# Impulse-Based Lung Injury Risk Curves for Behind Armour Blunt Trauma

Narayan Yoganandan, Alok Shah, Jared Koser, Lewis Somberg, Brian Stemper,
Valeta Carol Chancey, Blake Johnson, Barney Joseph McEntire

## I. INTRODUCTION

For advancing human safety and design of protective devices/personal protective equipment (e.g. body armour) in areas that include automotive, sports, military and other environments, injury risk curves are needed. From the developed risk curves, injury criteria can be established. For example, the 44 mm deflection injury criterion for behind armour blunt trauma (BABT) applications was determined from thorax impact tests to live goats [1]. Injuries were classified based on lethality. For chest and abdominal injuries, the American Association of Surgery Trauma separately scores chest wall injuries and organ injuries. The Abbreviated Injury Scale (AIS), used widely in automotive medicine, scores injuries based on anatomical considerations [2]. Other simplified clinical classifications include categorising injuries as mild, moderate and severe, or mild and moderate, with implications for treatment [3]. Likewise, many biomechanical outcomes can serve as potential candidates to explain the underlying injury mechanism and serve as metrics for developing injury criteria (e.g. impulse, viscous criterion). The objective of the present study is to develop injury risk curves for BABT applications using clinical classification of injuries and impulse as the biomechanical metric.

## II. METHODS

Institutional animal committee and sponsor approvals were obtained prior to live swine experiments. The animals were acclimated for at least two days in the veterinary unit before testing. Trachea tubes and intravenous lines were placed after inducing anaesthesia. Pressure transducers were placed in the aorta and lungs. A pressure transducer was guided into each lung through the trachea tube. Another transducer was introduced into the aorta. Impact loading was applied to the left lung region of the supine-positioned animal using two indenter shapes. The first indenter impact face design was hemispherical (~235 g mass), and it was based on the backface deformations from previous cadaver tests with hard body armour [4]. The second indenter impact face design was conical in shape, and it was based on expected backface deformations of less rigid armour. Indenter impact speeds ranged from 13 m/s to 65 m/s. An accelerometer attached to the indenter was used to record signals at a frequency of at least 100 kHz and filtered at 2 kHz. Necropsies were conducted after monitoring physiological parameters for six hours. Injuries were graded as mild, moderate, or severe by trauma surgeons. Rib fractures and injuries to the lung in the form of contusions and lacerations were identified. Impulse signals were calculated using the indenter mass and acceleration data. The peak impulse was used as a biomechanical metric for developing injury risk curves using parametric survival analysis [5]. Non-injury and injury data points were as right and uncensored variables. The quality of curves was assessed using 95% confidence interval bounds at discrete probability levels using the normalised confidence interval size, defined as the width of the interval normalised to the estimated value of the metric at the chosen risk level [6]. Injury risk curves are presented in this paper for mild and severity injury categroies.

## III. INITIAL FINDINGS

Forty-two live swine were impacted once. There were six animals with no injuries, 14 animals with mild injuries, 10 animals with moderate injuries, and 12 animals with severe injuries. The magnitude of the estimated (mean) impulse at the 10% and 50% risk levels for mild, moderate and severe injuries were 1.40 Ns (confidence interval range: 1.11 to 1.70), 2.12 Ns (1.84 to 2.40), and 2.42 Ns (2.10 to 2.73), respectively, and 2.35 Ns (2.11 to 2.60), 2.82 Ns (2.62 to 3.02), and 3.10 Ns (2.86 to 3.33), respectively. The qualities of the risk curves were in the good category at these levels. The risk curves are shown in Fig. 1 for mild and severe injuries, and the 95% confidence intervals are shown as shaded areas.

N. Yoganandan (e-mail: yoga@mcw.edu) is a Professor, A. Shah is the Director of Biomechanics Laboratories, J. Koser is a Senior Engineer, L. Somberg is a practicing civilian and former military surgeon and a Professor, and B. Stemper is a Professor, all at the Medical College of Wisconsin, Milwaukee, USA. B. Johnson, V. C. Chancey and B. J. McEntire are a Senior Engineer, the Director, and Research Engineer, respectively, of the Injury Biomechanics and Protection Group at the United States Army Aeromedical Research Laboratory, Fort Novosel, AL, USA. N. Yoganandan and L. Somberg are employees of the VA Medical Center, Milwaukee, WI, USA.

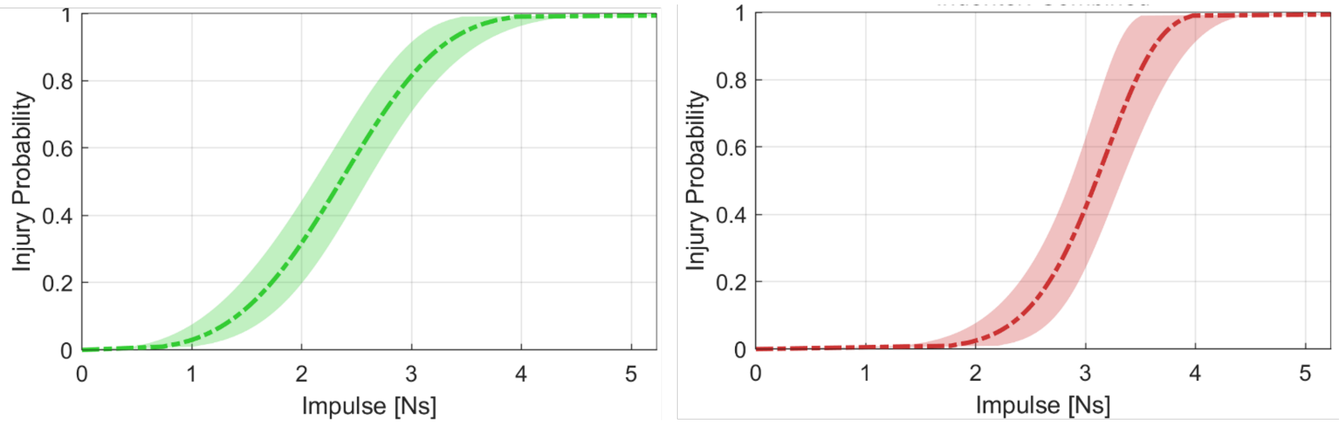


Fig. 1. Impulse-based survival analysis injury risk curves for mild (left) and severe (right) injuries. Shaded areas correspond to 95% confidence interval bounds. Dashed lines indicate the mean curves.

## IV. DISCUSSION

This is the first study to develop impulse-based survival analysis injury risk curves from live swine lung tests for BABT applications. The BABT impact load path included soft tissue deformation external to the rib cage, rib cage deformations, and deformations of the thoracic contents. Injuries such as lacerations, contusions and pneumothorax were produced in these tests. Several biomechanical variables can be used as potential injury candidate metrics to develop injury risk curves and define tolerance. In the present study, impulse was chosen as the candidate because it accounts for the load transmission to the torso and the time factor. While the inclusion of the temporal factor may not be relevant to pure rib fractures (peak force is often considered as the best correlate for bone fractures), it is important for organ injuries, and hence, the peak impulse metric accounts for the underlying mechanism of lung injuries. Other candidates that involve the time factor, such as viscous criterion (combination of velocity and compression profiles in the time domain) can be considered, and the development of those injury risk curves is considered as a future study [7]. Metrics such as impact velocity and energy may not be appropriate candidates because they are external variables and do not involve the tissue response of the surrogate, i.e. swine in the present case. A similar line of reasoning can be advanced for other metrics, including the blunt criterion. Injuries were classified in the present study based on treatment. It is possible to reclassify injury outcomes and develop risk curves based on different injury scoring schemes. Given that Warfighter protection is the main BABT application, it may be prudent to develop a scoring system based on combat operations. This requires the military subject matter experts that may include combat medics, trauma surgeons, and pathologists to re-score the observed injuries. Once injuries are militarily scored and risk curves are developed, it may be possible to arrive at the most efficacious set of curves for each injury severity to define BABT tolerance criteria and to develop strategies for assessing the performance of future body armour.

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## VI. REFERENCES

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