Behind armour blunt trauma lung injury risk curves from different backface deformation profiles

N. Yoganandan[1], A. Shah[1], J. Koser[1], L. Somberg[1], D. Wilson[1], B. Stemper[1], R. S. Salzar[2], C. R. Bass[3], V.C. Chancey[4], B. Johnson[4], J. McEntire[4]

[1]Department of Neurosurgery, 8701 Watertown Plank Road, Medical College of Wisconsin, Milwaukee, WI 53226, USA
[2]Center for Applied Biomechanics, University of Virginia,1215 Lee Street, Charlottesville, VA 22908, USA
[3]Biomedical Engineering, Wayne State University, 656 West Kirby Street, Detroit, MI 48202, USA
[4]U.S. Army Aeromedical Research Laboratory, 6901 Farrel Road, Fort Novosel, AL 36362, USA

Abstract. Behind armour blunt trauma (BABT) occurs from backface deformations of the body armour. Different armour designs induce different backface deformation profiles. Different profiles may induce different injuries to the thoracoabdominal complex at the same impact level. It is ideal to expose armour-covered surrogates (human cadavers) and record backface deformation profiles using high-speed radiography; however, such studies are limited. This research is about the development of injury criteria from different backface deformation profiles. The design of the first indenter was based on BFDs from an earlier human cadaver study that included a hardbody armour, with data obtained from flash x-rays. The second indenter was designed with a different expected backface deformation profile. While the first indenter was spherical, the second indenter was conical and covered approximately one-third of the indenter-surrogate thorax surface contact area covered by the first indenter. Live swine tests were conducted with both indenters. Transducers were inserted into the lungs and heart. After administering anesthesia, impacts were delivered to the left lung at 30 to 90 m/s, swine were monitored for six hours, vitals were obtained, animals were euthanized, and autopsies were conducted. One former military surgeon and another civilian trauma surgeon scored injuries into mild, moderate, and severe categories. The spherical indenter induced uniform loading to the thorax. The conical indenter induced focal loading to the thorax. Survival analysis was used to develop viscous criterion injury risk curves for both indenter designs and for all grades of injuries. Mean and 95% confidence interval bounds are given in the body of the paper. Their quality indices are presented. The main conclusion of the study is that generalized injury criteria can be developed for improved body armour design, and they can be used to enhance medical readiness of our Warfighters.

1. INTRODUCTION

1.1 Literature goat data and multiparameter injury risk curves

The current BABT criterion of 44 mm deformation depth in Roma Plastilina No. 1 clay for body armour evaluations is based on the following considerations [1-5]. Experiments were conducted in the 1970s at the United States government and other research facilities Edgewood Arsenal Laboratory, Law Enforcement Assistance Agency, Land Warfare Laboratory, Lovelace Foundation, and Calspan Corporation. Seventy-four goat tests were conducted in three groups. Thirty animals in the first group were impacted at varying velocities at the thorax region using noncompliant projectiles of different mass, diameter, and weight. Surviving animals were euthanized after a 24-hour survival period. Using projectile physical properties, impact velocity and animal mass and thickness at the impact site, multiparameter models were explored to differentiate between lethal and non-lethal outcomes. Sixteen animals in the second group were tested under similar impacting conditions to validate the optimum model from the first group. Twenty-eight tests were added to this group to further validate the model.

Gelatin and different types of clay and foam were used as simulants to determine the optimum surrogate for standardization tests. Initial tests were done with a 20% gelatin block placed behind a soft body armor and high-tenacity nylon. The test was captured using a high-speed film from which the transient peak deflections were estimated. Clay experiments did not use the film camera because of opacity. Deflections from the simulant tests were compared with additional goat experiments that used the same soft body armour and projectiles. Mean peak deflections and areas of penetration were presented for different projectiles and velocities for simulant experiments. The deflections in the Roma Plastilina No.1 clay (85 mm) and 20% gelatin were (91 mm) were greater than the goat deflection (82 mm). Because of

https://doi.org/10.52202/081621-0005

complexities in recording deflections and elastic properties of the gelatin, and the closeness of the Roma Plastilina No. 1 clay deflection to the goat, clay was suggested as a simulant for BABT evaluations. Goat deflection-based injury risk curves obtained from film analysis were assumed to represent clay risk curves. Figure 1 shows the mean deflection-based injury risk curve along with 95% confidence interval bounds [6]. A deflection value of 44 mm is associated with ten percent lethality risk.

1.2 Rationale for regional injury criteria

The deflection of 44 mm was suggested as a preliminary criterion by the original authors of the study. It still serves as the lethality-based legacy BABT injury criterion to assess the performance of personal protective equipment, i.e., body armour. The original authors emphasized that additional experiments should be conducted to improve the criterion; however, only recently, advances are being made to improve the criterion [2, 6]. The material composition, anatomy and geometry of the structures covered by the body armour (rib cage, lungs, liver, heart, spine, etc.) are different. Their physiological functions also vary. Taken together, these factors play a role in the biomechanical responses, and injury mechanisms of the musculoskeletal structures and thoraco-abdominal organs to BABT. It should be noted that standardized tests in the automotive field use different limits and metrics for thoracoabdominal injury criteria specifications [7-9]. The heterogeneity of the human system should be considered in any injury criteria aimed at injury prevention and mitigation. In other words, it is important to develop injury risk curves on a regional basis. This is an overall objective of the research project.

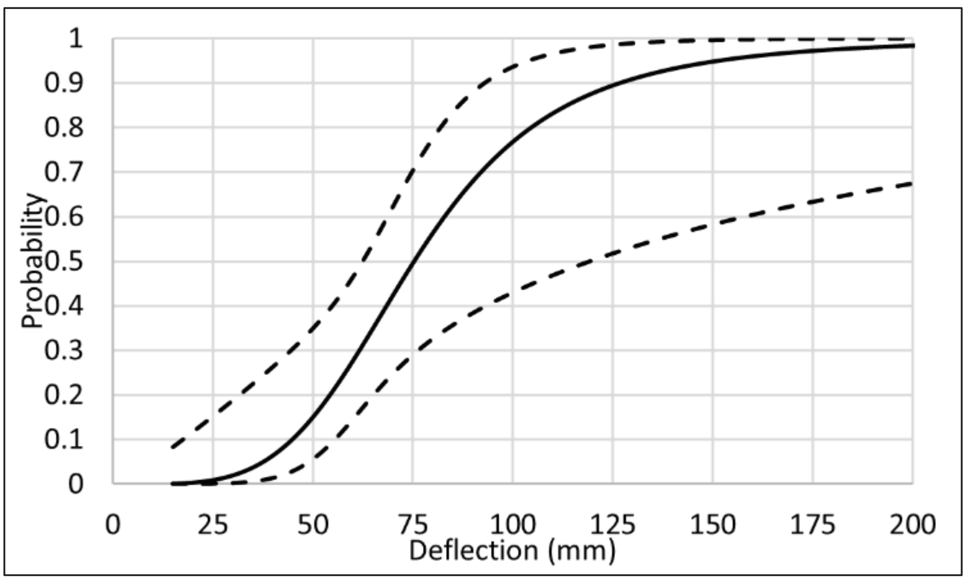

Figure 1: Deflection-based injury risk curves. Shaded areas show 95% confidence interval bounds. See text for details.

1.3 Objectives of the study

Specifically, the present study is focused on the lung region. The objectives were to develop physiologic Weibull distribution injury risk curves using the viscous criterion and survival analysis for statistical modeling for different severities of injuries from two indenter profiles using a swine model.

2. METHODS

2.1 Animal testing and instrumentation

Local institutional approval was obtained from the institutional animal care and use committee, and the same protocol was submitted to obtain approval from the United States Department of Defense, Army

Care and Use Review Office. Live swine were obtained from a local vendor and kept in the veterinary unit for at least 48 hours before preparation that included instrumentation and impact loading to the lung region. Trachea tubes and an intravenous line were inserted before anesthetizing the swine. Telazol and Xylazine were administered. Pressure transducers were placed in the lungs (Millar Houston, TX, USA). Another transducer was inserted into the right atrium by making an incision in the neck to isolate the jugular vein. The vessel was clamped, and a small incision was made to insert the transducer. Radiographs were taken to ensure placement of the transducers before the impact test. Isoflurane ventilation was used for continuous anesthesia delivery, and the protocol included maintaining the animal for six hours after impact loading. Temperature, pulse rate, heart rate, respiratory rate, blood pressure, peripheral capillary oxygen saturation, and electrocardiogram signals were recorded. The trauma surgeons of the study identified injuries to the skeletal and soft tissues including the lung organ. Figure 2 shows the schematic of the swine with pressure transducers and launching system with the indenter outside the launch tube.

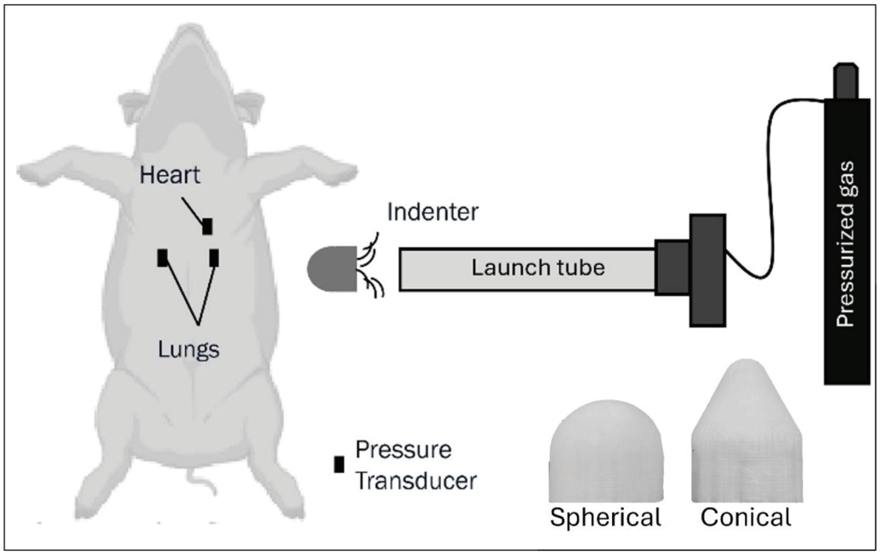

Figure 2: Schematic of the test setup for BABT impact. Launch tube and transducers are shown. Also shown are the two indenters, labelled spherical and conical.

2.2 Impact loading

The impact loading was accomplished using custom impactors (also termed as indenter) with a mass of ~230 g. Two indenters were used. The impact surface of the first indenter was based on previously documented hard body armour backface deformations from human cadaver tests [10]. The first indenter had a spherical shape. The second indenter was conical, and its impact surface area was approximately one-third of the first indenter. The angle of the cone was 57 degrees. The mass of the first and second indenters were ~230g and ~260g. Both indenters were printed with durable resin. A gas-driven launching system capable of producing a range of backface deformation velocities propelled the indenter to impact the lung region around the fourth and fifth intercostal spaces. A high-speed video camera was used to capture the impact loading in a plane parallel to the longitudinal axis of travel of the indenter, and video images were obtained at a rate of 10,000 f/s. Three parallel circumferential lines were drawn on the outside surface of the indenter to be visible for video imaging. The lines were tracked digitally to determine off-axis motion of the indenter before and after BABT impact loading. A triaxial accelerometer (Endevco, Depew, NY, USA) was mounted to the indenter. A digital data acquisition system (DTS Inc., Seal Beach, CA, USA) was used to gather data at ≥100 kHz and filtering was done at 2 kHz.

2.3 Development of injury risk curves

Injuries were graded as mild, moderate, or severe by the trauma surgeon authors. Peak magnitudes of the viscous criterion obtained using acceleration signals from the indenter were used to develop injury risk

https://doi.org/10.52202/081621-0005

curves using parametric survival analysis and Weibull distribution. Non-injury and injury data were assigned as right and uncensored variables. The confidence interval size was calculated as the width of the injury risk curve between plus and minus 95% confidence intervals. Normalised confidence interval size was calculated using the following equation at 10%, 25%, 50%, 75% and 90% levels of injury probabilities. The quality index was based on the following criteria:

$$\text{Normalised confidence interval size } = \frac{UL_p - LL_p}{VC_p} \quad (1)$$

Where p represents the probability of injury, VC_p is the mean or estimated value of the viscous criterion, and UL_p and LL_p represent the upper and lower limits of the 95% confidence intervals of the viscous criterion. A normalized confidence interval size value less than 0.5 was considered good, a value between 0.5 and 1 was considered fair, a value from 1 to 1.5 was considered marginal, and a value greater than 1.5 was considered unacceptable. This was according to established norm in biomechanical studies [11]. Viscous criterion injury risk curves are presented for both indenters and mild, moderate and severe injuries. The rationale for selecting this metric is provided in the discussion section.

3. RESULTS

3.1 Sample size and injuries

Forty-six live swine were used in the study. The sample size included four control animals, i.e., they were not subjected to any BABT impact loading to the lung region. No injuries were found at autopsy in control animals. Thus, any injuries from the impact-tested live animals were attributed to the blunt mechanical loading to the thorax. All impact-tested animals survived the six-hour period, i.e., there were no lethal outcomes, and this was true for both indenter impacts. Rib fractures and/or injuries to the lung in the form of contusions and lacerations were identified. There were six animals with no, 14 animals with mild, 10 with animals moderate, and 12 animals with severe injuries.

3.2 Injury risk curves from the spherical indenter series of tests

At 10%, 25% and 50% risk levels, the magnitudes of the viscous criterion for mild injuries were 1.65 m/s, 2.52 m/s, and 3.66 m/s, respectively. The quality indices ranged from good to fair to acceptable for all three types of injuries. Other data including 95% upper and lower confidence intervals are given in Table 1. Figure 3 shows injury risk curves from this series of tests.

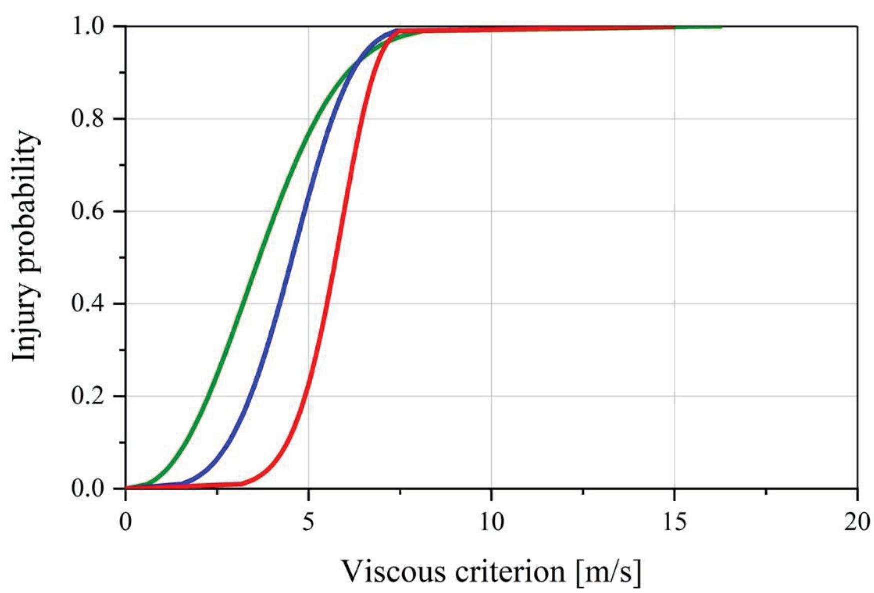

Figure 3: Lung injury risk curves from the spherical indenter. Left to right curves represent mild (green), moderate (blue) and severe (red) injuries.

Table 1: Summary of viscous criterion (m/s) values a from the spherical indenter for mild, moderate and severe injuries.

Risk	Mean value	Confidence interval upper bound	Confidence interval lower bound	Quality index
Mild injury				
5%	1.21	1.87	0.56	Acceptable
10%	1.65	2.37	0.92	Fair
25%	2.52	3.30	1.74	Fair
50%	3.66	4.45	2.85	Good
Moderate injury				
5%	2.34	3.18	1.50	Fair
10%	2.81	3.64	1.99	Fair
25%	3.64	4.40	2.88	Good
50%	4.55	5.25	3.86	Good
Severe injury				
5%	4.00	5.04	2.95	Fair
10%	4.42	5.36	3.48	Good
25%	5.08	5.86	4.30	Good
50%	5.74	6.42	5.07	Good

3.3 Injury risk curves from the conical indenter series of tests

At 10%, 25% and 50% risk levels, the magnitudes of the viscous criterion for mild injuries were 2.58 m/s, 3.97 m/s, and 5.67 m/s, respectively. The quality indices ranged from good to fair to acceptable for all three types of injuries. Other data including 95% upper and lower confidence intervals are given in Table 2. Figure 4 shows a comparison of the mean injury risk curves from this series of tests.

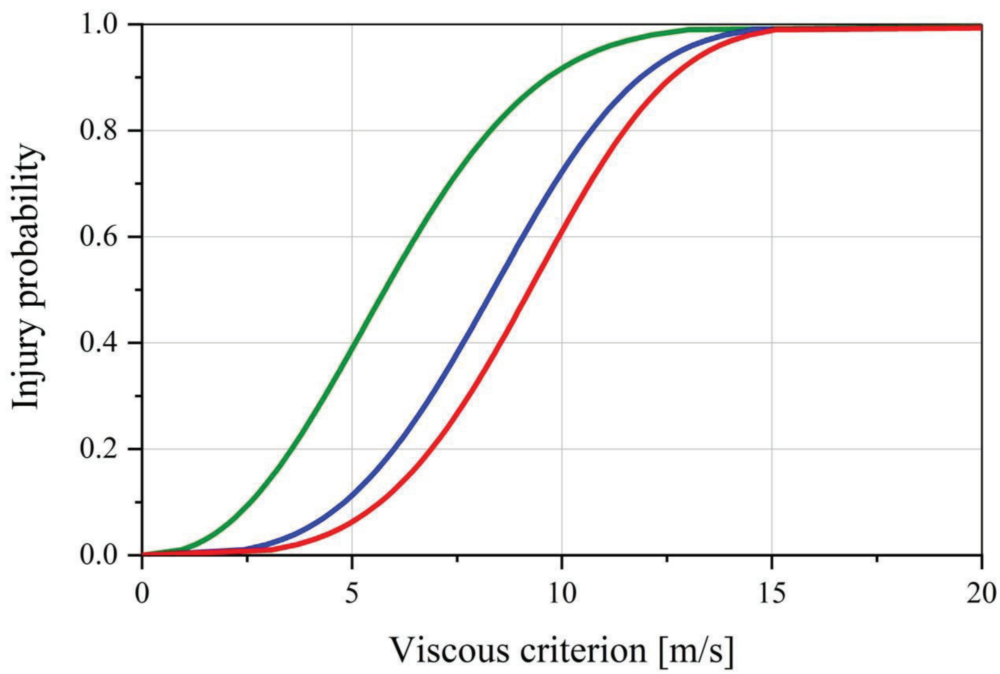

Figure 4: Lung injury risk curves from the conical indenter. Left to right curves represent mild (green), moderate (blue) and severe (red) injuries.

https://doi.org/10.52202/081621-0005

Table 2: Summary of viscous criterion (m/s) values from the conical indenter for mild, moderate, and severe lung injuries from survival analysis.

Risk	Mean value	Confidence interval upper bound	Confidence interval lower bound	Quality index
Mild injury				
5%	1.90	2.92	0.88	Acceptable
10%	2.58	3.73	1.44	Fair
25%	3.97	5.25	2.69	Fair
50%	5.78	7.16	4.40	Good
Moderate injury				
5%	3.90	5.63	2.17	Fair
10%	4.82	6.59	3.04	Fair
25%	6.46	8.24	4.69	Fair
50%	8.36	10.18	6.54	Good
Severe injury				
5%	4.71	6.75	2.66	Fair
10%	5.67	7.72	3.62	Fair
25%	7.36	9.35	5.36	Fair
50%	9.24	11.26	7.22	Good

3.4 Injury risk curves from both indenters

At 10%, 25% and 50% risk levels, the magnitudes of the viscous criterion for mild injuries were 1.90 m/s, 2.96 m/s, and 4.56 m/s, respectively. The quality indices ranged from good to fair to acceptable for all three types of injuries. Other data including 95% upper and lower confidence intervals are shown in Table 3. Figure 5 shows a comparison of the mean injury risk curves from this series of tests.

Table 3: Summary of viscous criterion (m/s) values from both indenters for mild, moderate, and severe lung injuries from survival analysis.

Risk	Mean value	Confidence interval upper bound	Confidence interval lower bound	Quality index
Mild injury				
5%	1.27	1.81	0.73	Fair
10%	1.90	2.54	1.25	Fair
25%	2.96	3.71	2.21	Fair
50%	4.56	5.40	3.71	Good
Moderate injury				
5%	2.25	3.07	1.43	Fair
10%	3.08	3.97	2.18	Fair
25%	4.35	5.31	3.39	Good
50%	6.09	7.14	5.04	Good
Severe injury				
5%	3.61	4.81	2.4	Fair
10%	4.60	5.84	3.36	Good
25%	6.02	7.29	4.75	Good
50%	7.82	9.18	6.46	Good

4. DISCUSSION

4.1 Rationale for the choice of thoracoabdominal organ

As stated in the introductory text, the objectives of the study were to develop injury risk curves on a regional basis to improve or enhance medical injury criteria (EMIC) for Warfighter protection and medical readiness and assist in improved body armour designs. The lung region was selected in the present study because of its vitality to the human system and bilateral symmetry. Lungs cover a large anatomical portion of the anterior torso in the human. Any injury criteria developed for the right lung is equally applicable to the left lung (physiological functions and injury tolerances do not differ from a biomechanical perspective). As an organ with air as primary occupier, its mechanisms of injury and tolerance are expected to be different from other organs that are also housed in the anterior thorax, i.e., heart and liver. Similar tests are necessary to develop injury risk curves for other organs, and the authors of this consortium are pursuing such efforts.

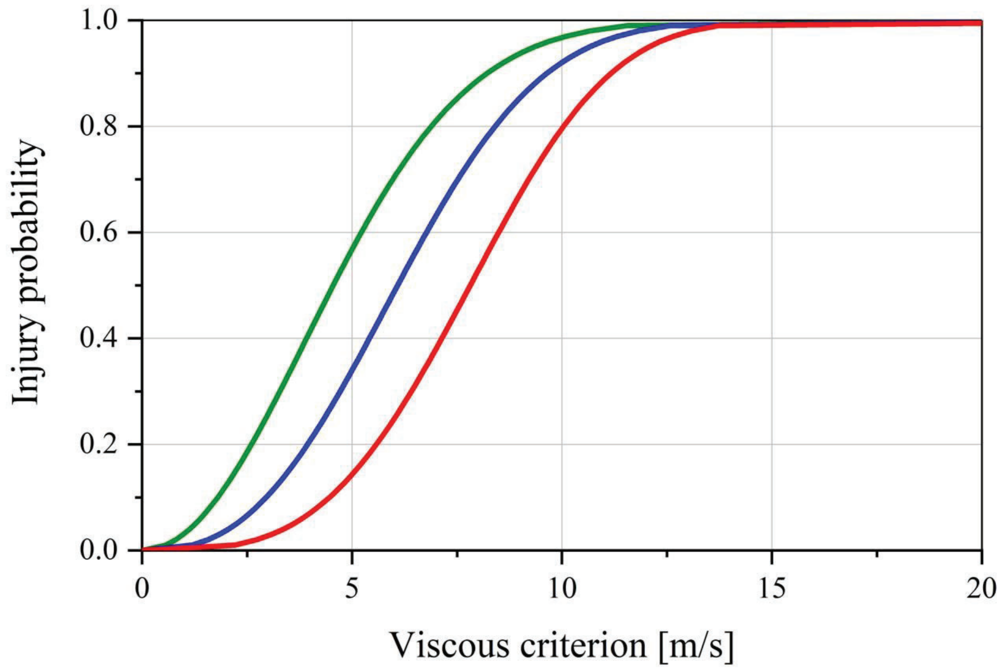

Figure 5: Comparison of lung injury risk curves from both indenter tests. Left to right curves represent mild (green), moderate (blue) and severe (red) injuries. Data are

4.2 Survival analysis and Weibull distribution

Parametric survival analysis was used to develop injury probability curves in this study. This type of analysis is becoming more popular for automotive, aviation, and military applications to define human tolerances for different body regions [12-16]. Recommendations from the International Standard Organization and earlier automotive dummy-based studies was one of the primers for the change from conventional binary regression to survival regression models [11]. The improvement in the previously recommended methodology are given elsewhere [17]. As stated in the objectives, the Weibull distribution was used as it is commonly used in impact biomechanics to develop injury risk curves; however, additional analysis can be done in the future to determine the optimal distribution. Standard textbooks provide details such as equations and the underlying theory of the Weibull function. Statistical metrics such as the Akaike information criterion, or its modifications thereof, can be used, and this is considered as a future study [18]. The use of the quality index via the normalized confidence interval size at discrete probabilities of injury is also commonly used in impact biomechanics [11]. The adjectival rating was based on the accepted. From these considerations, the present set of risk curves serve as initial injury criteria for lungs for BABT.

4.3 Justification for the viscous criterion

The legacy metric for standardized tests is based on a single peak residual deflection in the Roma Plastilina No.1 clay. This is based on the goat thorax deflection from thorax tests. Previous studies have shown that peak force best correlates for musculoskeletal system injuries such as compression fractures of spinal vertebrae [19]. The viscous criterion is shown to be a better predictor for organ injuries under impact loading [20-22]. It represents the energy dissipated by soft tissue deformation and is considered an underlying soft tissue/organ injury mechanism. The criterion includes the response of the torso unlike

https://doi.org/10.52202/081621-0005

a priori/external input metrics such as energy. Hence, the viscous criterion was used. Additional metrics such as force, impulse, energy density, and loading rate can also be used to develop risk curves and evaluate their correlatability to BABT injuries. They are future topics.

4.4 Rationale for the impacting system and injury risk curves from both indenter designs

The present study used an instrumented indenter to apply the BABT loads to the unprotected specimen, not live rounds being defeated by armour protecting the specimen. This is because, using any actual body armour will limit results to that armour design, i.e., results will not be generalizable. A recent study reported the following: "while a strength of the current study was the use of a single *body armour* (emphasis added) helmet type for all ballistic data collected with post-mortem human surrogates and load-sensing headforms to ensure strong matched-pair conditions, these injury outcomes are relevant for a single *body armour* (emphasis added) helmet and projectile type. Care must be taken to interpret these results in context of other helmet systems [23]." The same is true for torso coverage. The use of a single indenter design may be not adequate for similar reasons. While the spherical indenter design was based on backface deformation profiles from hard armor-covered human cadaver tests, to develop generalized risk curves, it was deemed necessary to include other designs [10]. The conical indenter was based an expected profile, different from the spherical indenter. It was intened to induce more focal loading and greater concentrated deflections, with a greater loading on local skeletal anatomy. This contrasted with a more distributed/uniform loading from the spherical indenter that engaged a larger area of the thorax with a wider different skeletal loading pattern. While skeletal deformations in both designs compressed the thoracic contents, the mechanism of load transfer was different between the two designs. Other indenter designs will likely lie within the boundaries of these two shapes; however, tests with actual body armor are needed. Once those data are available, it would be possible to check the generalizability of the risk curves.

Dual peaks representing the penciling effect may suggest that the body armor is less effective. Hard armors generally do not induce dual peaks. Additional tests are needed to not account for any twin peaks in the loading pattern to the thorax with other types of indenter designs. The delineation of pure pressure wave transmission to the torso resulting in lung injuries without the deformations of the skeletal and internal contents is a possibility; however, to the best knowledge of the authors, published studies developing graded injury risk curves are not available. This remains as an active research area and the authors are also pursuing this topic.

A comparison of risk curves and metrics shows that moderate injuries lie within the confines of the mild and severe injuries for both indenters and combined data from both indenters. This suggests that the bounding of the risk curves can be assumed for different backface deformations; however, the moderate injury risk curve shifts more to the right with the conical indenter. The moderate injury risk curve is approximately in the middle of the mild and severe curves with the spherical indenter. The rightward shift demonstrates the role of shape on the injury severity. The second indenter being conical induces a more focal loading to the anterior thorax, resulting in greater compressions of the thorax, while the larger area/volume of coverage of the spherical indenter applies a more distributed loading to the thoracic contents. In other words, stress concentration effects are likely more pronounced with the conical indenter. This implies that a body armour with greater local backface deformations around the lung region may impart more severe injuries than a design with more uniform backface deformations. Despite this difference, as the confidence intervals overlap, it may be reasonable as a first step to combine these data for a potential recommendation. Figure 6 shows the data at discreet levels. The developed injury risk curves are associated with mild, moderate and severe lung injuries. Greater levels of external insult to produce lethality are needed to develop lethality-based risk curves. The authors are currently pursuing those experiments.

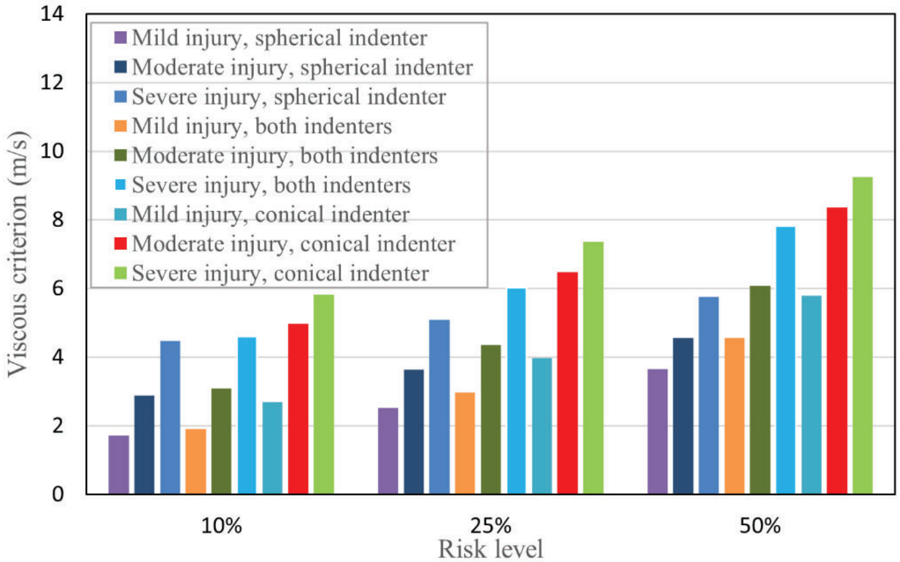

Figure 6: Mean values of the injury metric at discrete risk levels for all injuries. Data include from each indenter and combined data from both indenters.

4.5 Injury classifications

Many classifications are available to score injuries to bones and organs and soft tissues. The Abbreviated Injury Scale, AIS, is widely used for automotive applications [24, 25]. It is undergoing revisions since 1980 [24, 25]. The AAST is used for clinical treatment and classifies injuries separately based on chest wall and organ injuries. Other approaches have included the use of a four grade scale: return to duty within 72 hours, after 72 hours, after 72 hours with potential for duty-limiting conditions, and potentially fatal [26]. This classification scheme was used for inferring injuries sustained from autopsy findings from human cadaver tests. In contrast, the present study used three classifications for injuries based on treating trauma surgeons and physiological swine experiments with monitoring of vitals. Because the injuries were scored based on clinical treatment, and, as reiterated, tests were from live swine instead of cadavers, the chosen classification scheme is more applicable.

4.6 Limitations

As stated earlier, the human thoracoabdominal region houses complex structures: (a) materially they range from bony ribcage to soft tissues with widely varying mechanical properties and injury tolerances; (b) functionally also they are different: lungs being an air-related organ compared to heart, a muscle, etc.; (c) anatomically placements, i.e. rib cover, is also different: lungs fully covered by the rib cage while liver is partially exposed. Thus, injury tolerances are expected to differ. The present series of tests were focused on BABT lung impacts. It is important to conduct similar tests to the heart and liver obtain regional injury risk curves. Posterior anatomical coverage is important as threats to Warfighter's include all areas covered by the armour. The presence of neural structures in the spinal column poses challenges as monitoring physiological functions after injuries to bony elements (e.g., lamina[e]) are complex. One human cadaver (protected with experimental armour) test reported AIS=5 level injuries with spinal impact from a successfully defeated ballistic threat [10, 24]. Injuries included a laceration between thoracic vertebrae T9 and T12 and disintegration of their spinous processes into the spinal canal. The same cadaver test under the same initial conditions with sternal impact produced AIS=4 injuries. Similar studies with live swine are not available and would be necessary to define posterior impact BABT injury risk curves. This is a future study.

4. SUMMARY AND CONCLUSIONS

The present study developed physiology-based lung injury risk curves applicable to BABT loading. They were developed using an accepted animal model (live swine) with six-hour monitoring of all animals.

https://doi.org/10.52202/081621-0005

Dynamic loading was applied using an impacting system and indenter. The first/spherical indenter design was based on backface deformations obtained from hard body armour testing with human cadavers. The second/conical indenter design was based on expected profile that was distinct from the first/spherical indenter. The conical indenter induced more focal thoracic loading with potential increased stress concentrations near the impacted region than the spherical indenter. The two indenters represented a range of deformations profiles from current and future armour designs. Injury risk curves were developed using survival analysis and the viscous criterion metric, known to depict the injury mechanism for organs, and account for the temporal factor. The curves were developed for three severities, based on clinical assessments. The developed set of injury risk curves serve as a preliminary set for defining lung injury tolerance to BABT.

5. ACKNOWLEDGMENTS

This research was supported by the U.S. Army Medical Research and Development Command contract W81XWH-21-9-0015 and the Department of Veterans Affairs Medical Research. The views expressed in this material are those of the authors, and do not reflect the official policy or position of the U.S. Government, the Department of Defense, or the Department of the Army.

6. REFERENCES

[1] Clare, V. R., Lewis, J. H., Mickiewicz, A. P., and Sturdivan, L. M., 1975, "Blunt trauma data correlation," No. EB-TR-75016, Edgewood Arsenal, Aberdeen Proving Ground, MD.

[2] Prather, R., Swann, C., and Hawkins, C. E., 1977, "Backface Signatures of Soft Body Armors and the Associated Trauma Effects. ARCSL-TR-77055," U.S. Army Armament Research and Development Command Technology Center. Aberdeen Proving Ground, MD.

[3] Goldfarb, M. A., Weinstein, M. A., and Metker, L. W., 1975, "A method for soft body armor evaluation: medical assessment," U.S. Army Limited War Laboratory.

[4] Metker, L. W., Prather, R. N., and Johnson, E. M., 1975, "Methods for determining backface signatures of soft body armors. Washington, DC," U.S. Department of Justice.

[5] Montanarelli, N., Hawkins, C. E., Goldfare, M. A., and Ciurej, T. F., 1973, "Protective garments for public offiicals," U.S. Army Welfare Laboratory, Aberdeen Proving Grounds, MD.

[6] Yoganandan, N., Shah, A., Somberg, L., Baisden, J., Stemper, B. D., Bass, C., Salzar, R. S., Chancey, V. C., and McEntire, J., 2023, "A Novel Paradigm to Develop Regional Thoracoabdominal Criteria for Behind Armor Blunt Trauma Based on Original Data," Mil Med, 188(Suppl 6), pp. 598-605.

[7] Kuppa, S., Eppinger, R. H., McKoy, F., Nguyen, T., Pintar, F. A., and Yoganandan, N., 2003, "Development of Side Impact Thoracic Injury Criteria and Their Application to the Modified ES-2 Dummy with Rib Extensions (ES-2re)," Stapp Car Crash J, 47, pp. 189-210.

[8] FMVSS-214, 2008, "Federal Motor Vehicle Safety Standards," US Government, Washington, DC USA, https://www.gpo.gov/fdsys/granule/CFR-2011-title49-vol6/CFR-2011-title49-vol6-sec571-214.

[9] Prasad, P., 2015, "Injury crietria and motor vehicle regulations," Accidental Injury: Biomechanics and Prevention, N. Yoganandan, A. M. Nahum, and J. W. Melvin, eds., Springer, New York, pp. 793-809.

[10] Bass, C. R., Salzar, R. S., Lucas, S. R., Davis, M., Donnellan, L., Folk, B., Sanderson, E., and Waclawik, S., 2006, "Injury risk in behind armor blunt thoracic trauma," Int J Occup Saf Ergon, 12(4), pp. 429-442.

[11] Petitjean, A., Torsseille, X., Yoganandan, N., and Pintar, F. A., 2015, "Normalization and scaling for human response corridors and development of risk curves " Accidental Injury: Biomechanics and Prevention, N. Yoganandan, A. M. Nahum, and J. W. Melvin, eds., Springer,, NY, pp. 769-792.

[12] Rooks, T. F., Chancey, V. C., Brozoski, F. T., Salzar, R. S., Pintar, F. A., and Yoganandan, N., 2018, "Development of an injury risk curve for pelvic fracture in vertical loading environments," Traffic Inj Prev, 19(sup2), pp. S178-S181.

[13] Humm, J., and Yoganandan, N., 2021, "Lower Neck Injury Assessment Risk Curves Based on Matched-Pair Human Data for Anthropomorphic Test Devices," Mil Med, 186(Suppl 1), pp. 639-644.

[14] DeVogel, N., Banerjee, A., and Yoganandan, N., 2019, "Application of resampling techniques to improve the quality of survival analysis risk curves for human frontal bone fracture," Clin Biomech (Bristol), 64, pp. 28-34.

[15] Chirvi, S., Pintar, F., Yoganandan, N., Banerjee, A., Schlick, M., Curry, W., and Voo, L., 2017, "Human Foot-Ankle Injuries and Associated Risk Curves from Under Body Blast Loading Conditions," Stapp Car Crash J, 61, pp. 157-173.
[16] Abraczinskas, A., Olszko, A., Beltran, C., Baisden, J. L., Yoganandan, N., McGhee, J., McGovern, S., Lidl, G., Vasquez, K. B., and Chancey, V. C., 2021, "A Comparison of Nonhuman Primate Injuries in Horizontal Versus Vertical Sled +Gz (Head-to-Foot) Impact Accelerations," Mil Med, 186(Suppl 1), pp. 610-618.
[17] Yoganandan, N., Banerjee, A., Hsu, F. C., Bass, C. R., Voo, L., Pintar, F. A., and Gayzik, F. S., 2016, "Deriving injury risk curves using survival analysis from biomechanical experiments," J Biomech, 49(14), pp. 3260-3267.
[18] Akaike, A., 1974, "A new look at the statistical model identification," IEEE Transactions on Automatic Control, 19, pp. 716-723.
[19] Yoganandan, N., Moore, J., DeVogel, N., Pintar, F., Banerjee, A., Baisden, J., Zhang, J. Y., Loftis, K., and Barnes, D., 2020, "Human lumbar spinal column injury criteria from vertical loading at the base: Applications to military environments," J Mech Behav Biomed Mater, 105, p. 103690.
[20] Viano, D. C., and Lau, I. V., 1988, "A viscous tolerance criterion for soft tissue injury assessment," J Biomech, 21(5), pp. 387-399.
[21] Viano, D. C., and Lau, I., 1985, "Thoracic impact: a viscous toelrance criteria," Tenth International Conference of the Enhanced Safety of Vehicles, NHTSA, WAshinton, DC.
[22] Viano, D. C., Kroell, C. K., and Warner, C. Y., "Comparative thoracic impact response of living and sacrificed porcine siblings," Proceedings of the 21st Stapp Car Crash Conference.
[23] Iwaskiw, A., Howes, C., Hingorani, R., Bradfield, C., Mazuchowski, E., Clark, M., Luong, Q., and Drewry, D., "Loads assocaited helmet blunt trauma," Proceedings of the Personal Armour Systems Symposium. pp. 146-156.
[24] AIS, 1998, Abbreviated Injury Scale: 1998 update, American Association for Automotive Medicine, Arlington Heights, IL.
[25] AIS, 2015, Abbreviated Injury Scale: American Association for Automotive Medicine, Arlington Heights, IL.
[26] Howes, C., Mazuchowski, E., Rohrer, A., Clark, M., Luong, Q., and Drewry, D., "Injuries and Operational Implications Caused By Behind Armour Blunt Trauma Across Various Impact Locations " Proceedings of the Personal Armour Systems Symposium. pp. 168-176.

https://doi.org/10.52202/081621-0005