile and armour combination

The same projectile and armour combination was used for all tests in this study. The projectile chosen is relevant to current operational threats, while velocities were near muzzle velocity to represent a worst-case scenario. The armour was an ultra-high molecular weight polyethylene (UHMWPE) composite BMP which was affixed to a size medium helmet by being clipped on to the rail mounting system (Figure 1). Each BMP was shot once, either centred on the mid-sagittal plane 70 mm from the bottom edge or off-centre 50 mm from the mid-sagittal plane 48 mm from the bottom edge. In addition to the helmet and BMP, communication equipment, including a boom microphone placed directly beneath the impact location, were donned to create a realistic situation in which a boom microphone might influence the loading from the backface of the armour to the face. The boom microphone was 15 mm thick in the direction of the shot, taking up some of the air gap between the backface of the BMP and the wearer. All ballistic events had 0 degrees of obliquity from the strike face.

Figure 1. (Left) Helmet with BMP, showing striking locations; (middle) mid-sagittal plane maxilla impact location; (right) off-centre mandible impact location

2.2 PMHS methods

This study investigated the biomechanical response of PMHS and associated characteristic injuries incurred by BHBT centred over the face. Four head/neck specimens were selected based on a stringent criterion to reduce variation and avoid conditions that could influence injury outcomes (Table 1), including head sizes to ensure fitment in a size medium helmet. All PMHS were acquired under institutional review board exemption approval through Johns Hopkins Medical Institutions. Once received, high-resolution computed tomography (CT) scans (slice thickness of 0.625 mm) were acquired for specimens at the Johns Hopkins University Applied Physics Laboratory to ensure specimens had no apparent abnormalities or signs of trauma that could influence interpretation of injury, including detailed review of dental quality. Specimens were stored at −20 °C until being thawed at 4 °C 6 days prior to testing for instrumentation and test preparation. PMHS specimens were prepared through dissection of the neck, removing tissue to expose the cervical spine, and potted using polymethyl methacrylate, fixing the cervical spine at the level of C7. This potting fixture was used to position the neck and head/neck system during the live fire test.

Two anatomical locations were identified as sites of interest: (1) the maxilla on the mid-sagittal plane (centred between the two central incisors) and (2) the mandible approximately 45 degrees rotated from the mid-sagittal plane directly on the mandible below the teeth (Figure 1).

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Table 1. Test specimen information

Test ID	Age	Head Width (cm)	Head Length (cm)	Impact Location
BMP_01	55	15.75	20.00	Mid-sagittal maxilla
BMP_02	46	16.00	20.30	Mid-sagittal maxilla
BMP_03	64	16.25	18.50	Off-centre mandible
BMP_04	67	15.50	21.60	Off-centre mandible

2.3 PMHS BHBT experimental setup

Ballistic testing was conducted at a National Institute of Justice (NIJ)-certified ballistic range [10]. Inverted specimens were positioned to correspond to the tested impact location on the anatomy. Helmets and BMP were then donned, positioned to collocate the intended BMP and anatomical locations. Communication sets (including headphones and a boom microphone) were included in as-worn conditions, where the boom microphone was placed directly over the anatomical impact location, almost in contact with the wearer, representing a potential worst-case impact scenario. Pre-test photos and x-rays were taken, the latter of which was used to measure the air gap between the armour backface and the anatomical impact site. Specimens were then impacted, using live ammunition striking the BMP, with the armour backface from a nonpenetrating ballistic event (Figure 2). Projectile velocity measurements were obtained using two sets of Oehler Research model No. 57 infrared screens with Hewlett-Packard (HP) counter chronographs (universal counters, HP model No. 53131A). Velocity was measured 1.5 m from the helmet and BMP, and then velocity loss equations were applied specific to the projectile to calculate striking velocity.

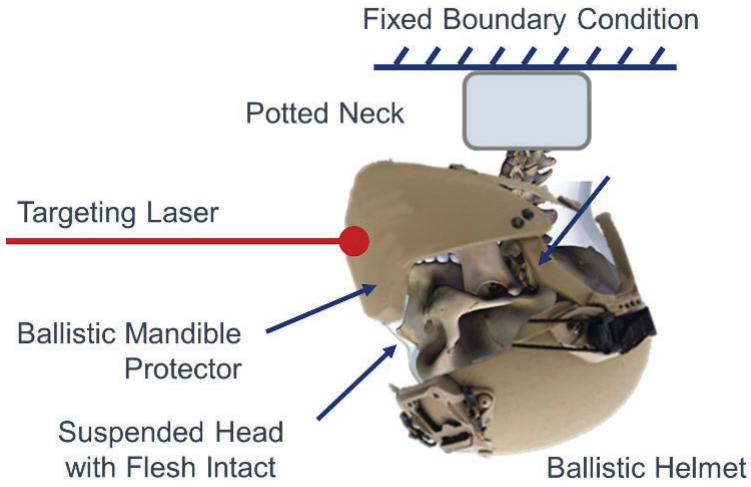

Figure 2. Graphic describing test setup, including fixed/potted neck, suspended PMHS, ballistic helmet and BMP and impact location (showing midsagittal maxilla impact)

Various instrumentation was used to better understand the loading event. A frangible break screen (Whitner, BS07-BCD, Baltimore, MD) was used at two locations, one at the last velocity gate (1.5 m from the helmet and BMP) to trigger data collection, and one adhered to the outer surface of the BMP to mark the timing of penetration of the outer shell of the BMP. Thin-profile piezoresistive force sensors (FlexiForce A301, Tekscan, Norwood, MA) were adhered to the front face of the boom microphone and to the surface of the skin at the targeted anatomical location. These sensors were used to gather the timing of loading events, including backface striking the boom, and backface/boom striking the PMHS. High-speed cameras (ACS-1-M60, NAC Image Technology, Tokyo, Japan) were used to capture the bullet entry and the system kinematics. The high-speed imaging was laterally and oblique to the shot direction and recorded at 100,000 and 50,000 frames per second, respectively. Sensor data were acquired at 1-MHz sample frequency using a Dewesoft data acquisition system (Dewe R4, HS-STG, Trbovlje, Slovenia), and cameras and data acquisition were synchronised together on the first break screen signal.

Injury outcomes were assessed using radiological evaluation of micro-computed tomography (μCT) images, using pre- and post-event scans, and anatomical dissections performed by a board-

certified forensic pathologist. This body of work uses dissection findings as ground truth to identify and characterise injury outcomes, as not all injuries were evident through μCT.

3. RESULTS

Typical post-test x-rays showed the round embedded in the ballistic armour, the deformation of the backface of the armour, and the injured anatomy (Figure 3). Injuries observed in the x-ray, while not definitive, showed facial and dental fractures.

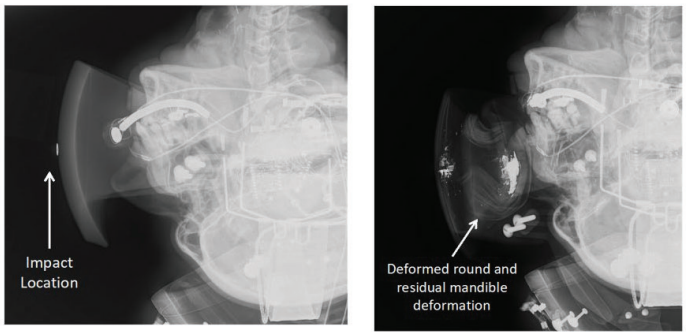

Figure 3. Lateral X-ray image of BMP and PMHS before impact (left) and image of BMP and PMHS directly after impact (right) for mid-sagittal maxilla impact (BMP_02)

Backface deformation of the BMP was substantial for this series of tests, appearing to fill the air gap present before impact. The air gap measured before impact was larger in the mid-sagittal centred striking location (approximately 45 mm) versus the oblique striking location (approximately 25 mm) because of the unique geometries of the BMP and the face (Figure 4).

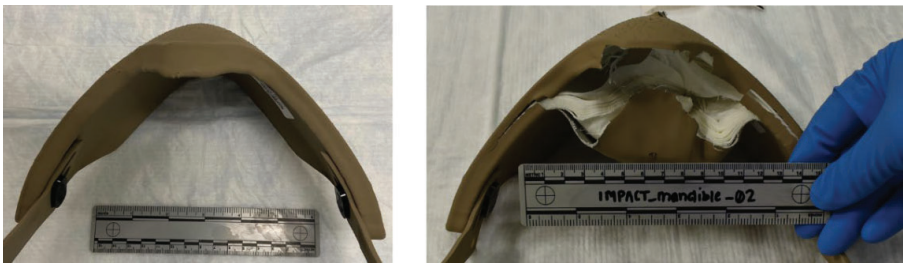

Figure 4. Top-down view of intact BMP (left) and residual backface deformation on the inner surface of the BMP (right) for mid-sagittal maxilla impact (BMP_02)

The impact location on the PMHS had foam and plastic fragments from the boom microphone embedded or adhered to the skin surface/wound. Injuries observed in the maxilla impact location included lacerations of the upper/lower lips, dental avulsions/fractures, maxilla fractures, and additional facial bone fractures (Figure 5).

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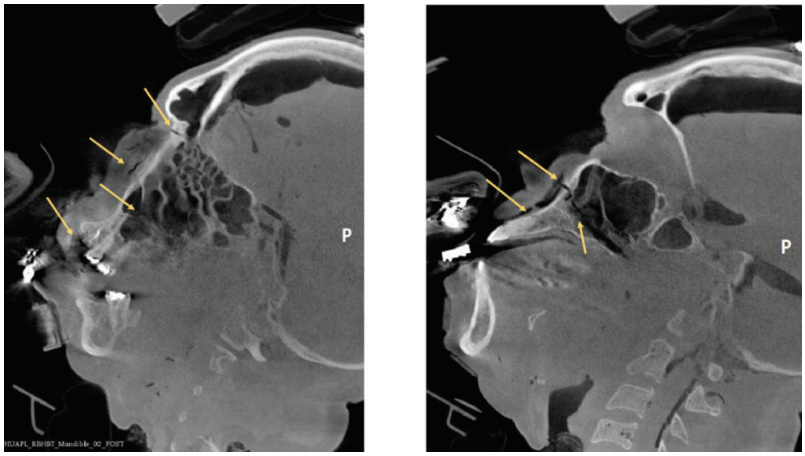

Figure 5. Post-test µCT of a mid-sagittal maxilla impact (BMP_02) showing facial fractures

Injuries observed in the off-centre mandible impact location included upper/lower lip and tongue lacerations, dental avulsions/fractures, and comminuted maxilla/mandible fractures (Figure 6).

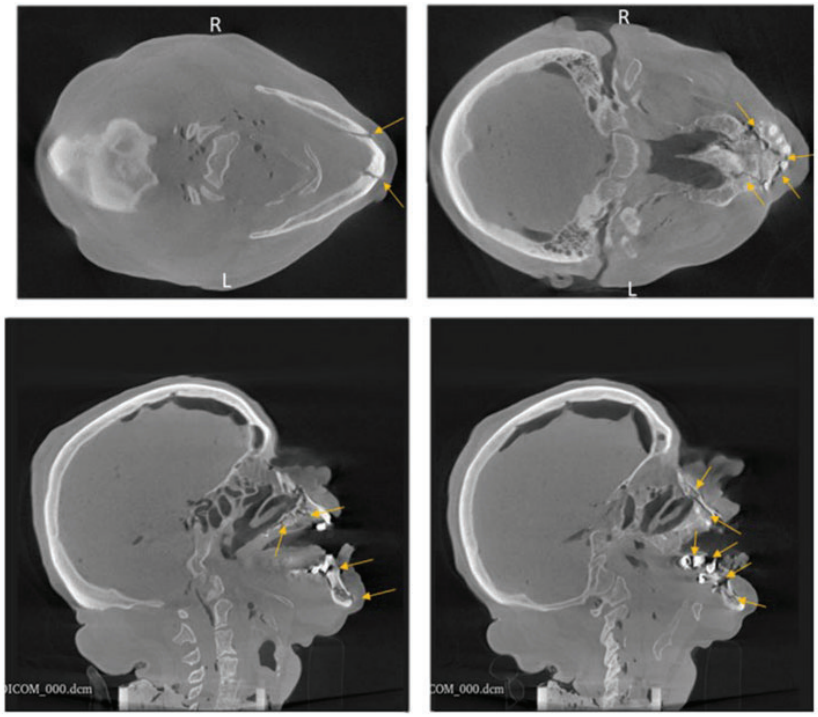

Figure 6. Post-test µCT of PMHS in axial (top) and sagittal (bottom) planes showing damage to the mandible and maxilla for an off-centre mandible shot (BMP_04)

The maximum abbreviated injury scale (MAIS) was used to quantify the most consequential injury. An alternative way to assess the severity of a complex injury is to use the New Injury Severity Score (NISS) injury model [11]. The NISS is calculated from MAIS scores and is the sum of the squares of most severe MAIS-coded injuries, regardless of body region. These injury outcomes can be found in Table 2. Individual injury codes can be found in Appendix A.

Table 2. Test conditions and injury results

Test ID	Impact Location	Air Gap (mm)	Injuries	Max. AIS	NISS
BMP_01	Mid-sagittal maxilla	45.48	a. Full-thickness laceration of the lower lip and lacerations of the oral mucosa b. Multiple tooth fractures/avulsions c. Multiple comminuted fractures of the maxilla with involvement of the lateral pterygoid plates, nasal sidewalls and nasal orbital ethmoid complexes; associated instability of the maxillary complex (Le Fort I-II) d. Right medial and inferior orbital wall fractures	2	9
BMP_02	Mid-sagittal maxilla	45.33	a. Laceration of the lower lip and lacerations of the oral mucosa b. Left zygomatic process fracture c. Left nasal sidewall and left medial orbital wall fractures d. Right nasal sidewall fracture e. Right inferior orbital wall fracture f. Multiple right-sided maxilla and hard palate fractures with involvement of right lateral pterygoid plate	2	12
BMP_03	Off-centre mandible	29.59	a. Laceration of the chin and oral mucosa b. Avulsion fractures of multiple upper and lower teeth c. Tongue laceration d. Comminuted maxilla fractures, involving left posterior aspect (partial Le Fort I) e. Multiple mandible fractures (left and right parasymphyseal, left ascending ramus)	3	17
BMP_04	Off-centre mandible	23.36	a. Laceration of the skin and soft tissue of the chin and oral mucosa b. Avulsion fractures of multiple upper and lower teeth c. Tongue laceration d. Comminuted maxilla fractures, with involvement of left posterior aspect (partial Le Fort I) e. Comminuted mandible fractures (symphyseal, left parasymphyseal, and dentoalveolar)	3	17

4. DISCUSSION

Injury results included soft tissue lacerations, facial bone fractures, and dental fractures/avulsions. All cases had complex midface fractures best described as a partial Le Fort fracture [12], ranging from Level I to II, indicating near separation of the hard palate or maxilla from the skull base. In addition, the comminuted mandible fractures of the off-centre impacts have the potential to adversely affect one's ability to maintain a patent airway, which would require immediate medical intervention.

Results show that injuries varied according to impact location, which may be attributed to regional anatomic differences, regional differences in contact conditions such as air gap, and/or armour performance. While this study was intended to gain a preliminary understanding of the types of injuries due to BHBT that were possible using relevant rounds and BMPs, it is of interest to explore the likelihood of these sources of regional sensitivity, as well as next steps, to support the potential of regional BHBT performance metrics.

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4.1 Regional tolerances

In the absence of the relationship between the as-worn conditions of the BMP and BHBT loading, it is important to evaluate previous work into characterizing load tolerances in facial trauma. Extensive research in the automotive safety industry has focused on understanding the risk of facial fractures from occupants impacting large structures like the dashboard or steering column. In simulations of dashboard impacts, Nyquist [13], observed that the mandible had a lower minimum fracture load (685 N) than the maxilla (1468 N). However, this study applied lower impact rates and forces over larger contact areas than those characterised in BHBT. In contrast, Nahum [14] using a 6.5 cm diameter cylindrical impactor on PMHS, observed that the maxilla (625–1980 N) exhibited lower regional tolerance to loading compared to the mandible (1900–4100 N). This difference in loading tolerances between studies highlights the importance of contact area because the maxilla exhibited lower regional loading tolerance than the mandible during highly focal impacts. The impact energies and velocities observed in Nahum's study ranged from 4.9–46.7 J and 3–5.4 m/s, respectively. More recently, Daniel [15] conducted anterior–posterior impacts to the mandible, centred on the symphysis of the mandible. These studies used a constrained mandible, in order to simulate the helmeted conditions and use of a chinstrap. The impactor was smaller in diameter (2.87 cm) and similar impactor velocities and energies (2.5-4.4 m/s and 9.8-31.8 J) than earlier automotive studies. Daniel found using this impactor that the mean force to cause fracture of the mandible was 2683 N which compares favourably to Nahum's study. The ballistic energy associated with the BMP tests conducted for this study were 2113–2164 J. Ballistic energies cannot be directly compared with previous impactor energies, due to the fact that energy is lost due to the partial penetration of the round in the ballistic shell. However, backface deformation velocities have been measured in similar BHBT events to estimate energy delivered to the head. The instantaneous kinetic energies at impact in other BHBT events [16] have ranged from 4–24 percent of the corresponding input ballistic energies at standoffs ranging from 12.7–19.1 mm. This approximation of BHBT kinetic energy contends that the impact conditions in Nahum's and Daniel's studies may be substantially less than the BFD energies estimated in this study. More controlled PMHS studies with faster loading conditions with greater energy, as well as realistic BHBT contact, than those observed in previous studies could ensure that true fracture tolerances are known to be used for regional BHBT performance metrics to the face due to BMP.

4.2 Air gap and contact conditions

It is a known phenomenon that the BFD of armour varies in shape over time [16], [17]. Typically, the backface of the armour begins to accelerate reaching a maximum velocity before experiencing exponential velocity decay. In Hisley's study [16], where a 9-mm round was used, the maximum velocity is observed in the first 12 mm of deformation. In Wen's study [17], which used a rifle round, it is unclear at what displacement velocity decreases, but the authors of this paper estimate it at less than 20 mm. For the BMP used in this study, there were substantial air gaps ranging from 23.36–29.59 mm in the mandible shot, and 45.33–45.48 mm in the maxilla shot conditions. Given the exponential decay of BFD velocity reported in the literature, the difference in BFD velocity between approximately 25 mm and 45 mm could be substantial. As a result, the energy delivered through BFD (which corresponds to BFD loading) may be significantly lower for the maxilla than for the mandible. This discrepancy could obscure the observation that the maxilla sustained fewer injuries under identical ballistic conditions, as the actual BFD loading may not be equivalent. It remains crucial to understand the relationships between ballistic conditions, standoff distance, and BFD loading for BMP at different impact locations. In addition to the air gap-dependent backface velocity, the presence of the boom microphone could have influenced the loading from the backface of the BMP to the wearer. The hard plastic in the boom microphone was observed to be shattered after the test, and could have influenced the soft tissue injuries in the tests. The stiffness and strength of the hard plastic is likely much less than that of the skeleton and the ballistic material of the BMP, so it is hypothesised that the overall effects of the boom mic in the load path are minimal as it relates to skeletal injuries.

4.3 BHBT performance

Armor and helmets are known to exhibit regional differences in performance [6]. In BHBT, this performance is often measured by metrics from different backing conditions. Some can measure loading dynamically, such as unbacked DIC [16], high-speed x-ray [18], and load cells. Others can measure backface deformation statically, such as deformation left in clay [10] and residual deformation of the armour [7]. In our study, the only measurable way to assess armour performance is through measuring

residual backface deformation, as no prior BHBT armour performance testing was conducted nor was the backface of the armour dynamically measured during our testing. In our testing, residual backface deformation was larger in the mid-sagittal maxilla than the off-centre mandible. This is likely to be driven more from the differences in air gap between the backface of the armour and the face, then the ballistic performance differences at those two locations.

To allow for future BMP BHBT performance to be standardised, steps should be taken to (1) evaluate the loading of these ballistic conditions to compare to injury to establish a dose response relationship for BMP BHBT and facial injury, and (2) provide a repeatable, flexible platform on which to evaluate future BMP systems and ballistic threats. Unique facial anatomy-based clay template in tandem with existing clay-based headforms such as the Peepsite headform [19] could be useful in quantitively measuring BFD loading. Clay headforms, however, lack biofidelity and dynamic measurements, and may only provide comparisons between BMP. Load cell-based headforms, such as BLSH and ATLAS, may offer a link to facial fracture observed in literature [20] and provide dynamic measurements. These headforms were primarily designed to assess BHBT by using high-magnitude loadcells that are more resilient to high-rate, high-magnitude loading seen in BHBT. However, these headforms were designed to assess ballistic helmet testing locations and do not have the instrumentation to assess facial loading. The Facial and Ocular CountermeasUre Safety (FOCUS) headform [5] has a form factor that can measure the relevant loading scenarios in BMP, however it is unclear if the instrumentation can support measurements in the high-frequency, high-magnitude loading environment produced by BMP BHBT. Steps should be taken to further adapt and mature BHBT testing platforms to enable the link from BHBT dose into injury response and support future BMP performance standards.

4.4 Limitations

This study is the first known to recreate BMP BHBT loading on PMHS through a limited number of tests and impact locations. There are most likely specific influences from this BMP design and round/armour type interactions that relegate these specific conclusions to this armour and threat pairing only. These results indicate that BMP BHBT injuries are possible and include lacerations and fractures to the anatomy of the face. While PMHS models have limitations in providing a physiological response (such as haemorrhaging, contusions, and any nervous system injury), the skeletal injuries from this study should be considered appropriate given the bone and dental quality of the specimens used. In addition, other studies have shown that postmortem bone, when hydrated, can approximate the mechanical parameters of bone from a living individual, even after a freeze cycle [21],[22]. The injuries observed in this study were characterised by using (1) the Le Fort Classification and (2) AIS. The Le Fort system was developed for military use in the early 1900s [12] and was specifically designed to assess and characterise injuries from blunt trauma to a large area of the face [20], and it may be inadequate for the focal loading believed to be present in this study. Additionally, AIS was originally designed for the automotive industry and may lack the specificity to adequately capture the types of injuries seen in BHBT events. There are other maxillofacial injury classifications, such as the fracture severity ranking scale [23] and the Maxillofacial Injury Severity Score [24] that could be evaluated for their utility to use in describing BHBT injury from BMP.

5. CONCLUSION

BHBT injuries from BMP are likely to result in less severe outcomes than penetrating injuries at the same anatomical locations, given the high likelihood of lethality of penetrating wounds and the significant challenges associated with reconstructive surgery for high-velocity small arms injuries [25]. BHBT injuries are generally considered survivable, reinforcing the justification for BMP use.

Regional sensitivity to injury severity was observed, particularly in relation to facial fractures. Mandibular injuries are considered more severe than maxillary injuries likely due to the potential complications in maintaining an airway caused by unstable mandibular fractures. This information can inform the optimization of BMP to reduce injury risk through further research, the development of BHBT testing standards, and the establishment of performance thresholds.

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APPENDIX A

Table A-1. Complete injury coding data

APL Identifier	AIS Coding of injury observed	
BMP_01	2 [251205]	Multiple fractures of same orbit
	2 [250806]	LeFort II
	1 [251408]	Teeth, any combination of dislocation/fracture/avulsion
	1 [210602]	Skin/subcutaneous/muscle, face, [includes eyelid, lip, external ear, forehead] laceration, minor; superficial
BMP_02	2 [250800]	Maxilla fracture
	2 [251231]	Medial wall fracture
	2 [251205]	Multiple fractures of same orbit
	1 [251802]	Zygoma fracture [includes zygomaticomaxillary complex (ZMC) and malar fractures], non-displaced [KN I]
	1 [250400]	Facial bone(s) fracture
	1 [210602]	Skin/subcutaneous/muscle, face, [includes eyelid, lip, external ear, forehead] laceration, minor; superficial
BMP_03	3 [251900]	Panfacial fracture
	2 [250614]	Open/displaced/comminuted [any or combination]
	2 [243404]	Tongue, laceration, deep; extensive
	1 [251408]	Teeth, any combination of dislocation/fracture/avulsion
	1 [210602]	Skin/subcutaneous/muscle, face, [includes eyelid, lip, external ear, forehead] laceration, minor; superficial
BMP_04	3 [251900]	Panfacial fracture
	2 [250614]	Open/displaced/comminuted [any or combination]
	2 [243404]	Tongue, laceration, deep; extensive
	1 [251408]	Teeth, any combination of dislocation/fracture/avulsion
	1 [210602]	Skin/subcutaneous/muscle, face, [includes eyelid, lip, external ear, forehead] laceration, minor; superficial

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