Preliminary Lethality Risk as a Result of BABT to the Heart

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Abstract. Behind armour blunt trauma (BABT) results from a ballistic projectile interacting with protective body armour, leading to local deformation of the armour into the torso. The risk of a serious BABT injury increases when the anterior thorax is impacted due to the proximity to critical organs. In the case of an upper thorax impact where interaction with the heart occurs, a range of injuries are possible. In this study, 27 BABT impacts to the heart were performed using a live porcine model as a surrogate for the human. The porcine specimens were impacted with a range of energies using a generalized blunt indenter with the shape and recruited mass of the backface of deformed body armour. Injuries ranged from short-term changes in the electrocardiogram (ECG) and temporary apnea to long-term disturbances in the ECG, caused by a loss of coordinated blood movement, and unrecoverable respiration. Generally, increasing energy resulted in an increased risk of serious cardiac contusion and loss of organized electrophysiological function. An alternate injury mechanism was also observed at low- to mid-range energies that resulted in immediate ventricular fibrillation (as seen in commotio cordis) if the impact coincided with the rise of the "T-wave" in the normal cardiac cycle. Injury risk functions were developed exploring the risk of lethality based on energy. Preliminary thresholds of injury coinciding with the range of energy levels were observed; impacts below 100 J generally resulted in no or short-term changes to the cardiac cycle and less than a 5% risk of lethality. An input energy of 220 J showed a 50% risk of lethality with test cases generally resulting in serious cardiac arrhythmias, apnea, and death. This and future injury risk functions are vital to yield functional protective armour designs based on required level of performance and individual combat situations.

1. INTRODUCTION

Body armour is designed to protect military personnel from injury or death resulting from ballistic munition penetration into the human body. This protection is achieved by the dissipation of energy of the munition through deformation of armour material, which often results in backface deformation (BFD). The BFD of the armour may cause localized high rate loading onto the body surface, which can result in severe non-penetrating injuries. The BFD mechanism may result in structural and physiological damage to the underlying anatomical structures through an injury modality referred to as behind armour blunt trauma (BABT) [1-3].

Current body armour standards are derived from studies performed in the 1970s. These studies dictated the use of Roma Plastilina #1 clay as the standard backing material for body armour evaluation and determined a BFD acceptance criterion of less than 44 mm into the clay [4-6]. From a medical standpoint, the clay deformation criterion does not correlate to any particular injury modality or severity. Due to this, current body armour systems do not account for differences in injury tolerances across various thoracoabdominal regions. Since the human torso is not a homogenous structure, the location of a BABT impact may result in injuries of widely varied severities for similar inputs. Therefore, the use of a uniform level of protection across the human torso likely leads to armours that are overdesigned, heavy, and cumbersome, limiting soldier mobility on the battlefield [7]. By quantifying the risk of injury across the various thoracoabdominal regions, it may be feasible to optimize the level of protection to lower risk body regions as a means for minimizing weight. However, improved evaluation tools and standards must first be developed to accommodate these competing design goals.

Post-mortem human subjects (PMHS) have historically been used as surrogates to represent live humans during assessments of skeletal fracture and tissue damage due to high-rate stimuli seen in military theatre, the automotive industry, and more. However, PMHS lack the physiology that is necessary to investigate injuries associated with the underlying anatomical systems that constitute a physiological response. To incorporate physiological damage metrics, live animal models are often chosen, as they can be monitored to observe the progression of injury response over time. Large animal models, such as the porcine

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model, are often used as a representation of the human torso for physiology and biomedical responses [8-12].

Thoracic trauma is a significant mechanism of injury in both civilian and military casualties—thoracic injury is a contributing factor in up to 75% of all trauma-related deaths and was the primary cause of over 1/3 of battlefield deaths during World War II [13, 14]. Thoracic trauma can cause morbidity and mortality through several mechanisms, including 1) airway obstruction through direct tracheal or bronchial injury, 2) loss of pulmonary function through contusion, rib fractures or hemothorax/pneumothorax, 3) exsanguination through direct vessel injury, 4) cardiac failure due to contusion, valve rupture, or dysrhythmia, and 5) cardiac tamponade due to direct cardiac wall or vessel injury [14]. Of these injury patterns, rib fractures, pulmonary injury, and blunt cardiac injury (BCI) are the most relevant injury patterns encountered in BABT, with fatalities reported from BABT pulmonary and cardiac injuries (15).

Cardiac injury, while less common than pulmonary injury in the context of blunt force trauma, conveys significant risk—up to 25% of traumatic deaths occur due to cardiac related injuries [16]. Cardiac contusion is the most common injury pattern observed, with a wide range of possible initial clinical presentations including chest pain, shortness of breath, or arrythmia. Subclinical myocardial contusion, an elevation of cardiac biomarkers (i.e. troponin) without symptoms or electrocardiographic changes, is likely of little clinical consequence. However, early development of arrythmia or cardiac failure symptoms is associated with both significant early and late complications including pump failure, complications due to clinically significant arrythmias, and myocardial necrosis with scar formation or delayed heart wall rupture [17]. Commotio cordis, the development of sudden cardiac death due to arrythmia after blunt chest trauma, is also potentially relevant to BABT. In prior porcine modeling, this phenomenon was largely dependent on impact timing relative to the cardiac cycle, as well as force of impact within the vulnerable time window [18].

While the potential for cardiac injury in BABT is apparent, current data on BCI is almost entirely from motor vehicle impacts (occupant and pedestrian) or falls [16]. As such, the spectrum of BCI risk from BABT is unknown. The objective of this study is to use a porcine cardiac model to simulate BABT and to develop injury risk functions from these results.

2. METHODS

2.1 Porcine Testing

Simulated BABT impact tests were conducted in vivo with 27 live Yorkshire pigs (mass = 43.44 ± 3.73 kg, length = 108.92 ± 5.03 cm) using a custom-designed, high-rate linear impacter system and ballistic indenter. The ballistic indenter was three-dimensionally (3-D) printed with carbon fiber-reinforced nylon (Markforged, Watertown, MA) where the impacter mass and shape was based on flash X-ray measurements of a 7.62-mm test round (7.62 ball round – 9.72 g) impacting a thick Ultra-High Molecular Weight Polyethylene (UHMWPE) armour plate selected for high deformations and low probability of penetration for round velocities of approximately 670-800 m/s armour[3]. From these flash X-ray images, the backface velocity of this type and thickness of armour was measured in the range of 50 to 60 m/s. This indenter was designed to characterize the onset of BABT injury from a generic threat rather than any specific type of ammunition or body armour. The indenter was 101.6 mm in diameter with a mass of 250 grams to represent the approximate recruited mass of the ammunition and body armour into the torso. The indenter was equipped with an Endevco 7270A-20k accelerometer to measure the impact event. The impacter system was pneumatically driven and capable of propelling the indenter at velocities greater than 50 m/s.

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Figure 1. 3D-printed indenter modeled after backface deformation profile (left) and custom pneumatic impacting system for simulating BABT with live porcine specimens (right)

For each impact test, the impact site was chosen to cover the greatest surface area of the heart while maintaining a fully orthogonal impact between the indenter and the thorax. This impact location was lateral to the midline to avoid the sternum and typically spanned left ribs 3-6, overlapping with the cranial lobe of the left lung. The impact site was confirmed using ultrasound to ensure positioning was consistent between tests. Impact timing was controlled to avoid the phenomena known as commotio cordis, where ventricular fibrillation is induced due to blunt impact during the upstroke of the T wave [18]. This impact timing was initially performed manually with the goal of impacting during the QRS complex of the ECG. However, this proved to be too inconsistent and impact timing was modified to utilize a custom, automated impact timing control system. The control system used the ECG signal to impact consistently within the QRS complex for the remaining tests. Impact energy was varied from 20 Joules to over 300 J to get a range of injuries for the purpose of developing injury risk functions. A complete test matrix is provided in Table 1.

All specimens were procured through the UVA Center for Comparative Medicine and were acclimated upon arrival for a full three days (72 hours). On the day a specimen was tested, they were induced using Telazol and kept under anaesthesia with isoflurane and medical air for the duration of the impact event. Local analgesics (Bupivacaine) were also administered to the impact site prior to testing. This anaesthesia is not expected to influence the injury response of the specimens, especially since supplemental oxygen was avoided in the delivery of the isoflurane. Specimens were instrumented with Millar pressure transducers (PT) in the descending aorta via an introduced femoral catheter to measure arterial pressure during the impact event. Live patient monitoring data such as Electrocardiogram (ECG), heart rate, blood oxygen (Sp02), and respiration rate were also measured. Following each impact, specimens were monitored until they were determined to be recoverable (i.e., in a medically stable condition), at which point they were recovered from anaesthesia and returned to their housing area for continuous monitoring (up to 8 hours) for signs of discomfort or respiratory distress. Each porcine specimen was imaged using CT with contrast. Once radiology was complete, the specimen was euthanized, and the imaging data was transferred to a radiologist for diagnosis. A comprehensive post-euthanasia necropsy was performed immediately following euthanasia to determine and document injuries to the tissue. If a specimen reached a critical endpoint (i.e., signs of medical distress) prior to recovery from anaesthesia, the specimen was immediately euthanized followed by post-euthanasia necropsy and injury documentation. CT was not conducted for these specimens. All testing was completed under approved protocols from the University of Virginia Animal Care and Use Committee (protocol: 4379-12-21) and the U.S. Army Animal Care and Use Review Office (protocol: MT21006.031.e002).

Table 1. Test matrix with specimen mass and input conditions

Specimen Test ID	Specimen Mass (kg)	Input Velocity (m/s)	Impact Energy (J)
H01	43.6	12.79	20.04
H02	42.3	15.31	28.71
H03	45.3	19.18	45.99
H04	48.0	22.61	63.89
H05	49.0	28.04	98.28
H06	41.8	32.74	134.01
H07	42.8	36.56	167.07
H08	42.8	37.71	177.73
H09	38.8	38.90	189.17
H10	42.8	31.99	125.32
H11	47.0	31.37	123.02
H12	44.2	31.73	125.83
H13	44.0	39.38	193.87
H14	48.0	45.31	256.57
H15	45.0	47.58	282.98
H16	41.4	44.12	243.33
H17	42.8	48.53	294.37
H18	39.4	25.79	83.15
H19	43.4	38.24	182.80
H20	47.0	41.99	220.44
H21	48.0	38.72	187.45
H22	51.0	37.87	179.30
H23	37.0	11.66	17.34
H24	42.4	21.83	60.75
H25	41.0	26.92	92.41
H26	36.4	34.45	151.28
H27	37.6	38.03	184.38

Once euthanasia was complete and confirmed by the veterinary staff, the necropsy was performed by first creating a Y incision starting from the sternal notch, bifurcating at the xiphoid process, and following the costal cartilage dorsally towards the spine. The tissue was reflected bilaterally away from the ribcage to reveal skeletal injuries to the sternum, ribs, and costal cartilage. The diaphragm was then reflected to reveal the pleural cavity. Any injuries to the heart were documented *in situ*, before removing the organs for further examination and documentation.

2.2 Data Acquisition and Processing

Accelerometer and pressure transducer data were sampled at 500 kilohertz (kHz) with a 100-kHz antialiasing filter using a High-Speed SLICE data acquisition system (DTS, Seal Beach, CA). Following data acquisition, sensor offset was removed from the indenter acceleration trace, and the data were filtered using a phaseless 4-pole Butterworth low-pass filter with a cutoff frequency of 2 kHz [19]. The filtered acceleration data was

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then used to calculate impact energy (Joules; J) which was then normalized based on specimen mass using the equal-stress equal-velocity scaling method [12, 20-22]. Here the porcine data were normalized to a mass of 39.55 kg, representing the mass of the torso of a 50th percentile male human [12, 23].

2.3 Data Censoring, Predictor Selection, and Injury Risk Function (IRF) Generation

Using survival analysis, injury risk functions (IRFs) were evaluated for lethality, and input energy was used as the predictor metric. All injurious tests were included as right censored data, and all non-injurious test data was left censored. IRFs were generated using the Survival package [24] within RStudio (RStudio PBC, Boston, MA, USA). The statistical distributions considered for each IRF included the Weibull, log-logistic, and log-normal distributions, with their cumulative distribution functions defined by Equations 1 through 4:

$$Weibull: F(x;\lambda;k) = \begin{cases} 1 - e^{-\left(\frac{x}{\lambda}\right)^k} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{1}$$

$$log - logistic: F(x;\alpha;\beta) = \frac{1}{1+\left(\frac{x}{\alpha}\right)^{-\beta}} \tag{2}$$

$$log - normal: F(x;\mu;\sigma) = \frac{1}{2} + \frac{1}{2} erf\left(\frac{\ln(x)-\mu}{\sqrt{2}\sigma}\right) \tag{3}$$

where x is the response variable (e.g., impact energy, etc.), λ, α, and σ are the scale parameters, k and β are the shape parameters, and μ is the location parameter. The erf term in the log-normal distribution is the standard Gaussian error function which is defined as:

$$erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt \tag{4}$$

3. RESULTS

Twenty-seven (27) simulated BABT impact tests were performed for this study with input energies ranging from 15 J – 295 J. Injuries were observed to the heart, lungs, ribs, and superficial soft tissues. More specific to the heart, conduction abnormalities, arrythmias, apnea, and contusions were observed. However, special consideration was given to the instances where the impact resulted in a critical endpoint as it was desired to determine the limits of lethality. Of the 27 impacts, 4 were excluded due to impacting on the T wave of the ECG, inducing commotio cordis. 5 resulted in the specimen meeting the humane endpoint criteria and were euthanized immediately following impact. In these cases, the impact was recorded as resulting in lethality, and injury risk functions were developed for this specific outcome. The Weibull based distribution was selected as the optimal distribution since it had the lowest Brier Score Metric (BSM) and Kolmogorov–Smirnov (KS) test statistic (Dmax) values as well as a comparable AIC value (Table 2). The Weibull distribution is also ideal to use in this situation since extrapolation to smaller risks is likely to be important and the distribution passes through (0, 0).

Table 2. Lethality IRF model fit statistics

Distribution	Dmax	AIC	BSM
Weibull	0.413	21.1	1.7
loglogistic	0.429	21.2	1.94
lognormal	0.427	21	1.93

The Weibull based lethality IRF with energy as the predictor metric is shown in Figure 2, where the shape parameter *k* is 3.66182 and the scale parameter *λ* is 243.24161. Mean risk levels are shown in Table 3 with a 50% risk of lethality at 220 J.

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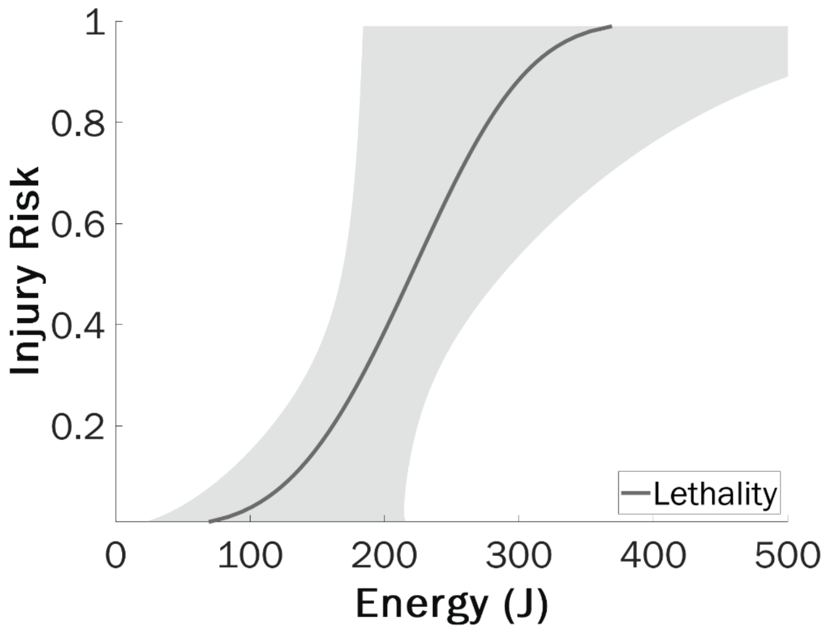

Figure 2. Injury risk function with 95% confidence intervals describing the risk of lethality in a live porcine model using input energy as the predictor metric and a Weibull distribution.

Table 3. Mean risk of lethality based on input energy

Risk Level	5%	10%	25%	50%	75%	90%	95%
Energy (J)	108.1	131.6	173.1	220.1	265.9	305.5	328.2

4. DISCUSSION

The lethality risk curve presented in Figure 2 considers factors that may affect the subsequent care of the injured warfighter. The injuries that are represented by the risk curve include trauma to the heart that leads to a fatality despite the presence of medical assistance or proximity to a trauma center. Cases of impact that lead to apnea are very much dependent on the ability of the wounded to start breathing again on their own or the resuscitative efforts of another. For the tests performed in this study, apnea was allowed to continue for several minutes before external ventilation was delivered. Still, one cannot say definitively if the specimen would have started breathing again on its own.

Cardiac arrythmia of varying severity was often induced by the impacts. In most cases, dysrhythmias were transient, but longer-term outcomes from cardiac contusion and risk for persistent or recurrent arrythmia, heart failure, and other sub-acute complications are not well-characterized by these data. Though these impacts resulting in arrythmias are not to be trivialized, they are being interpreted in this context as survivable. There were instances of sinus arrest followed by ventricular escape with a few instances of subsequent R on T phenomenon and ventricular tachycardia or fibrillation. These rhythms are significantly hemodynamically compromising and represent higher risk impacts. Separate injury risk functions could be developed for less-than-lethal impacts which would be useful in more conservative armour designs.

As the ultimate purpose of this research is to develop a set of physiologically based injury criteria for the development of new body armour designs, the analysis of the collected data will address the factors that may be important to designers. As a preliminary analysis, the focus is developing a risk function based on lethality of a backface armour blunt thoracic impact. Other risk functions based on serious, but less lethal injuries, including cardiac contusion and varying arrhythmia can be assessed and yield functional protective armour designs based on required level of performance and individual situations.

Protection against commotio cordis is not being considered in the analysis because of the apparent low energy required to induce it and reliance on a non-modifiable risk factor (time of impact relative to cardiac

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cycle). Effective protection may require extremely heavy/stiff armour over the heart region which may be impractical for many current ballistic threats. In addition, because the risk window for a high-risk-timed impact event is limited, the likelihood of a commotio cordis event from a ballistic impact is small compared to the likelihood of an impact event resulting in a non-commotio-related cardiac arrhythmia, contusion, or laceration.

5. CONCLUSION, ACKNOWLEDGEMENTS, AND REFERENCES

Injury risk functions were developed for lethality using energy as the response variable for BABT. A Weibull-based IRF was generated from 27 impact tests performed on live porcine specimen. Preliminary injury risks coinciding with the range of energy levels were observed; impacts below 100 J resulting in a less than 5% risk of lethality and energies above 220 J resulted in a 50% risk of lethality. Other heart injury modalities were observed such as cardiac arrythmias, apnea, and heart contusions, but they were not analyzed further for this study. Future risk functions based on these less lethal injuries may be generated to yield functional protective armour designs based on required level of performance and individual situations.

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