Modeling and Evaluation of the Human Torso

Joint Services Small Arms Systems Annual Symposium, Exhibition & Firing Demonstration May 7-10, 2007

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Background

- Soft armor vests are an essential component of personnel protection
  - Prevent penetration of tissue piercing ballistics into the thoracic region
- The use of strong, deformable materials provide ballistic resistance
  - Allows backface deformation; augmented by higher energy threat conditions
  - Potential for Behind Armor Blunt Trauma (BABT)
- Need to understand the relationship between the mechanical insult and the risk of internal injury

High-rate Blunt Impact Research

- Recognized need for evaluating soft armor vests and investigating BABT
  - NIJ Standard 0101.04 – ballistic resistance
  - Ballistic gelatin – energy transfer
    - *van Bree (1998, 2000); Lyon (2000)*
  - Animal models – physiological response of living tissue
    - *Liden (1988); Baosong (1996); Yen (1998)*
  - Post Mortem Human Subjects (PMHS) – develop injury criterion
    - *Viano (1988); Bir (2003, 2004); Sturdivan (2004)*
  - Computational Models
    - *Wang (1995), Plank (1998), Roberts (2005)*
  - Physical Surrogate Models
    - *Lyon (1999), Roberts (2006)*

Motivation

- Investigate the ability of the torso models to
  - Detect the transfer of impact energy to the thoracic tissues
  - Measure potential injury risk predictors
  - Evaluate influence of factors including
    - Impact location
    - Surrounding local environment
    - Remote tissue response
- Compare the torso model response trends with the clay deformation observed from similar impact conditions

Goal

Understand human thorax response to blunt ballistic impact

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Establish Injury Criteria based on BABT injury risk

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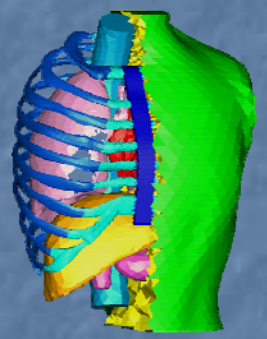
Assess incapacitation from resulting injuries; contribute to the development of optimal engagement equipment

Approach

- Create both a computational and physical human torso model
  - Human Torso Finite Element Model (HTFEM)
  - Human Surrogate Torso Model (HSTM)
  - Current models complete with:
    - Skeletal Structure (ribs, sternum, cartilage and vertebral column)
    - Organs (lungs, liver, heart, and stomach)
    - Soft tissue (muscle, skin, viscera)



HTFEM

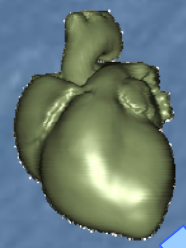
HSTM

Approach (cont.)

- Simulate ballistic impacts on HTFEM
  - Obtain deformations, organ pressures and acceleration of sternum
- Conduct ballistic experiments on HSTM
  - Obtain organ pressures and sternal acceleration
- Validate model response
- Employ models in understanding torso response under various threat conditions
  - Flexibility of computational or experimental evaluation

Model Development

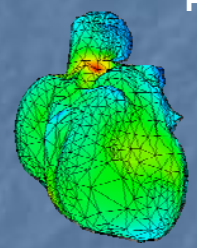
Human Geometry



Rendered Digital Model

Rapid Prototype/ Physical Model

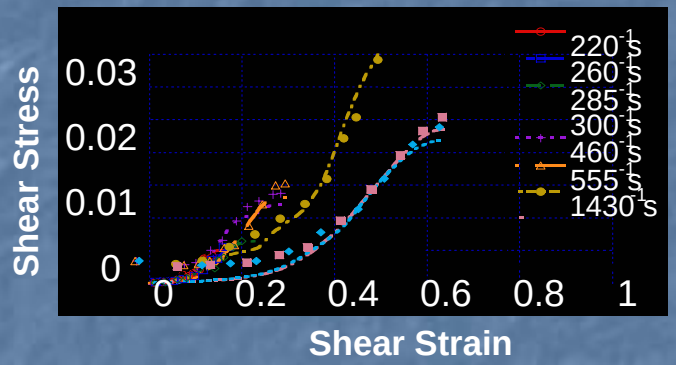
Finite Element Model



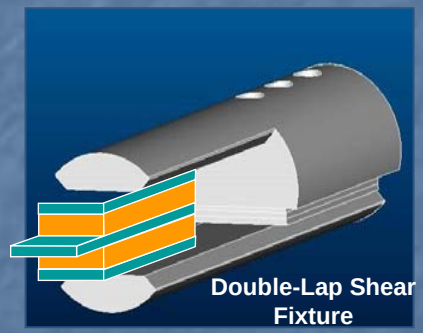
HSTM

HTFEM

Biosimulant Tissues

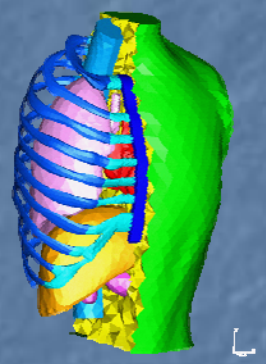


High-rate Tissue Testing

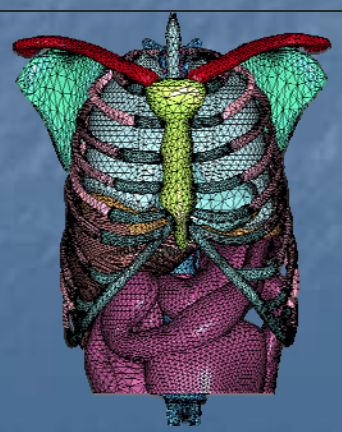


Human Torso Finite Element Model (HTFEM)

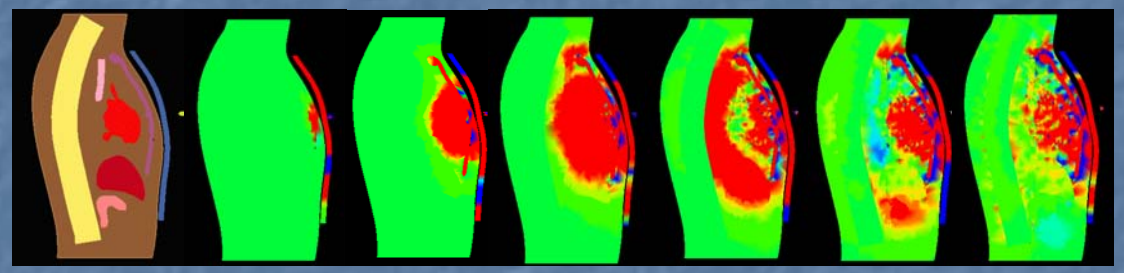
5th Percentile HTFEM



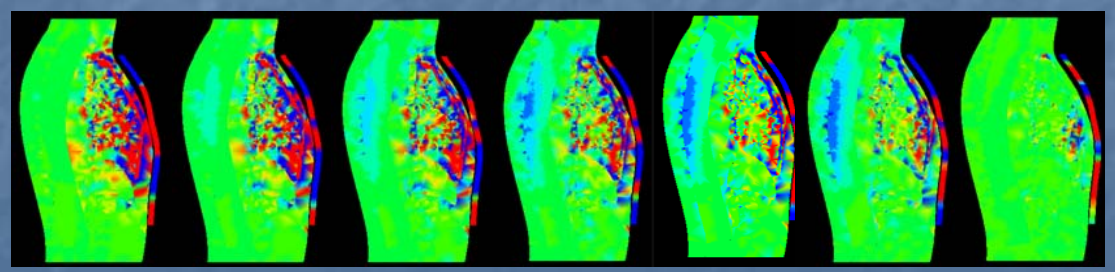
50th Percentile HTFEM



9 mm; 425 m/s; Sternal shot location



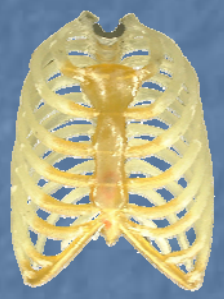
T= 0.0 ms .20 ms .25 ms .30 ms .35 ms .40 ms .50 ms

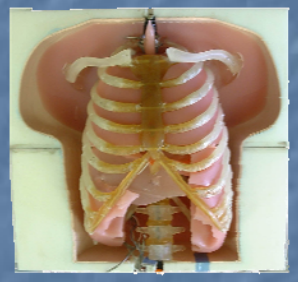


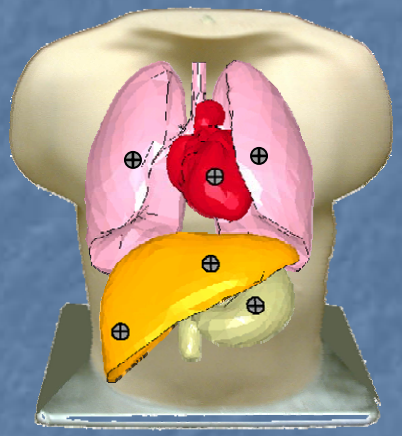
T= .75 ms 1.00 ms 1.25 ms 1.50 ms 1.75 ms 2.00 ms 5.00 ms

Human Surrogate Torso Model (HSTM)

- Fabricated from biosimulant materials
  - Organ material properties evaluated under high strain-rate materials testing
  - Bone simulant material
- HSTM instrumented with sensors
  - Pressure sensors in organs
  - Accelerometer on sternum
  - Load cell in vertebral column

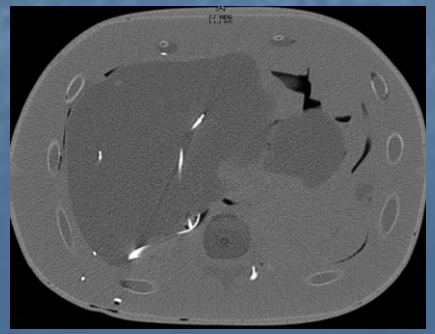






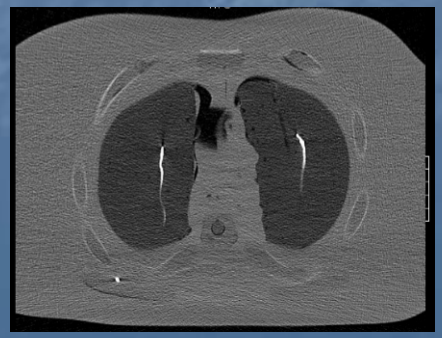
A Look Inside the HSTM

Intestinal cavity



Liver

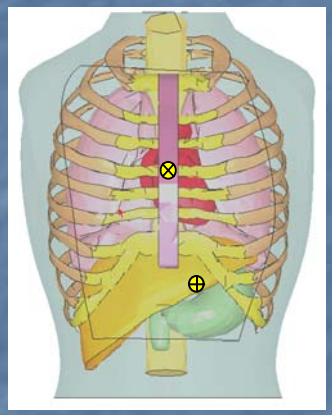
Heart



Lungs

Ballistic Impact Conditions

- Shot Locations
  - Sternum: 1 in. superior to the vertical level of T6
  - Stomach: 1 in. lateral to mid-line and slightly superior of stomach



- Threat conditions
  - NIJ Standard 0101.04 test conditions
  - Soft armor only

Vest Type	Caliber	Ammo Mass (grains)	Impact Velocity (ft/s)
I	.22	40	1079
IIa	9-mm	124	1119
II	9-mm	124	1204
IIIa	9-mm	124	1430

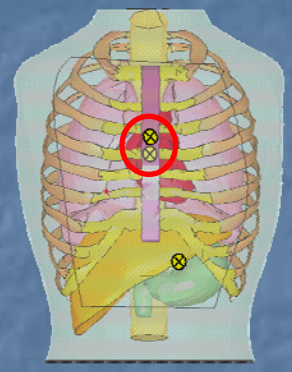
Experimental Methods

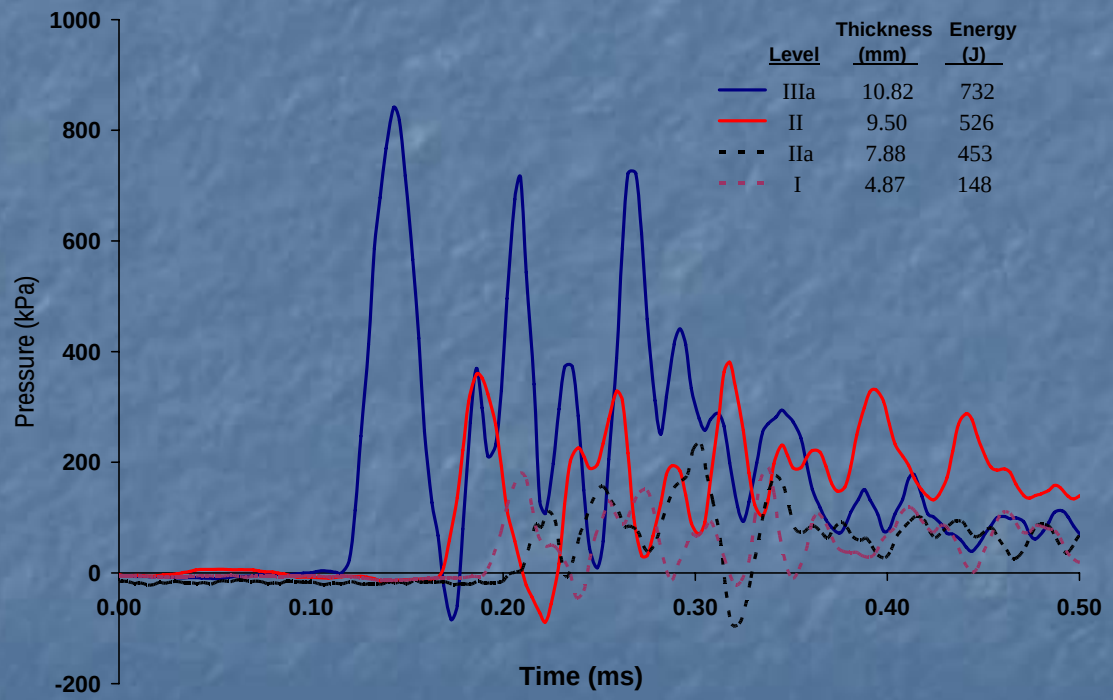
Impact over the Sternum

Level II vest; 9 mm bullet; IV = 1180 ft/s

Experimental Results

Sternum Impact Location (Heart sensor response)



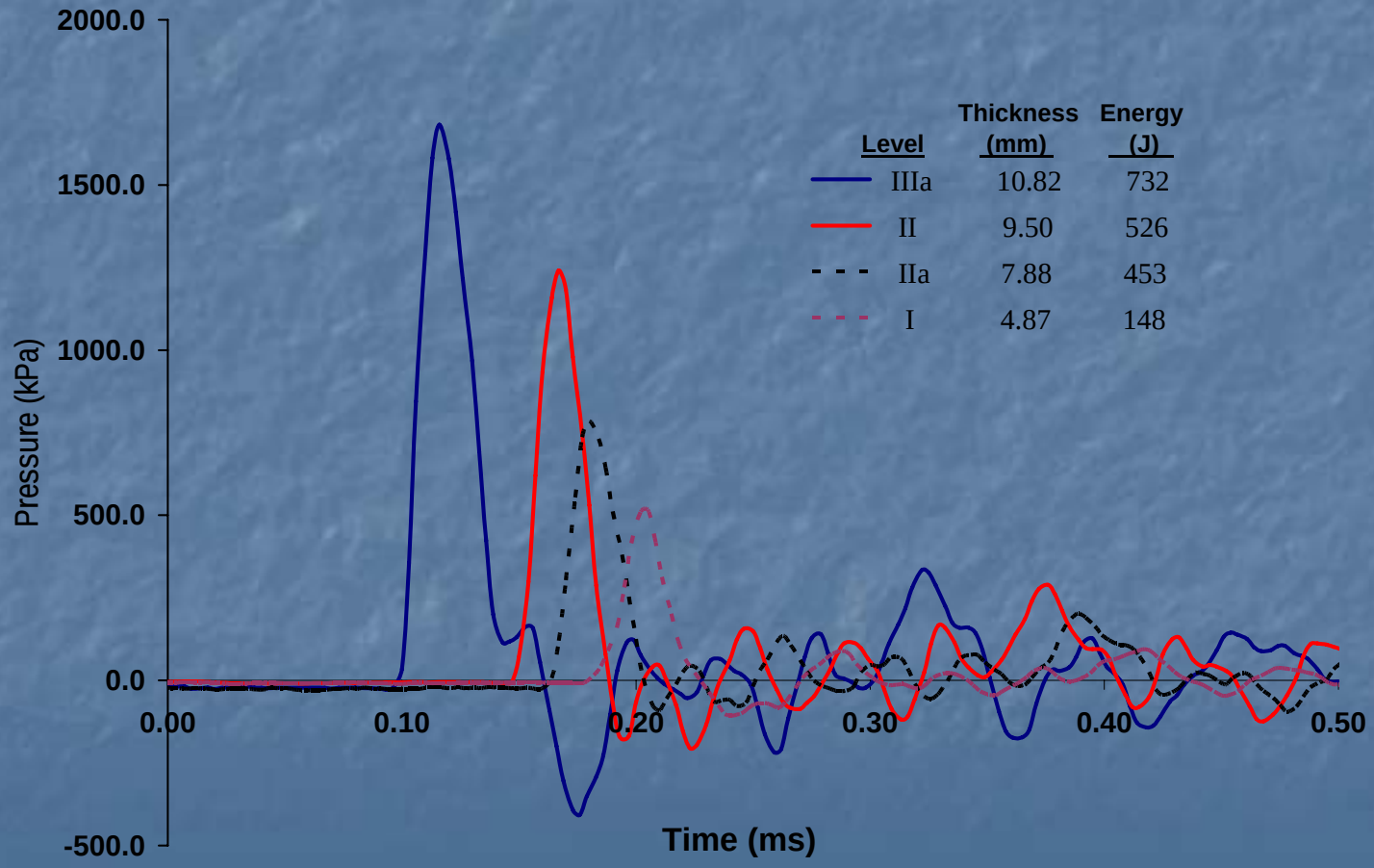


	Heart	
Test Level	Pressure (kPa)	dP/dt (kPa/ms)
I	181	10170
IIa*	111	11412
II	359	18360
IIIa	841	32260

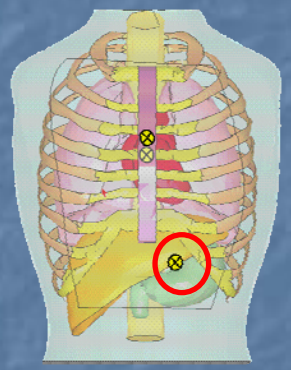
* Impact location approximately 1” low

Experimental Results

Stomach Impact Location
(Stomach pressure response)



Level	Thickness (mm)	Energy (J)
IIIa	10.82	732
II	9.50	526
IIa	7.88	453
I	4.87	148

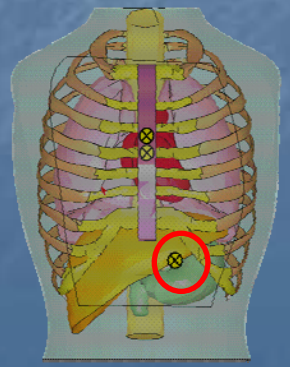


Experimental Results

Stomach Impact Location

(Stomach and Liver response)

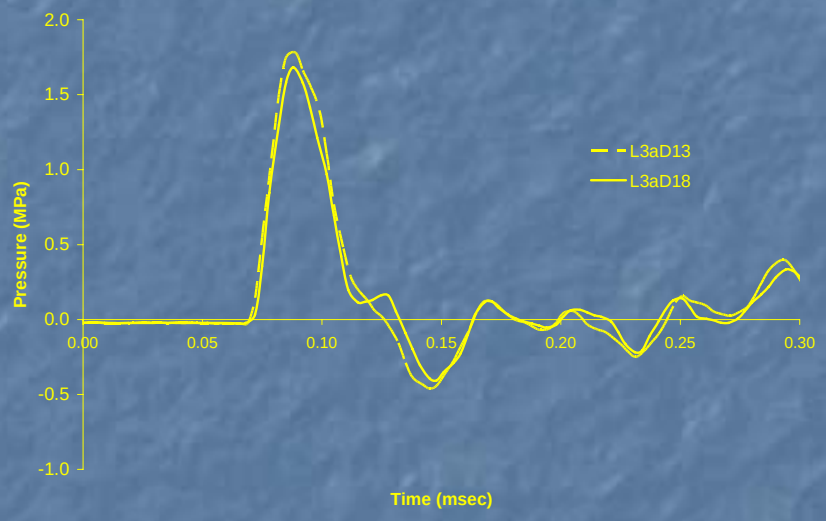
	Stomach		Liver – Left Lobe		Liver – Right Lobe	
Test Level	Pressure (kPa)	dP/dt (kPa/ms)	Pressure (kPa)	dP/dt (kPa/ms)	Pressure (kPa)	dP/dt (kPa/ms)
I	517	25500	310	17700	69	4000
IIa	779	39400	469	33200	145	13500
II	1241	69200	979	65500	269	22300
IIIa	1682	98900	1406	69030	496	27800



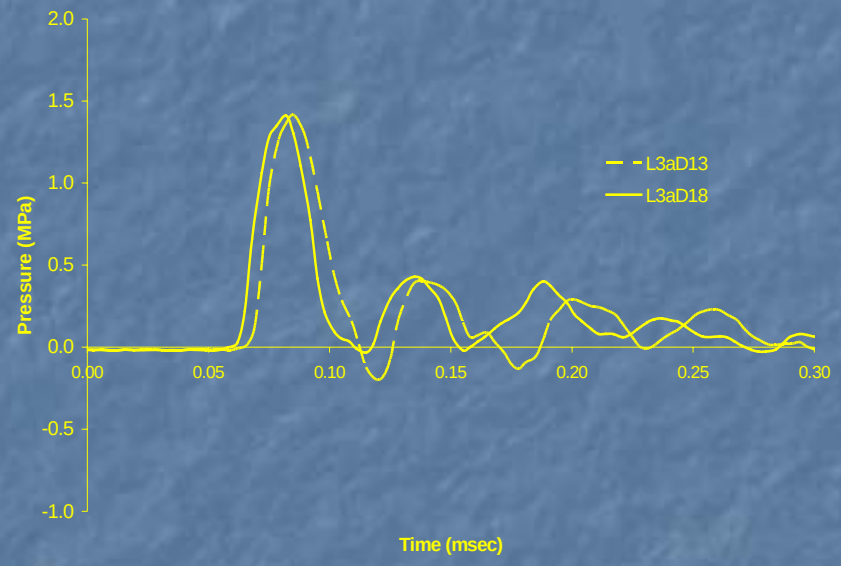
Repeatability

9 mm Bullet at 1410 ft/s

Level IIIa Soft Armor Vest



Stomach



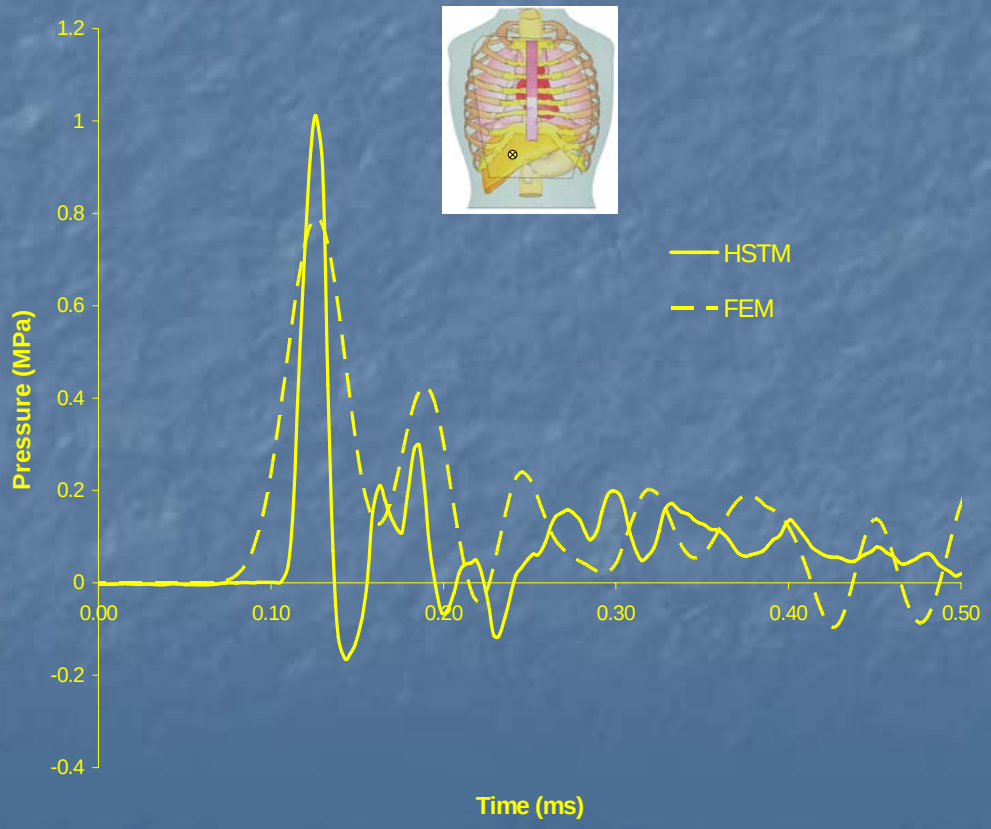
Left Lobe of the Liver

HSTM vs. HTFEM

(Left Lobe of the Liver)

9 mm bullet at 1090 ft/s

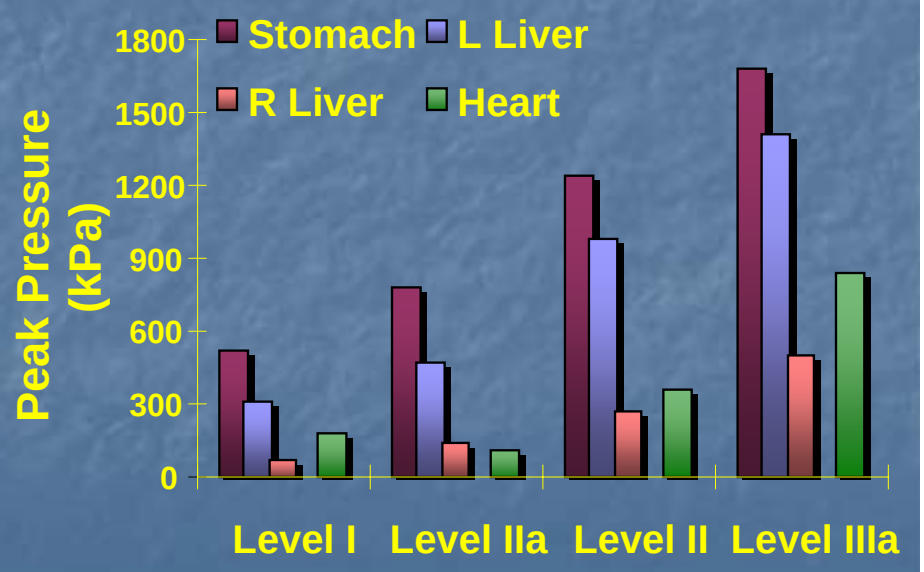
Level II soft armor vest



Discussion

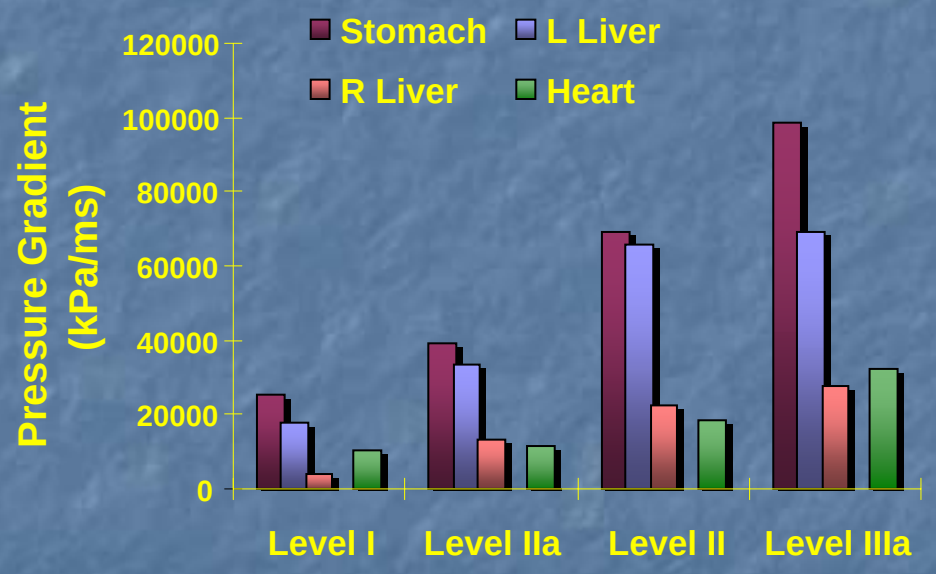
- Increasing severity of impact conditions produced rising initial peak pressures*
  - Heart: $P_{LIIIa} = 4.5 \times P_{LI}$
  - Stomach: $P_{LIIIa} = 3.25 \times P_{LI}$
  - Vest thickness increase does not completely counteract impact energy increase

- Pressures from sternal impacts less than those from stomach impacts
  - Bony structure dissipates energy
  - Produces triple pressure spike
- Peak pressure reduced in liver versus stomach



Discussion

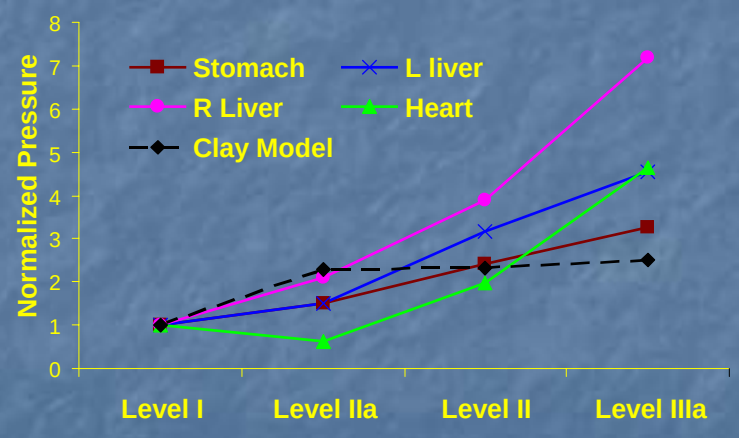
- Increasing severity of impact conditions produced increasing rates of pressure change (dP/dt)
  - Follows trends similar to pressure peaks



Discussion

- Clay/vest FEM validated for Level II impact
  - Model adapted to produce Level I, IIa, and IIIa clay displacements due to vest Backface Signature (BFS)
  - All vests "passed" since 44 mm BFS level not exceeded
- Normalized values based on Level I results
  - Pressure increases at a much steeper rate with each change in test condition
  - Clay deformation change decreases with increased test conditions

Test Level	Clay Deformation (mm)
I	14.5
IIa	33.4
II	33.8
IIIa	36.4



Conclusions

- Surrogate torso models have been evaluated under NIJ-Standard 0101.04 impact conditions
  - Provides dynamic measurement of impact response
  - Differentiates between the severity of impact conditions
  - Demonstrates sensitivity to impact location
- Greater impact energy results in disproportionately greater increase in organ pressure versus clay deformation
- Torso models may provide additional information in assessing incapacitation from resulting injuries
  - Contribute to the development of optimal engagement equipment
- Future work:
  - Understand ceramic plates
  - Transfer function between PMHS injury and torso model response
  - Further development of biosimulant materials to improve model biofidelity

Acknowledgments

The authors would like to acknowledge the
Office of Naval Research (ONR)
for supporting this research under contract awards
N00014-03-PD-2-0010
and
N00014-04-PD-2-0279(1)