Temple University

Effects of Impact Velocity and Chest Deformation on Lung Injury: In Vivo Model to Elucidate Behind-Armor Blunt Trauma

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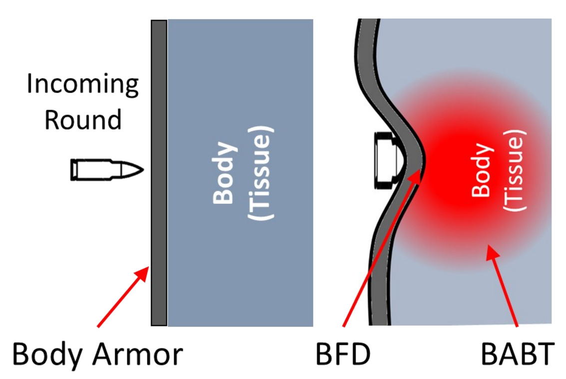
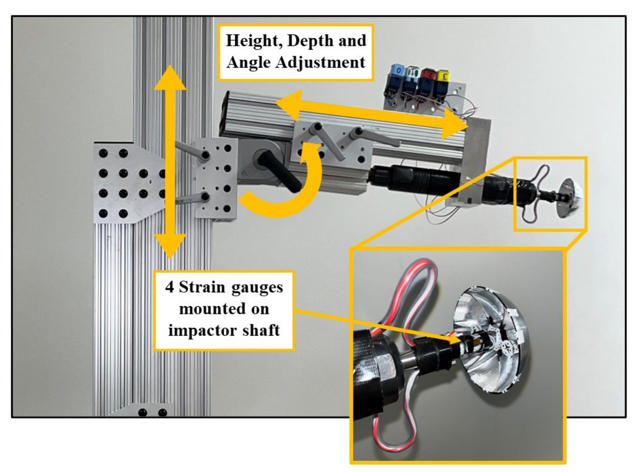
INTRODUCTION

Behind-armor blunt trauma (BABT) is defined as a non-penetrating injury caused by the rapid deformation of body armor. BABT to the thorax can cause debilitating rib fracture and lung contusion, which can progress to fatal respiratory distress. The biomechanics of lung injury in BABT is not clearly understood; translational information for modelling and development of protective armor has been derived primarily from inanimate materials. BABT is associated with Back Face Deformation (BFD) of the body armor.



The goal of this study was to conduct a set of in vivo large animal tests using a refined impactor device to systematically characterize the effect of impact velocity and deformation depth on lung injury.

MATERIALS AND METHODS



Impactor Design and Instrumentation:

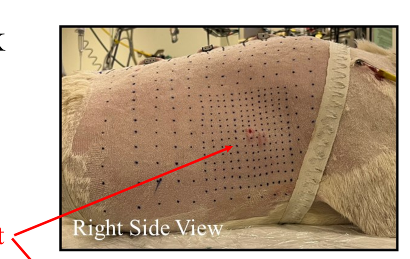
- Captive Bolt Stunner (Schermer KR) was modified to deliver strike velocities at ~40m/s and ~70m/s
- Custom 80-mm Hemispherical Impactor Head simulated BFD
- Four Strain Gauges mounted to the impactor shaft for force measurement were calibrated quasi-statically and verified with dynamic testing. (Sampling rate 50,000 Hz)
- A custom impactor stand was fabricated capable of adjusting impactor height, distance to body (depth), and angle.

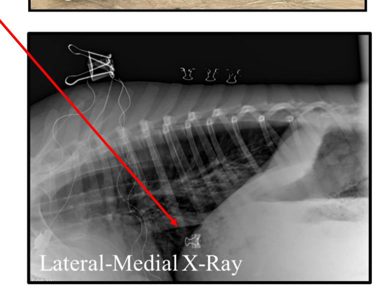
In vivo Ovine Lung Injury Model :

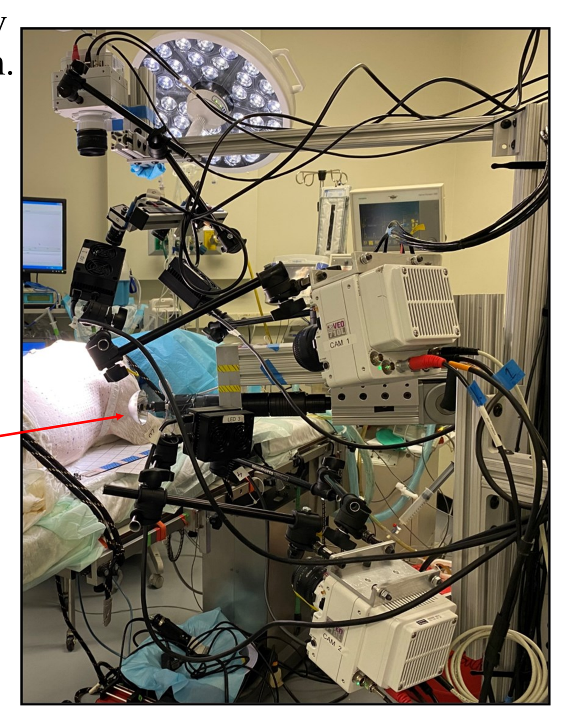
- Non-lethal in vivo ovine lung injury model resulted in clinically relevant lung injury from blunt thoracic impact.
- Katahdin (male) sheep, 31 ± 0.29 kg, n = 24, were tested in Sphinx Position.
- Animals were anesthetized and instrumented for physiologic measurements, including ECG leads, pulse oximetry, rectal probes, respiratory inductance plethysmography bands, systemic and pulmonary arterial catheters, and peripheral venous catheter.
- Animals were supported with CPAP, SIMV, intravenous anesthesia, fluids, and thermal blanket.
- Pre– and Post-Injury DV and LM serial X-rays were taken.
- The test paradigm included continuous and serial measurements of the cardiopulmonary function.

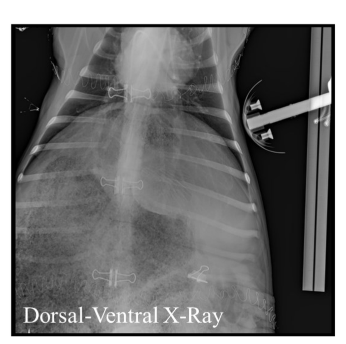
Impact Site:

- Target – Hilum of the right lung: causes lung injury while minimizing risk of injury to abdominal organs and the heart.
- Impact centered at the intersection of ribs 6 - 7 intercostal space, referenced up from the most caudal rib, and 1 cm dorsal to a horizontal line drawn caudally from the shoulder parallel to the spine
- Impactor is positioned perpendicular to the chest wall
- Distance of the impactor to animal body is adjusted to set the target impact depth.









High Speed Imaging:

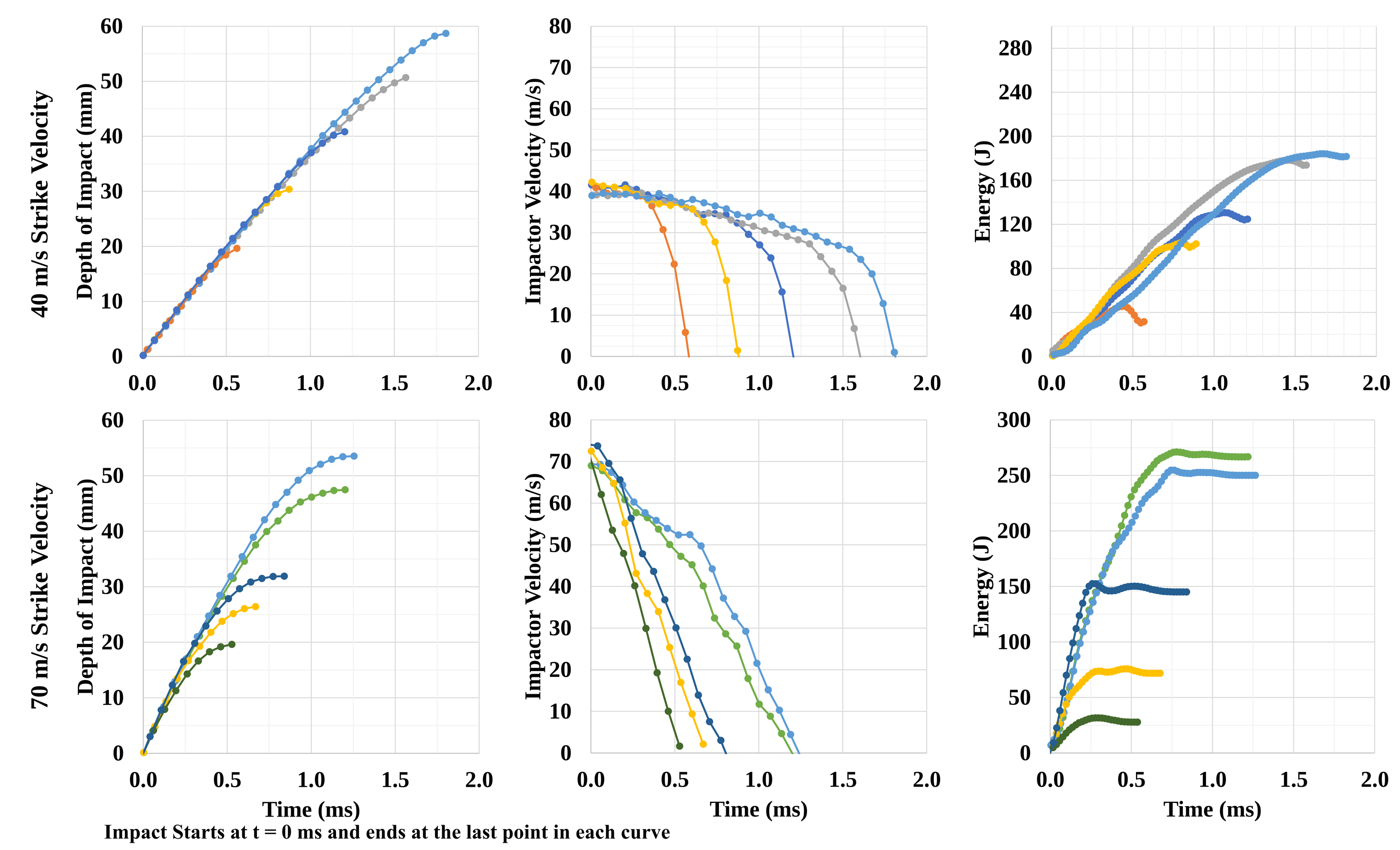
- Stereo High-speed Photography (Phantom VEO) at 15000 fps was used to measure the impactor displacement and chest wall deformation.

Impact Energy and Impulse:

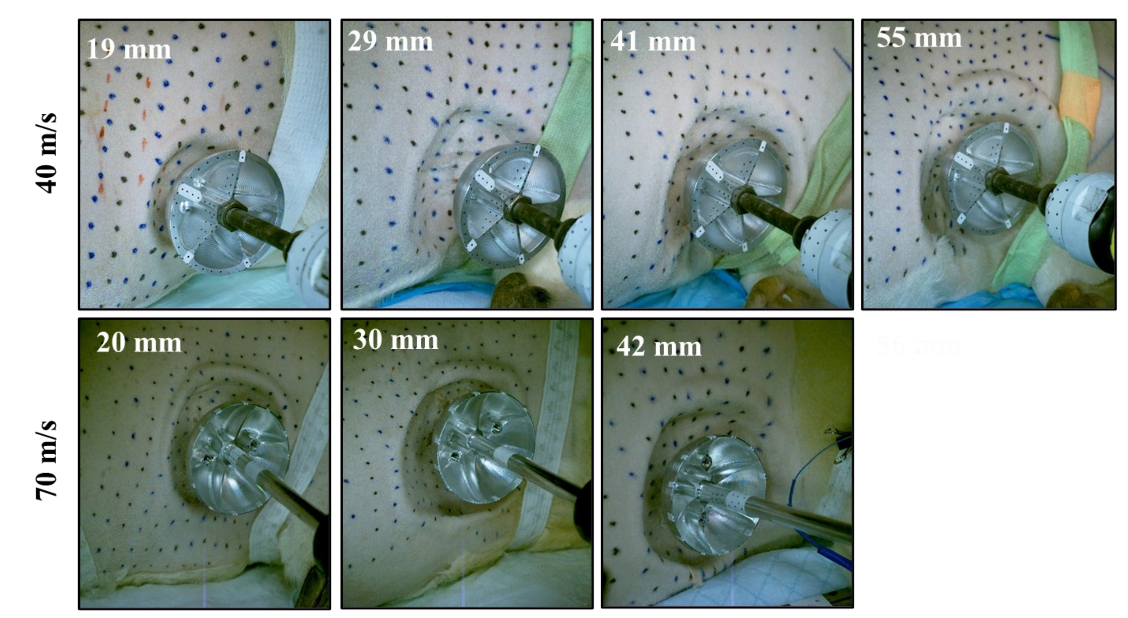
- From Force and Displacement of the Impactor the Impact Energy (in Joules) and Impact Impulse (in N.s) were calculated.

RESULTS AND DISCUSSSION

Mechanical Characteristics of the Impactor



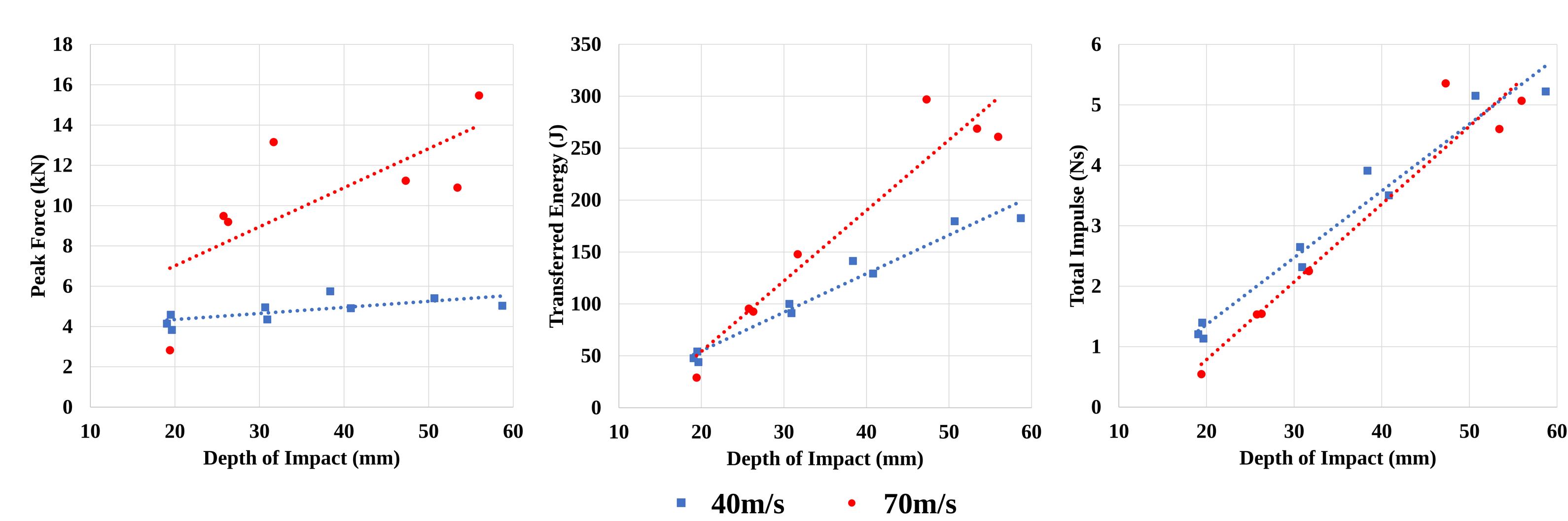
Chest Wall Deformation at Maximum Stroke



	Strike Velocity 40 m/s	Strike Velocity 70 m/s
Number of Tests	12	12
Avg. Weight (kg)	30 ± 3	31 ± 3
Avg. Strike Velocity (m/s)	40 ± 1	72 ± 2
Min Depth (mm)	19	18
Max Depth (mm)	55	42

± show standard deviation

Summary of Impact Kinetics vs Depth of Impact



- Reproducible strike velocity was achieved for different depths of impact.
- Transferred energy and total impulse varied linearly with depth of impact (R^2> 0.92)
- The impact peak force and the transferred energy were significantly larger at the higher strike velocity expect for small (~20 mm) depth of impact.
- The impact total impulse was not dependent on the strike velocity. Larger force was associated with shorter duration of impact.

Assessment of the Severity of Injury

~40 m/sec

ARL #	16	11	17	21	15	12	19	22	18	14	13	20
Initial Impact Velocity (m/s)	39	39	41	40	40	40	41	40.5	39	39	39	39
Depth of Impact (mm)	55	52	41	38	39	36	30	30	29	25	20	19
Duration of Impact (ms)	1.9	1.9	1.4	1.26	1.3	1.2	1	1	1	0.8	0.6	0.6
CV Instability (msec)			x	x					x			
Fracture			x	x					x			
Gross Tissue	4	3+	3+	2+	3	2	3	2	4	2	1+	2

~70 m/sec

ARL #			24	30	25	26	29	23	27	33	34	31	28	32
Initial Impact Velocity (m/s)			72	71	72	72	73	64	70	71	72	71	65	69
Depth of Impact (mm)			42	38	30	31	30	24	24	21	21	20	19	18
Duration of Impact (ms)			1.1	0.92	0.8	0.8	0.83	0.63	0.66	0.6	0.6	0.52	0.55	0.51
CV Instability (msec)			x	x	x			x						
Fracture			x	x	x	x	x			x	?able			
Gross Tissue			4	4	4	3+	3	<1	3	3	2	1+	2+	2

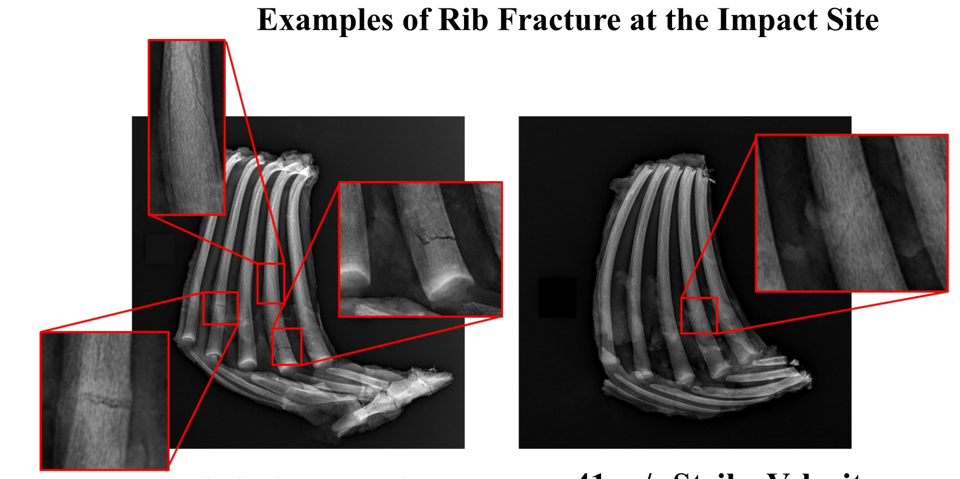
Weighted Parameters

- Pleural Cavity
- Hemothorax
- Tissue Hemorrhage
- Tissue Laceration
- Rib Fracture
- CV Instability

Severity	Score	Color
Minimal	0 - 1+	
Mild	1+ - 2	
Moderate	2+ - 3+	
Severe	3+ - 4	

- Two hours after impact, the exterior chest wall was inspected and a thoracotomy was performed under surgical anesthesia. Tissue harvest was performed for ex vivo assessment of ribs and structural alterations in the lung by histomorphologic assessment.
- Severity of injury was assessed qualitatively based on presence of rib fracture, bleeding in the pleural cavity, visible damage to the lung, and cardiopulmonary parameters.

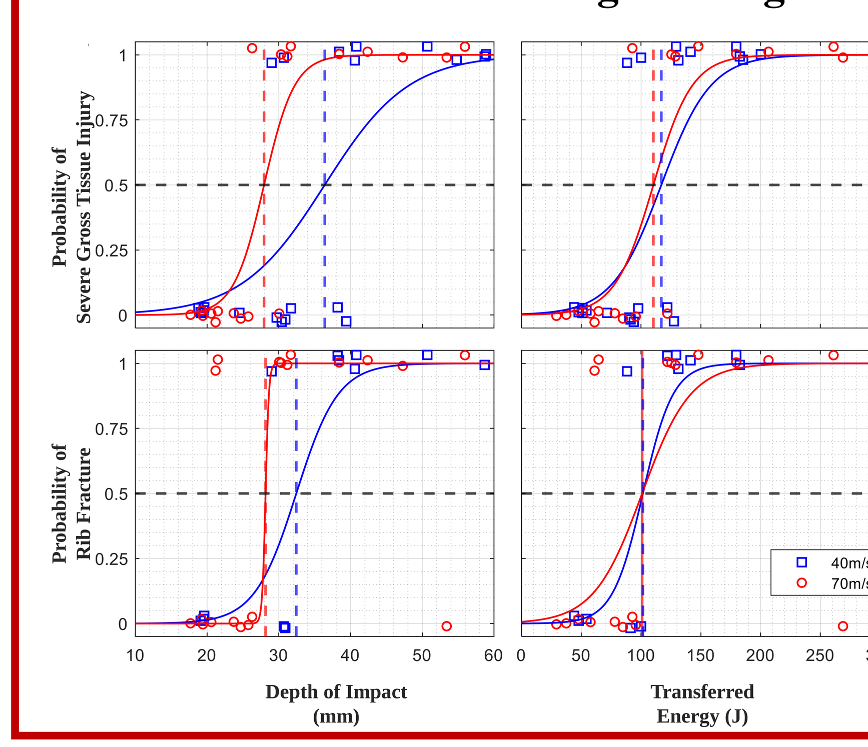
Examples of Rib Fracture at the Impact Site



72 m/s Strike Velocity
31 mm Depth of Impact

41 m/s Strike Velocity
41 mm Depth of Impact

Logistic Regression Model of Injury



- Probability of severe Gross Tissue Injury (>3.5) and Rib Fracture were evaluated with respect to depth of impact and transferred energy .
- For Gross Tissue Injury and Rib Fracture, the threshold of injury based on the Transferred Energy is almost the same for both velocities.
- With 75% increase in velocity, the threshold of 50% probability of injury decreases 22% for Depth but decreases only 6% for Energy.

50% Probability of Injury	Depth (mm) 40m/s	Depth (mm) 70m/s	Energy (J) 40m/s	Energy (J) 70m/s
Severe Gross Tissue Injury	36	28	117	110
Rib Fracture	32	28	102	101

CONCLUSIONS

- By refining and characterizing the dynamics of a humane, non-penetrating captive bolt impactor, we have extended the application of our in vivo ovine model as a surrogate for lung injury in BABT.
- Preliminary results show that the threshold of lung injury can be characterized based on the striking velocity of the impact and the deformation depth.
- While our investigation is ongoing, our results indicate that the threshold of deformation for injury is inversely related to impact velocity.

ACKNOWLEDGEMENT

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