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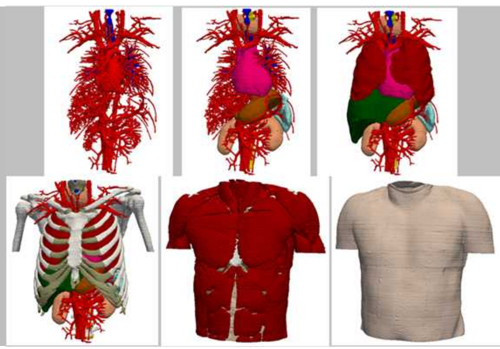

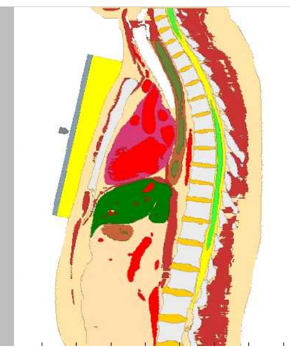

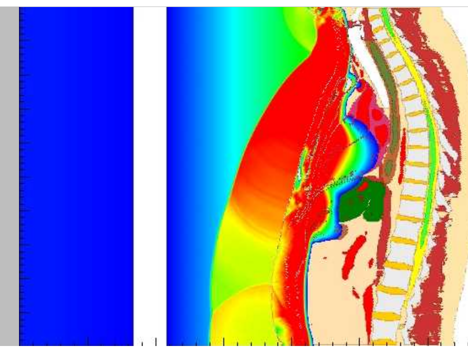

Virtual Simulation of Blast, Behind-Armor Blunt Trauma, and Projectile Penetration Leading to Injury of Life-Critical Organs in the Human Torso

Candice F. Cooper, Paul A. Taylor

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Terminal Ballistics Technology TBT Target Protect Target Defeat

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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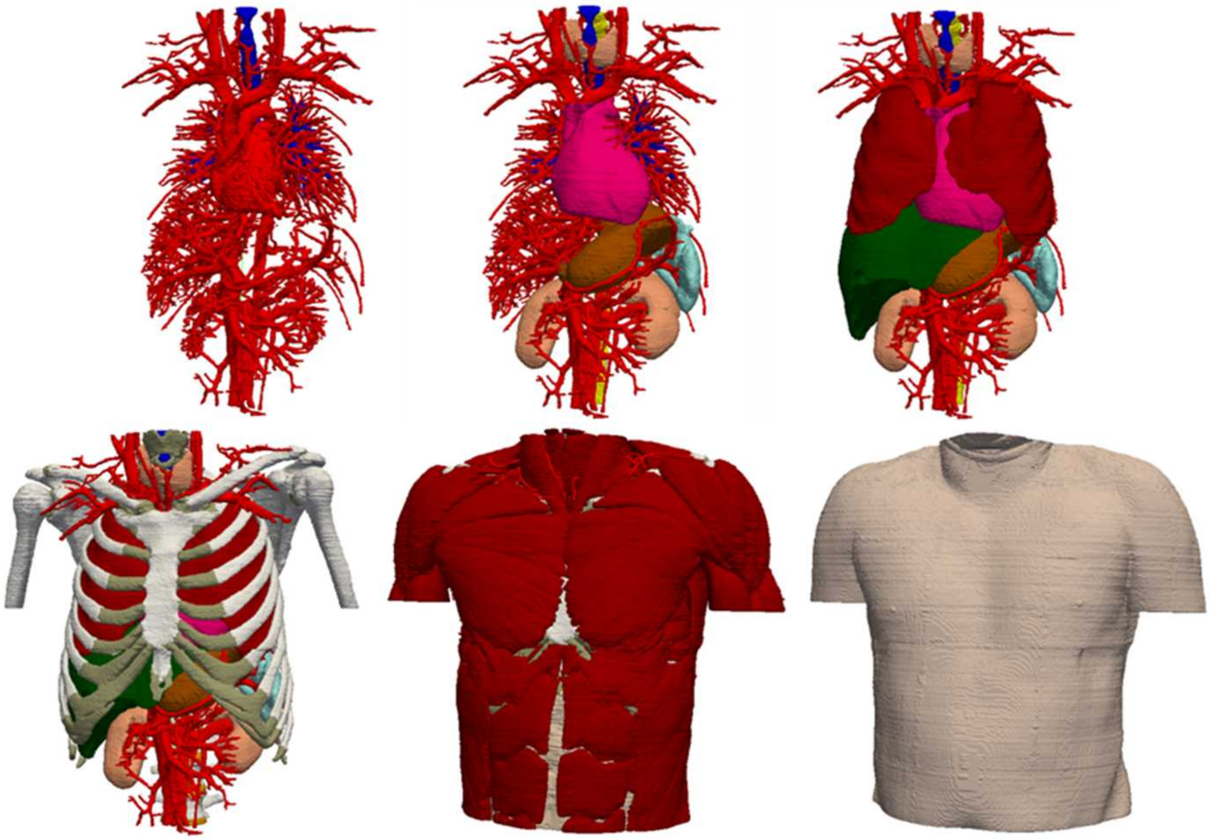
Human M&S: An investigation into wound injury and body armor assessment

- Trial-and-Error testing of body armor
  - Generally utilizes clay models or other physical surrogates
  - Limited to measurements of surface material deflection and monitoring at specific sensor sites
  - Testing against blast impact is almost nonexistent
- Advantages to human M&S in wound injury investigation and body armor assessment
  - Reduces expensive field testing and use of surrogates, animals, and cadavers
  - Simulations can be conducted ad infinitum
  - Model can be interrogated extensively
  - Could reveal novel design concepts otherwise possibly overlooked

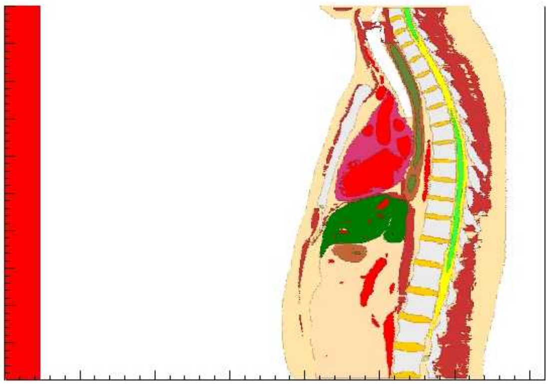
Human Torso Model Development

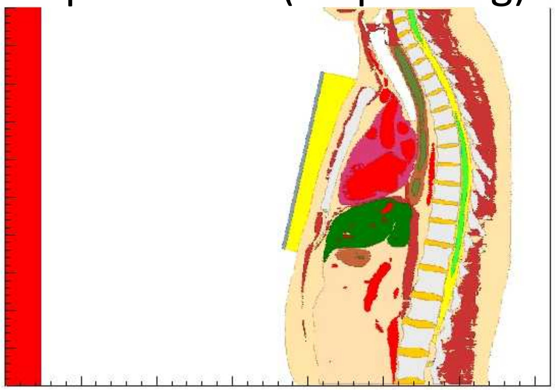


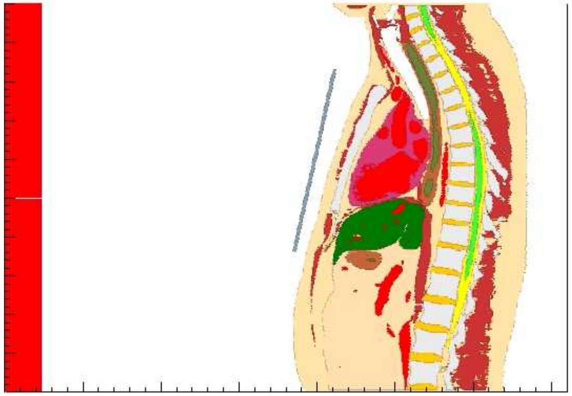
- Model developed from 495 1mm thick axial cryosections of the Visible Human Project male data set (CT & color images)
- Segmentation of 19 distinct materials
- High anatomic fidelity: spatial resolution of 1 cubic millimeter

Simulations

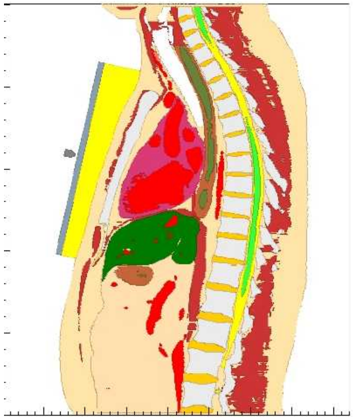
- Simulations conducted utilizing Sandia National Laboratories Eularian shock wave physics code CTH.
  - 360 kPa (260kPa over pressure) frontal blast simulation
    - Without chest protection
    - With notional padded chest protection
    - With notional chest protection (no padding)







  - Projectile impact simulation



Material Representations

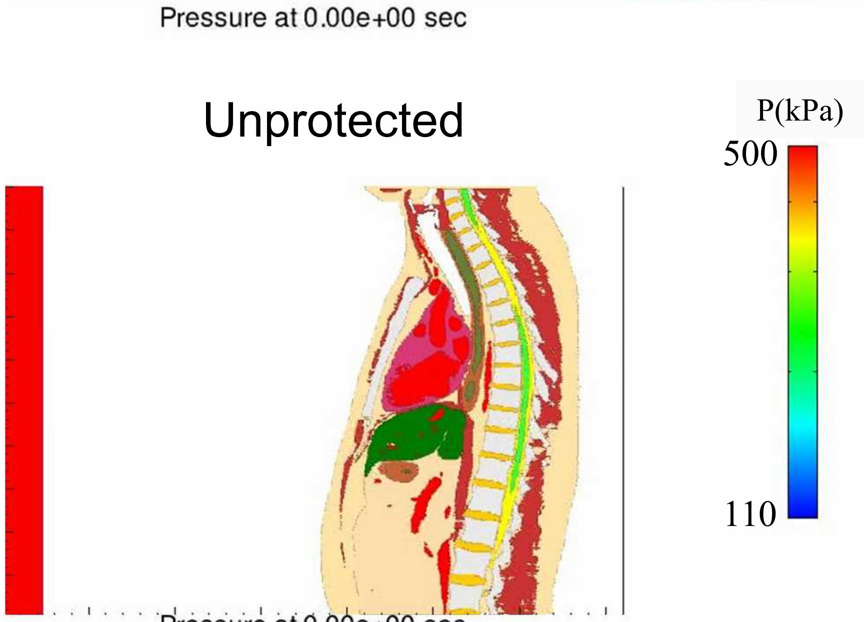
Material Component	Volumetric Response	Deviatoric Response
Bone	Mie-Gruneisen EOS	Von Mises
Intervertebral Discs	Mie-Gruneisen	Von Mises
Costal Cartilage	Mie-Gruneisen	Von Mises
Larynx	Mie-Gruneisen	Von Mises
Vasculature/Blood	Tillotson-Brundage EOS	-
Airways/Air	Sesame Tabular EOS	-
Lungs	Mie-Gruneisen	Von Mises
Liver	Mie-Gruneisen	Von Mises
Kidneys	Mie-Gruneisen	Von Mises
Spleen	Mie-Gruneisen	Von Mises
Heart	Mie-Gruneisen	Von Mises
Muscle	Mie-Gruneisen	Von Mises
Stomach	Mie-Gruneisen	Von Mises
Stomach Contents	Tillotson-Brundage	-
Spinal Cord	Tillotson-Brundage	Viscoelastic
Cerebrospinal fluid	Tillotson-Brundage	-
Abdominal Cavity Contents	Mie-Gruneisen	Von Mises
Thyroid	Mie-Gruneisen	Von Mises
Skin	Mie-Gruneisen	Von Mises
Chest Plate	Mie-Gruneisen	Transverse-Isotropic
Chest Plate Padding	Mie-Gruneisen	Von Mises
9mm Projectile	Mie-Gruneisen	Steinberg-Guinan-Lund Plasticity [16]

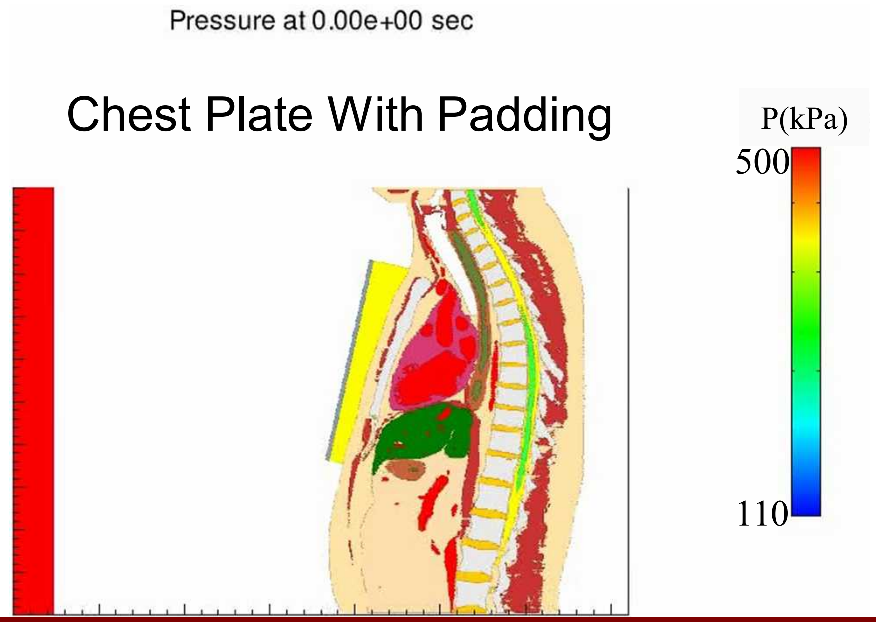
- Advanced equation-of-state(EOS) and constitutive models represent each of the 19 torso materials as well as armor/projectile materials

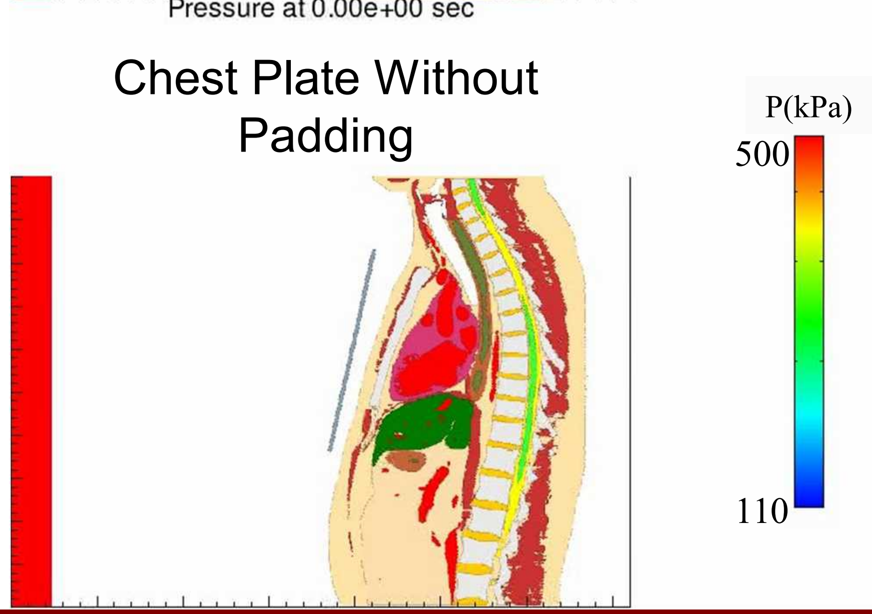
- Tillotson-Brundage EOS captures the susceptibility of fluid cavitation under isotropic tension (tensile pressure)

Frontal Blast Simulation

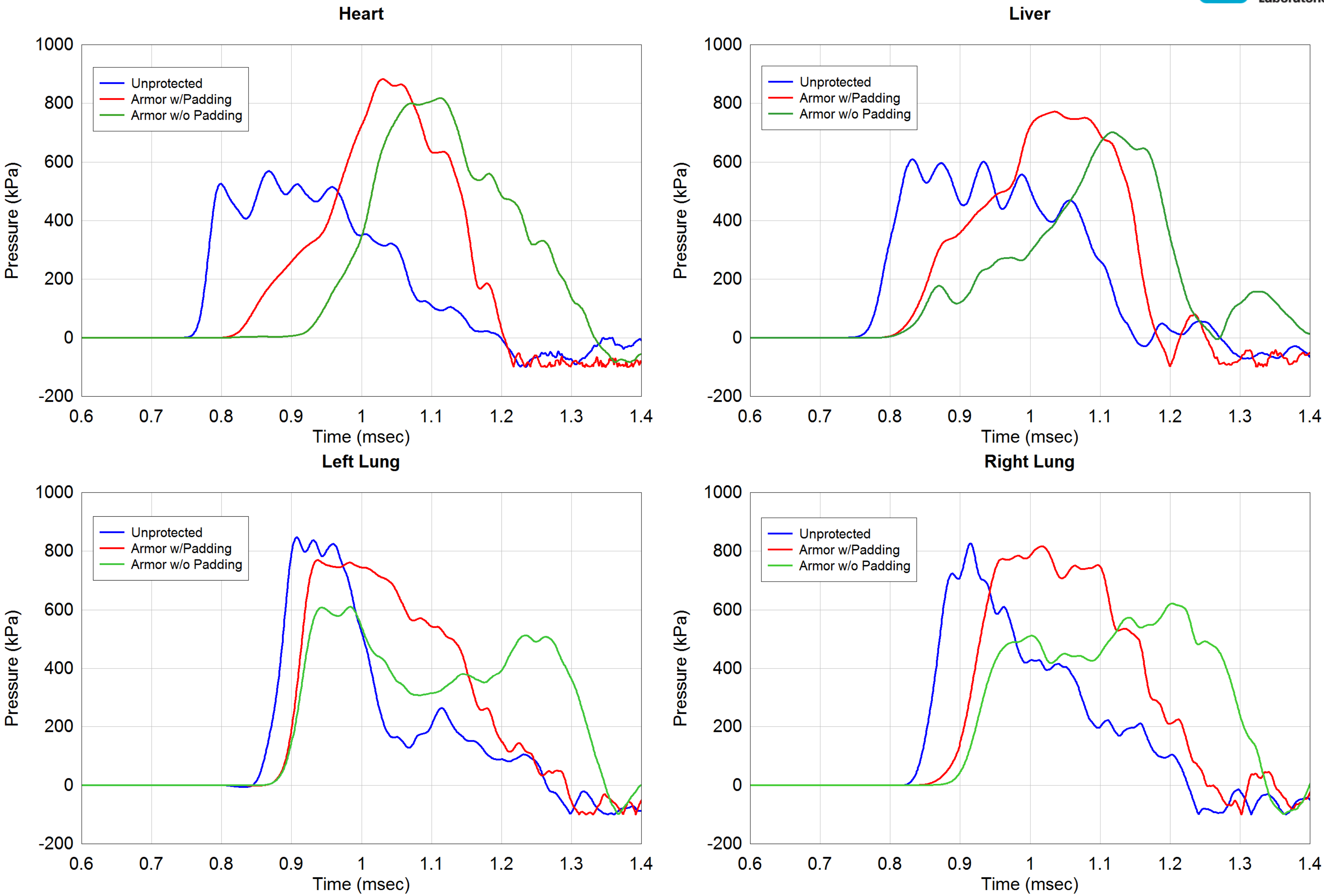
- 360kPa (260kPa over pressure) frontal blast
- Representative of conditions that a warfighter might experience during exposure to an IED detonation





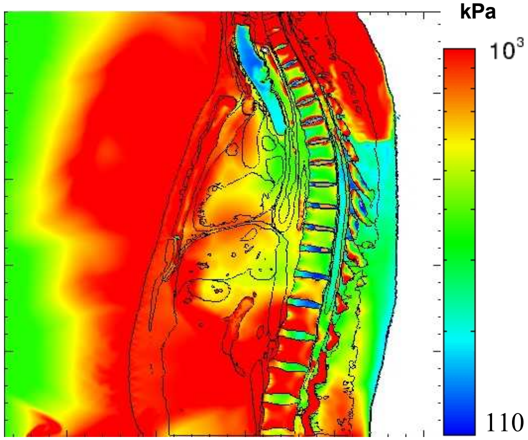


Frontal Blast Simulation Results

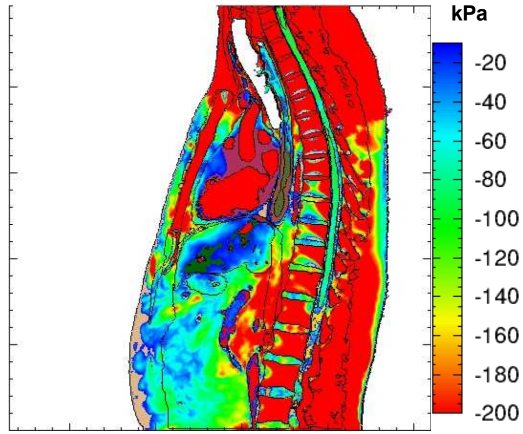


Frontal Blast Simulation Results

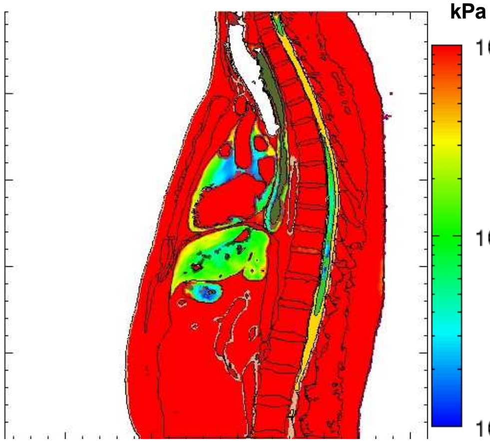
Maximum Compressive Pressure



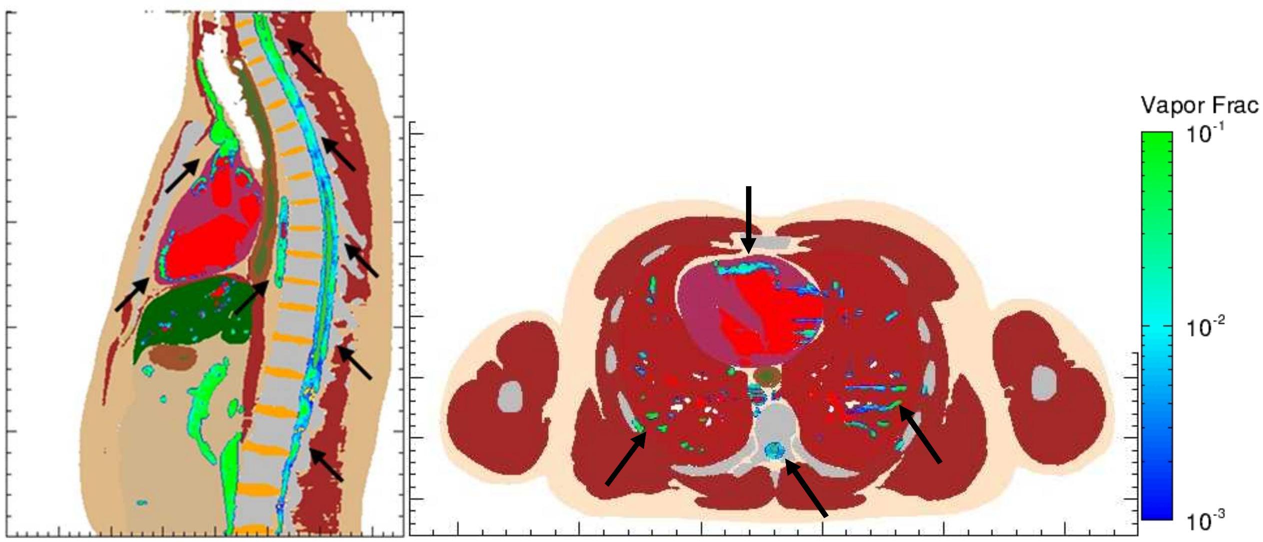
Maximum Tensile Pressure



Maximum Von Mises Stress

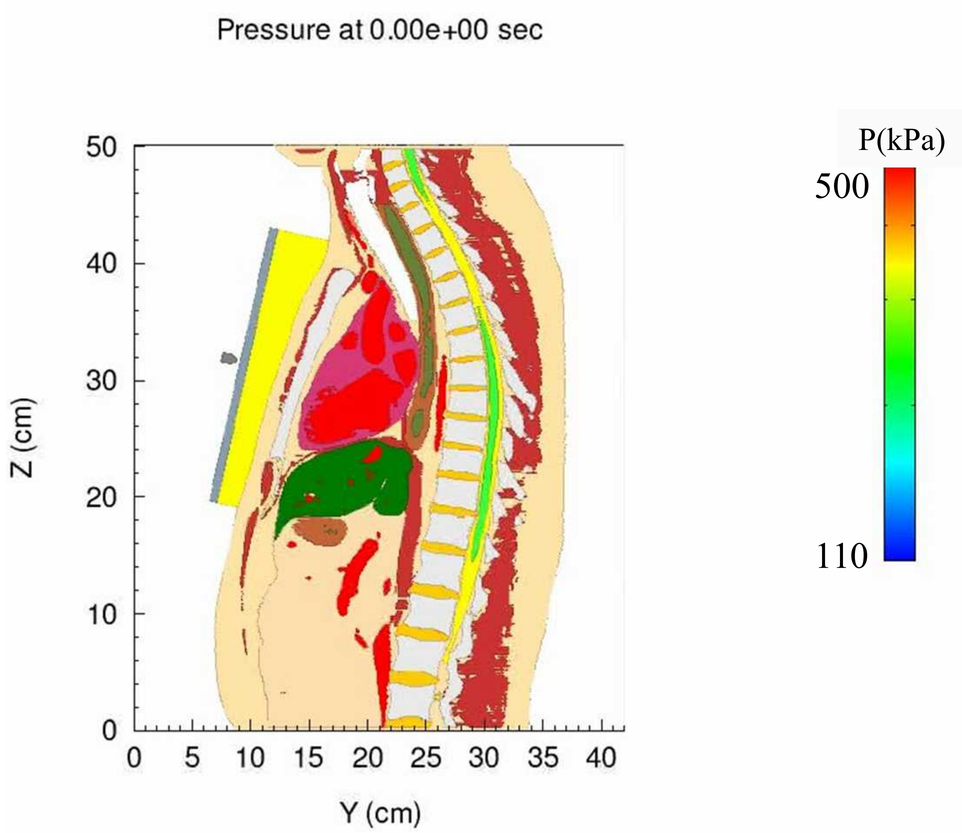


Maximum Vapor Volume Fraction (Cavitation)



Projectile Impact Simulation

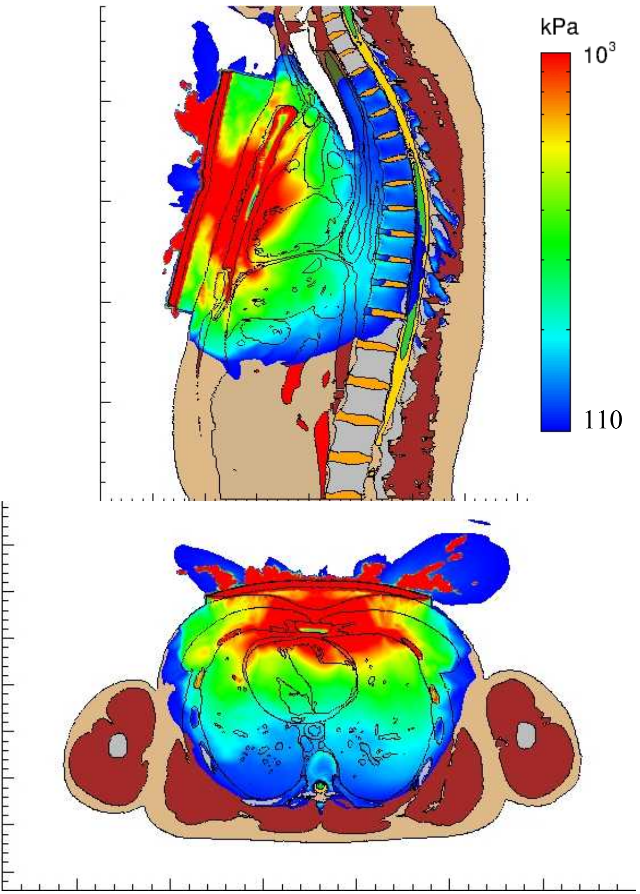
- Notional chest armor backed with padding
- Mock representation of a 9mm full metal jacket bullet
- Ballistic impact velocity of 370 m/s



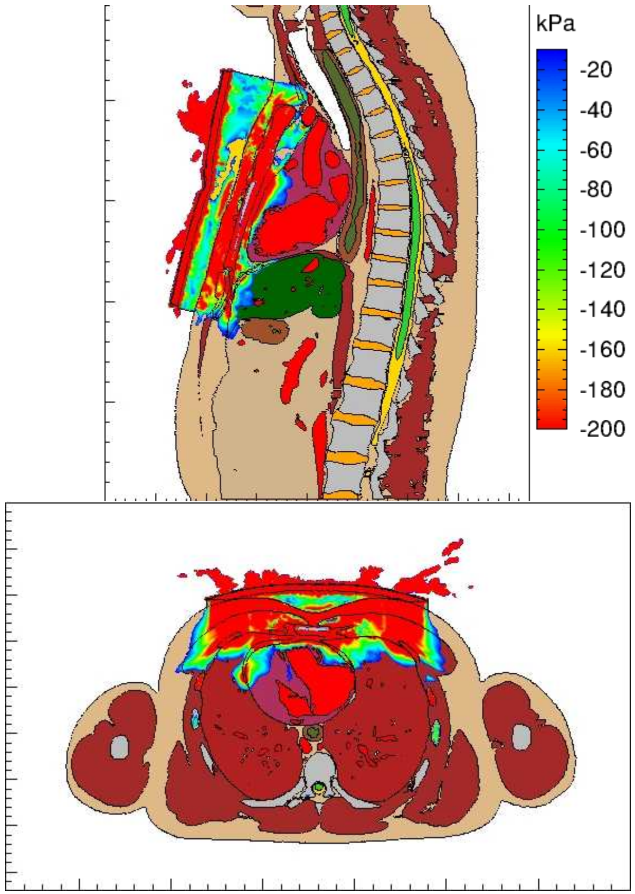
Projectile Impact Simulation Results

Sandia National Laboratories

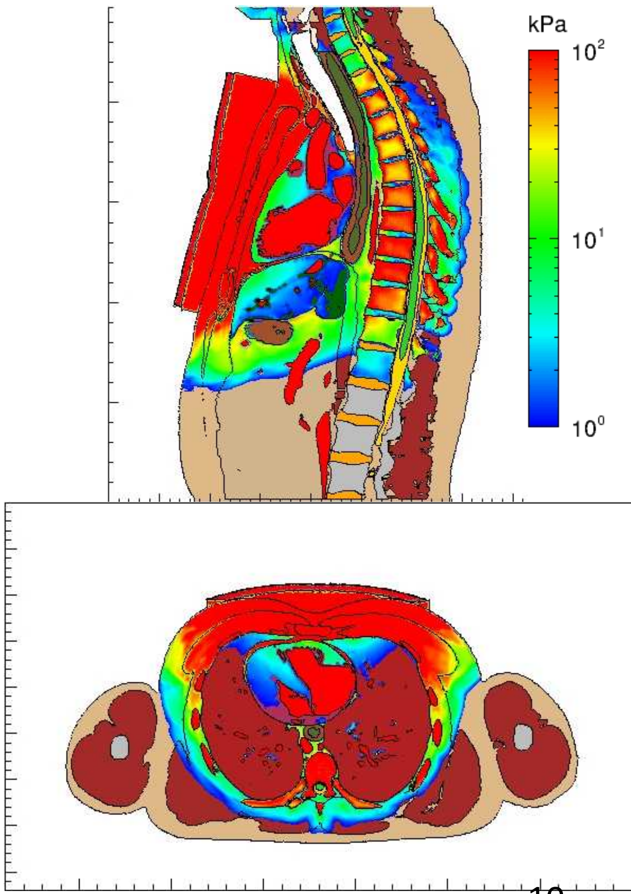
Maximum Compressive Pressure



Maximum Tensile Pressure

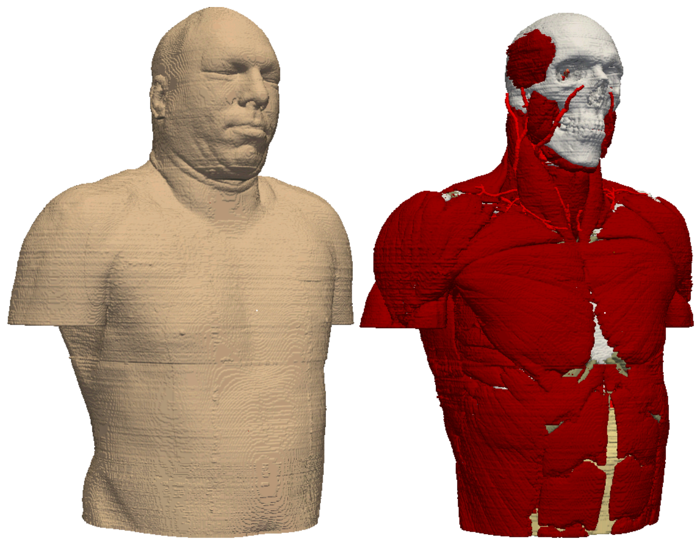


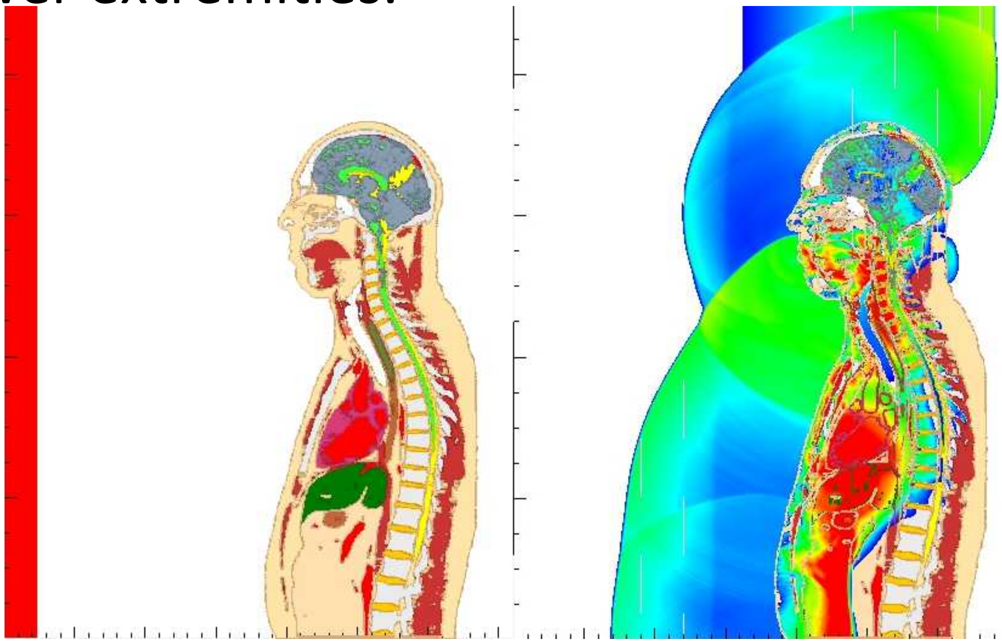
Maximum Von Mises Stress



Current & Future Work

- Side and rear direction blast simulations and additional projectile impact simulations have been conducted
- New Head-Neck-Torso model, utilizing SNL Head-Neck model[1], currently undergoing verification
- Possible extension of Head-Neck-Torso model to include urogenital region and lower extremities.
- Model Validation





[1] Taylor, P. A., Ludwigsen, J. S., and Ford, C. C., 2014, "Investigation of blast-induced traumatic brain injury," Brain Inj., **28**(7), pp. 879–895.

Conclusion

- High fidelity simulation methods are advantageous in the analysis of subtle wound injury mechanics and the relative merit assessment of armor systems.
- M&S effort intended to be used in collaboration with, and validated against, laboratory and field test data.
  - M&S may assist in the design of laboratory and field tests
  - Currently attempting to validate and fine-tune our constitutive models
- M&S can play a role in armor development by reducing the need for expensive field testing and by possibly revealing novel design concepts that may be overlooked by an exclusive test-and evaluation approach.
  - Relative merit performance of armor systems can be conducted without completely validated models

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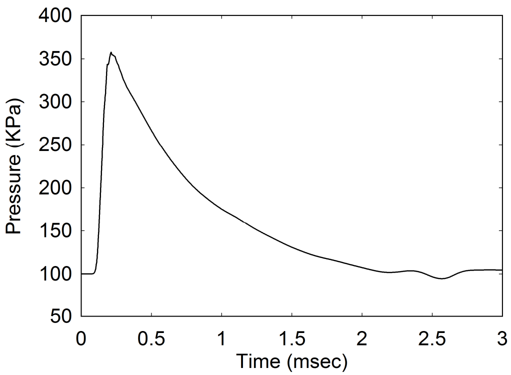
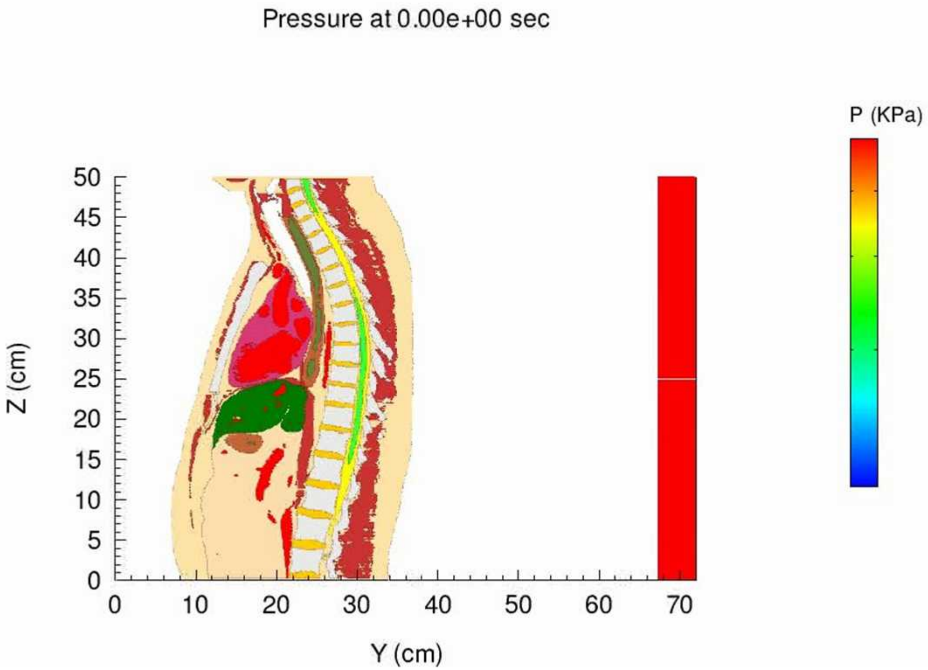
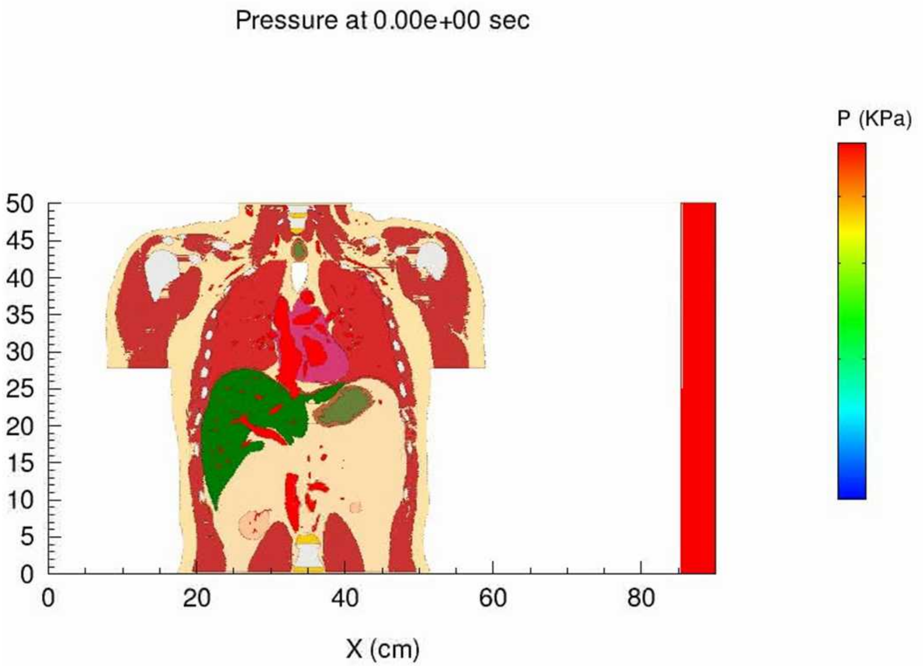
Supplemental Slides

Simulated Blast Pulse (Similar to classical Friedlander waveform)





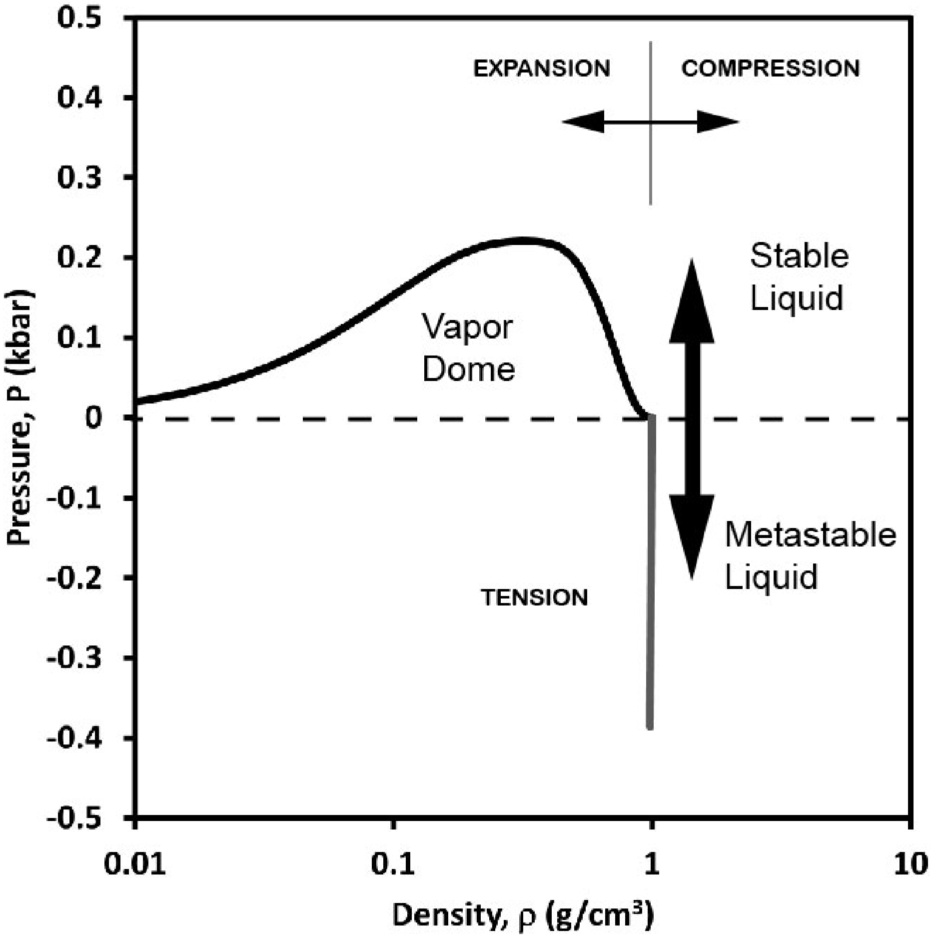


Supplemental Slides

New EOS for Shock-loaded Metastable Fluids

- *Extend* Tillotson EOS to capture tension and cavitation in fluids
- EOS fit to general form in compression, expansion, and tension

$$P(\rho, E) = \left[a + \frac{b}{\frac{E/E_0}{(\rho/\rho_0)^2} + 1} \right] \rho E + f(\rho)$$



Supplemental Slides

Physical properties of materials comprising the torso model.

Material	Density (g/cc)	Bulk Modulus (MPa)	Shear Modulus (MPa)	Yield Stress (MPa)	$\sigma_{fracture}$ (MPa)	$\varepsilon_{fracture}$
Bone	1.21	4762	3279	95	77.5	0.016
Intervertebral Discs	1.0	8.33	1.79	--	77.5	--
Costal Cartilage	1.0	8.33	1.79	--	77.5	--
Larynx	1.0	8.33	1.79	--	77.5	--
Vasculature/Blood	1.05	T-B fit	--	--	--	--
Airways/Air	1.22e-3	See Fig. 4	--	--	--	--
Lungs	0.7	150	Table 2	--	10.0	--
Liver	1.06	280	Table 2	--	10.0	--
Kidneys	1.1	276	Table 2	--	10.0	--
Spleen	1.1	276	Table 2	--	10.0	--
Heart	1.0	380	Table 2	--	10.0	--
Muscle	1.2	34.8	--	--	10.0	--
Stomach	1.05	480	0.096	--	10.0	--
Stomach Contents	1.0	T-B water		--	--	--
Spinal Cord	1.04	T-B fit	Table 3	--	--	--
Cerebrospinal fluid	1.004	T-B fit	--	--	--	--
Abdominal Cavity Contents	1.2	34.8	5.88	--	10.0	--
Thyroid	1.2	34.8	5.88	--	10.0	--
Skin	1.2	34.8	5.88	--	10.0	--
Chest Plate	1.44	2084	TI fit	--	--	--
Chest Armor Foam	0.136	4.44	3.33	--	77.5	--
9 mm FMJ Bullet	11.689	45826	8600	54	460	--

Supplemental Slides

Viscoelastic material parameters for the spinal cord

	Short-term Shear Modulus G_o (KPa)	Long-term Shear Modulus G_∞ (KPa)	Decay Constant β (sec^{-1})
Spinal Cord	41.0	7.8	40