Development of Impulse-Based Rib Fracture Injury Criterion for Behind Armor Blunt Trauma

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I. INTRODUCTION

Body armor significantly benefits military personnel by reducing the risk of penetrating injury and decreasing the local energy transfer from the projectile to the body. This dissipation of energy is accomplished through a combination of momentum transfer and deformation of the armor which can contribute to a blunt high-rate loading from the armor Back Face Deformation (BFD) to the underlying anatomy. Injuries associated with this scenario are known as Behind Armor Blunt Trauma (BABT).

Current body armor standards have led to designs that are overly heavy for the warfighter, limiting their mobility on the battlefield. BABT threats are rarely linked to human injury and death, leaving an open question as to whether body armor is overdesigned against current threats [1]. The standards used to evaluate body armor are also based on the profile of BFD into a clay surrogate which lacks a direct relationship with a human physiological response [2]. Due to the complex nature of the human thorax, it is hypothesized that regional variations in anatomical vulnerability will result in varying tolerances to injury during BABT which cannot be captured with the current clay surrogate. This study is part of a larger program to develop local injury criteria associated with each thoracic region but will focus on the development of an injury criterion for thoracic rib fractures during a BABT impact.

II. METHODS

Nine male whole-body post-mortem human subjects (PMHS) approximating a 50th percentile male (mass = 81.8 ± 7.1 kilograms [kg], height = 179.6 ± 23.1 centimeters [cm]) were impacted at various velocities on the thorax, targeting ribs three through five over the lungs. All tissue donation, testing, and handling protocols were approved by the University of Virginia Institutional Review Board – Human Surrogate Use (IRB-HSU) Committee and the Army Human Research Protections Office (HRPO). Each PMHS was instrumented with strain gauge rosettes (Micro-Measurements MMF313001) on the sternum and bilateral second, fourth, sixth, eighth, and tenth ribs. In addition to the instrumentation, the PMHS were perfused with a saline drip through the carotid artery to aid in specimen biofidelity. Prior to testing, the intubated specimens’ lungs were exercised and left fully inflated but not occluded.

A custom free-flight impactor was designed to approximate the shape of the BFD produced by previous BABT events [3]. The impactor was equipped with a single-axis accelerometer (Endevco 7270-20k) and an onboard data acquisition system to measure input acceleration for each impact test. Data was sampled at 200 kilohertz (kHz) with a 40 kHz antialiasing filter and was further filtered post-test with a 2 kHz low-pass Butterworth filter. Using this impactor, the nine PMHS were impacted within an energy range of 30-300 Joules (J) on both sides of the thorax for a total of 19 impact tests (PMHS 01 was impacted to the right lung twice; once at a sub-injurious level and once at an injurious level). The nine specimens were palpated after each individual impact for injury examination. After impactor testing was completed, post-test computed tomography (CT) scans, radiology reports, and comprehensive autopsies were performed to diagnose injuries on each specimen. The injury and fracture data from these tests were used to develop an injury risk model using impulse as the metric. Impulse was calculated by integrating the force time-history of the impactor accelerometer from impact time to fracture time as detected by strain gauges for most injured cases. Impulse was calculated from impact time to peak for the uninjured cases as well as for cases in which the fracture time was unable to be determined.

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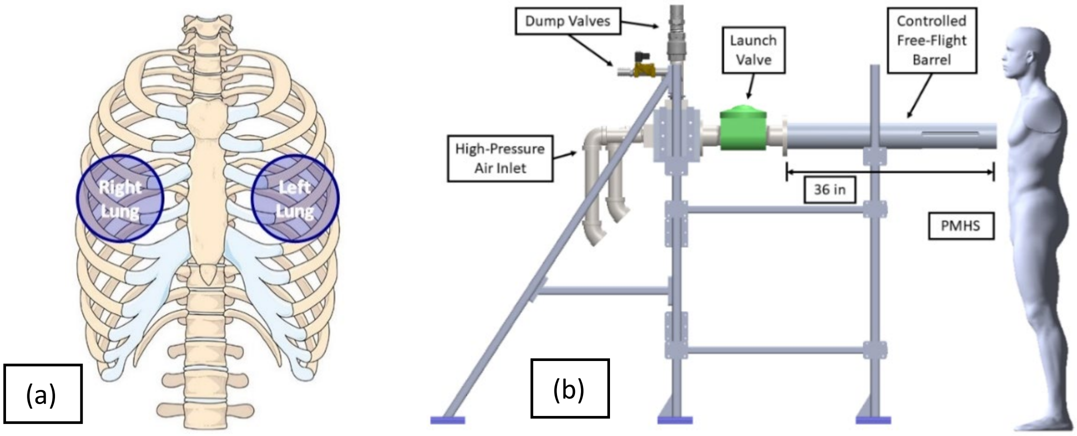

Figure 1. (a) Target impact locations and (b) experimental setup

III. INITIAL FINDINGS

Impact accelerations to the thorax ranged from 500 – 4,000 G. Rib fractures were noted in most tests with impact energy greater than 60 J. In total, structural damage was found in 53% of rib impacts. A survival analysis was performed using this injury data, and an impulse based injury risk function was developed for BABT events. While impulse was selected as the metric for this publication due to its consideration of the force-time history of the impact event, further analysis is ongoing to develop risk functions using other metrics such as energy, force, momentum, and displacement. The full injury risk function is shown in Figure 2. In this case, the 50th percentile risk of rib fracture was observed at 2.54 Newton seconds (Ns), and the curve produced an AIC of 40.5.

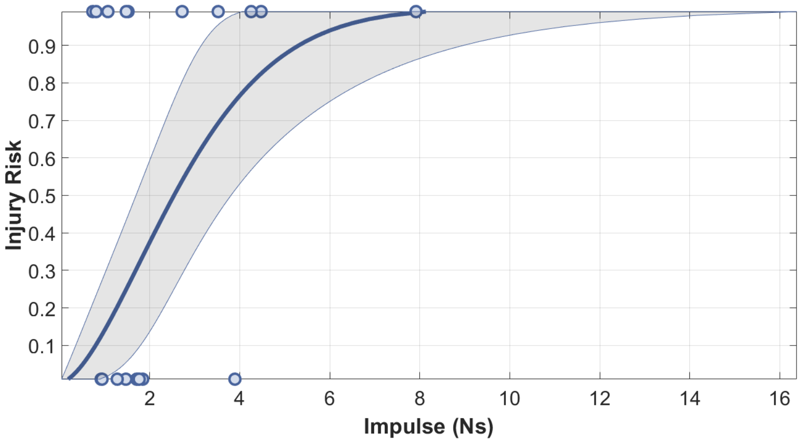

Figure 2. Rib fracture injury risk from BABT impulse with 95% confidence intervals.

IV. DISCUSSION

This study developed a test methodology for BABT and an injury risk function for rib fracture as a function of impulse in PMHS. Continuing efforts are being made to understand the physiological threat to life associated with the thorax in BABT (in such regions as the sternum, abdomen, and spine) to allow for body armor design optimization. Although efforts were made to prepare each PMHS to mimic *in vivo* conditions, the lack of physiological response limits the ability to assess the full clinical implications of a BABT impact. Physiological injuries such as pulmonary contusion may occur in conditions where a rib fracture does not occur and may prove to be more significant in theater. Further research is being conducted to better understand the relationship between the structural and physiological responses during BABT.

V. REFERENCES

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