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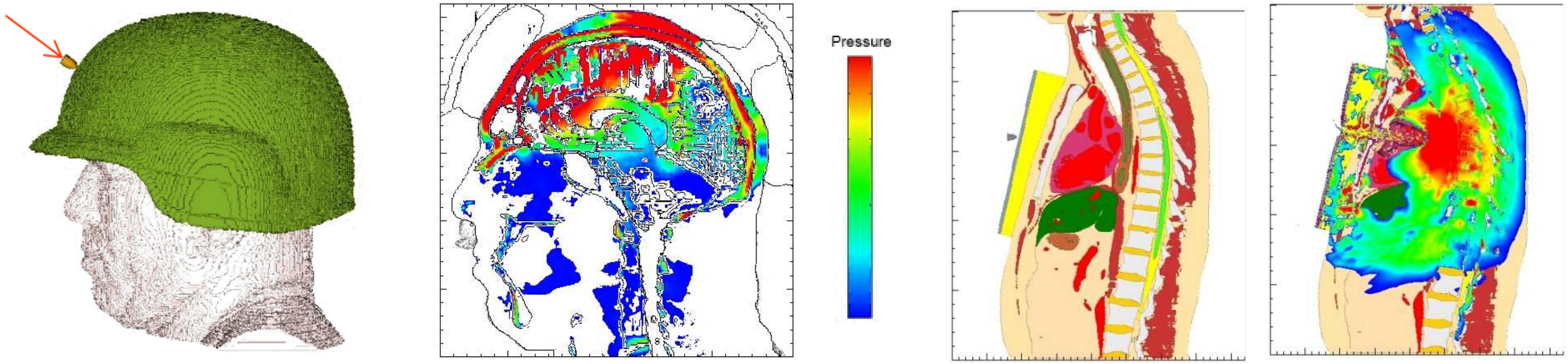
Exceptional service in the national interest

Assessing Armor Performance Using High Fidelity Wound Ballistics Simulations



Wound Injury Technical Briefing – University of Nebraska–Lincoln

Ryan Terpsma

Sandia National Laboratories

October 8th, 2015

Partially funded through the NNSA Laboratory-Directed Research and Development (LDRD) Program, and through the U.S. Naval Health Research Center Office of Naval Research, Mr. James Mackiewicz and Dr. Tim Bentley, project funding managers

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Wound Injury Investigation Team

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- Ryan Terpsma

Background

US Soldiers are surviving blast and impacts due to effective body armor, rapid evacuation, and availability of critical trauma care

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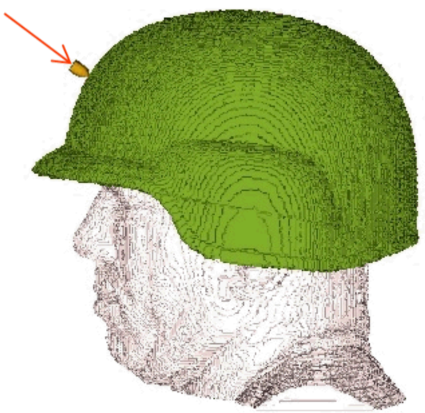
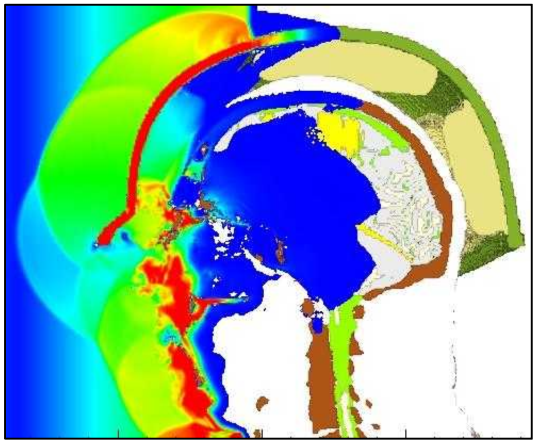
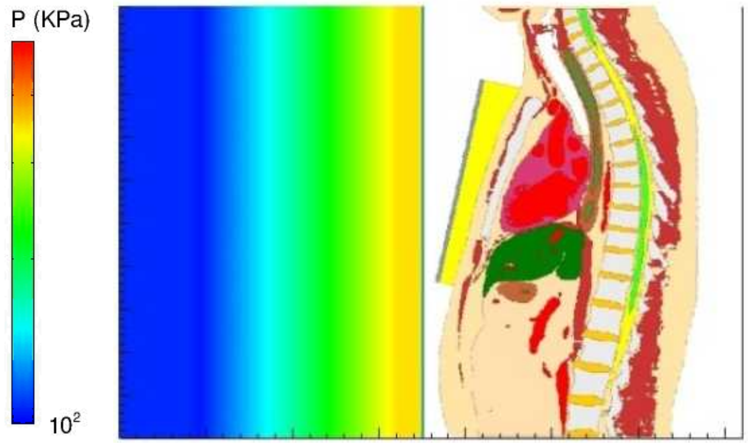
Background

- Closed-Head Blast Injuries are leading cause of traumatic brain injury (TBI) in military personnel returning from combat [1,2]
  - As of 2010, 160,000 US warfighters sustained TBI
  - 69% as a result of IED blast exposure in Iraq & Afghanistan
- Our focus is on Blast and Blunt Trauma Injury and investigating mechanisms associated with injury
  - Once know, want to mitigate damage mechanisms through armor design







[1] Defense & Veterans Brain Injury Center TBI numbers: DoD numbers for traumatic brain injury. 2010
[2] Fischer, H., 2007, United States Military Casualty Statistics: Operation Iraqi Freedom and Operation Enduring Freedom, Congressional Research Service Report RS22452.

Methodology

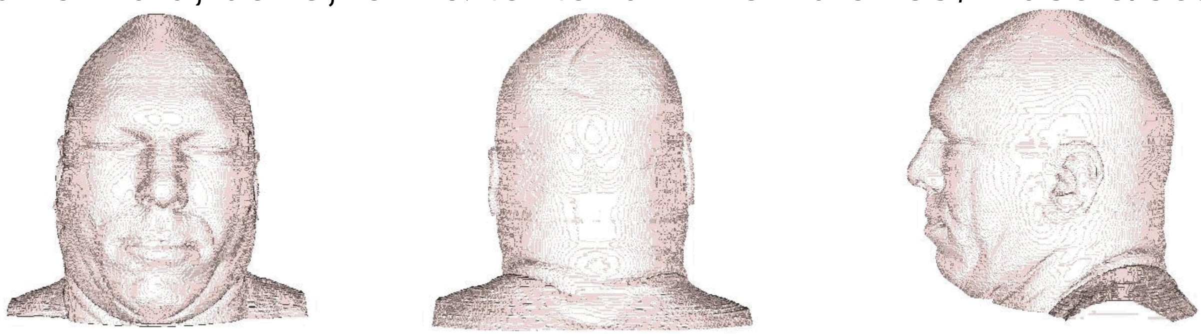
- Develop digital human models & simulation methodologies to:
  - Investigate wound injury mechanics to life-critical anatomical regions of warfighter
  - Conduct relative merit assessments of prototype personal armor designs
- Technical Approach to Injury Investigation
  - Develop high-fidelity digital models of human head-neck and torso
    - Validate M&S with various head, neck, & torso injury data
  - Simulate injury scenarios experienced by warfighter due to blast, blunt impact, ballistic projectile impact & penetration
  - Compare/correlate predictions w/ clinically observed injury
    - Collaboration with Corey Ford, MD, PhD, UNM Health Sciences Center
    - Identify wave physics variables that correlate with injury; e.g.,
    - Traumatic Brain Injury (TBI): Shear Stress, Pressure, Deviatoric Strain Energy, Isotropic Compressive & Tensile Energies
      – Goal: Determine critical values for threshold injury → Ongoing Effort

Model Development

Head-Neck Model

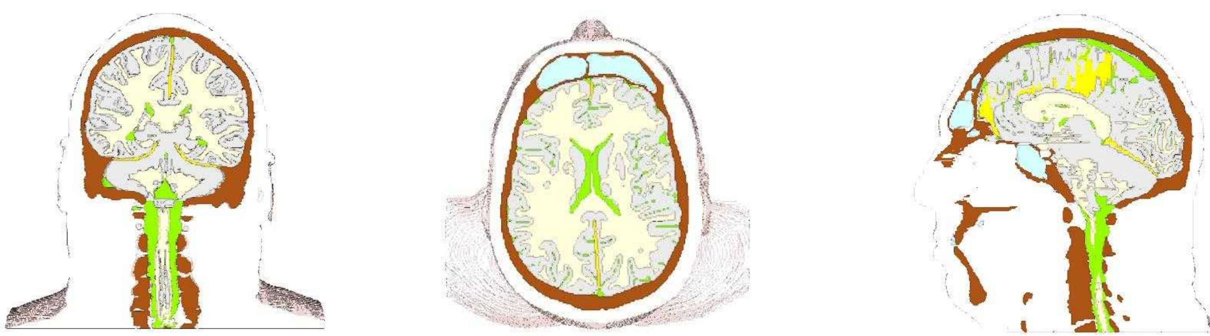
- Finite volume model from Visible Human Project [3] data
  - Constructed from 256 1mm-thick, axial slices of anatomical sections of human male from the VHP
  - Anatomically correct distributions of white & gray brain matter, cerebral spinal fluid, bone, falx & tentorium membranes, muscle/scalp

Full Model Images:



Model Size:
5.9M Cells
(resolution: 1 mm^3)

Coronal, Axial, & Sagittal Cuts:

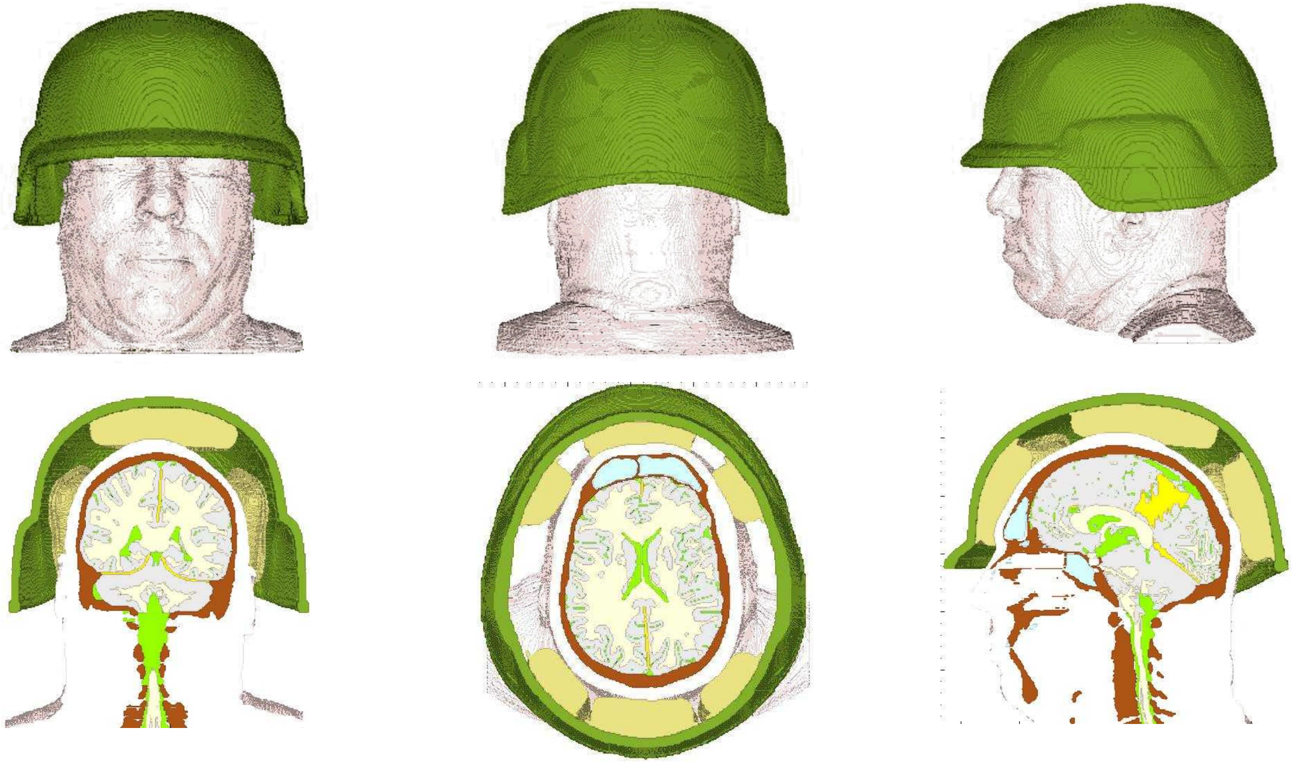


[3] National Institutes of Health, 2007, "The Visible Human Project," National Library of Medicine http://www.nlm.nih.gov/research/visible/visible_human.html

Model Development

Protective Armor – Helmet Model

- Finite Volume Helmet Model (1 mm^3 resolution)
- Example: Prototype helmet
  - Helmet shell: Kevlar Composite
  - Pads: Polyurethane Foam

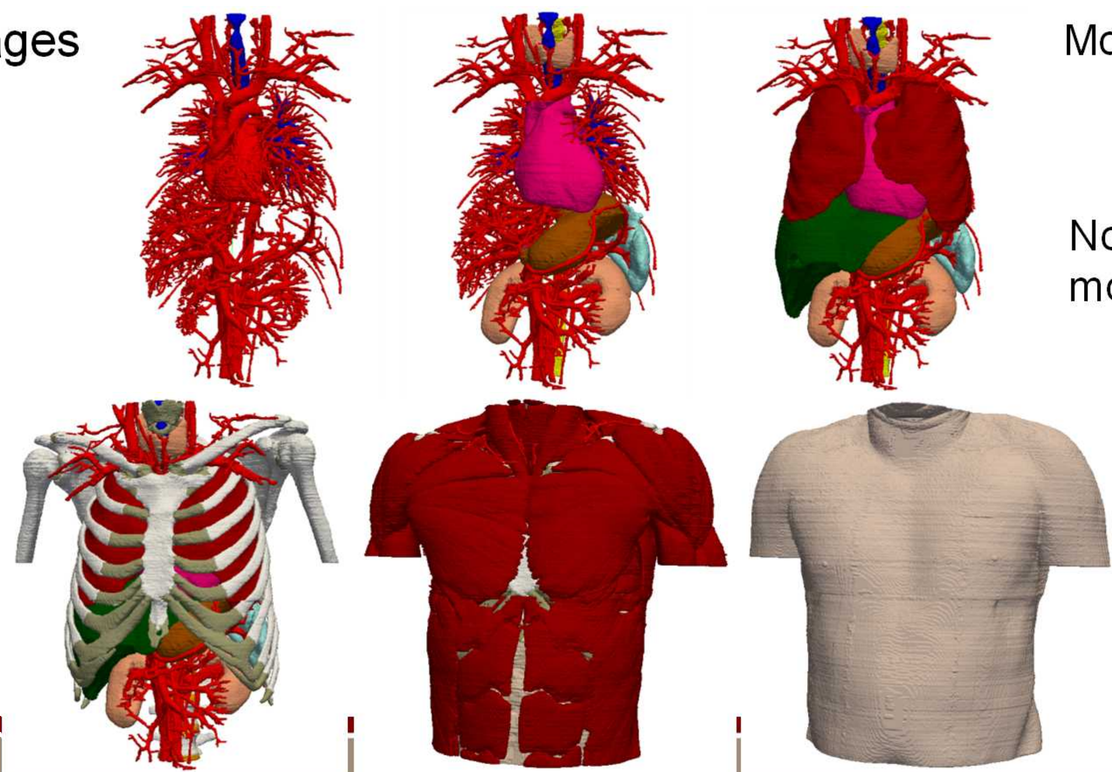


Model Development

Torso Model

- Finite volume model from Visible Human Project data
  - Constructed from 495 1mm-thick, axial slices of anatomical sections of human male from the VHP
  - Anatomically correct distributions of Bone, Cartilage, Intervertebral Disks, Blood, Vasculature, Airways, Lungs, Heart, Liver, Stomach, Kidneys, Spleen, Spinal Cord, Muscle, & Skin

Model Images



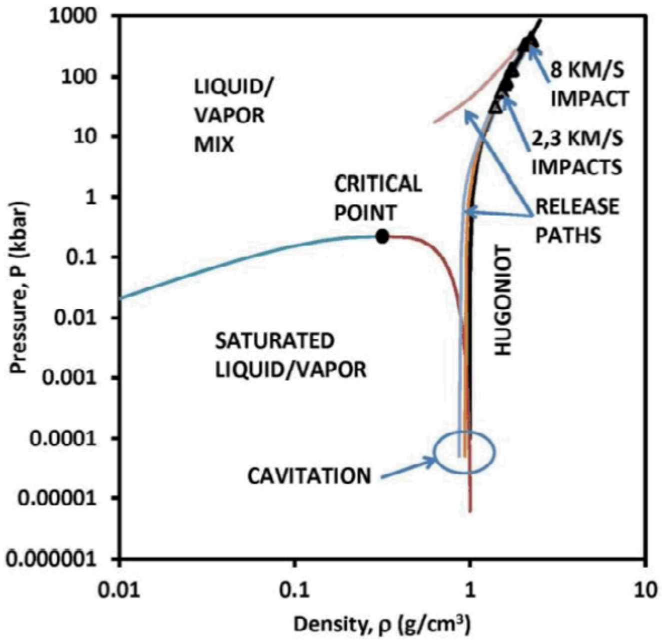
Model Size: 42.8M Cells (resolution: 1 mm^3)

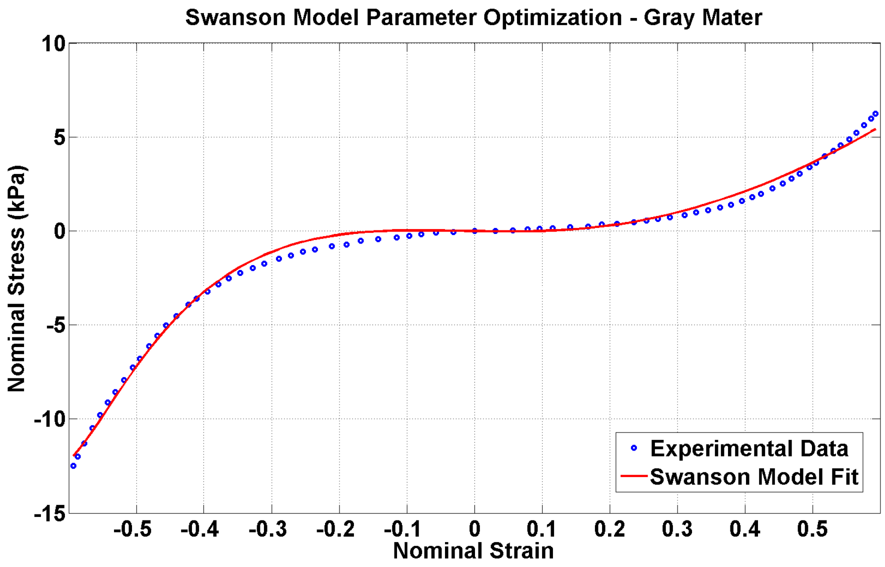
Note: Head & Torso models can be attached

Model Development

Material Response

- Non-linear Swanson model (white/gray mater, lungs, heart, spleen, kidneys, liver, muscle)
- Linear elastic (foam padding, skin, membranes, bone)
- Transversely Isotropic (helmet, body armor)
- Tillotson-Brundage Equation of State (cerebral spinal fluid, blood)[4]



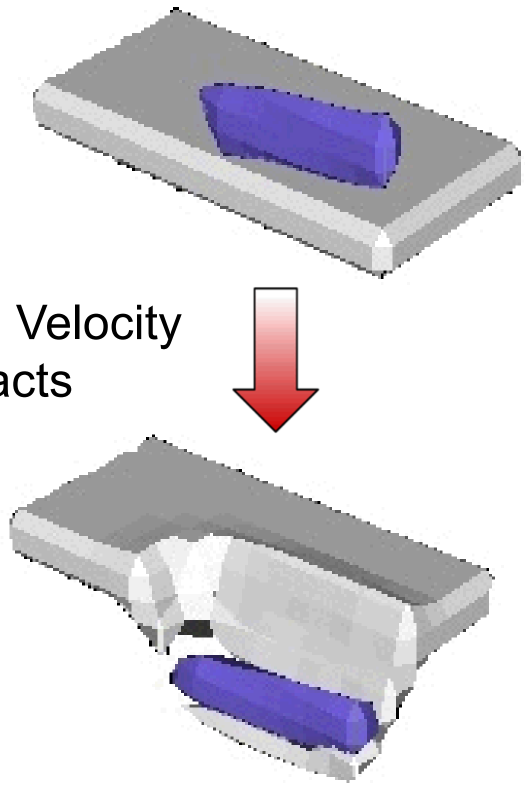


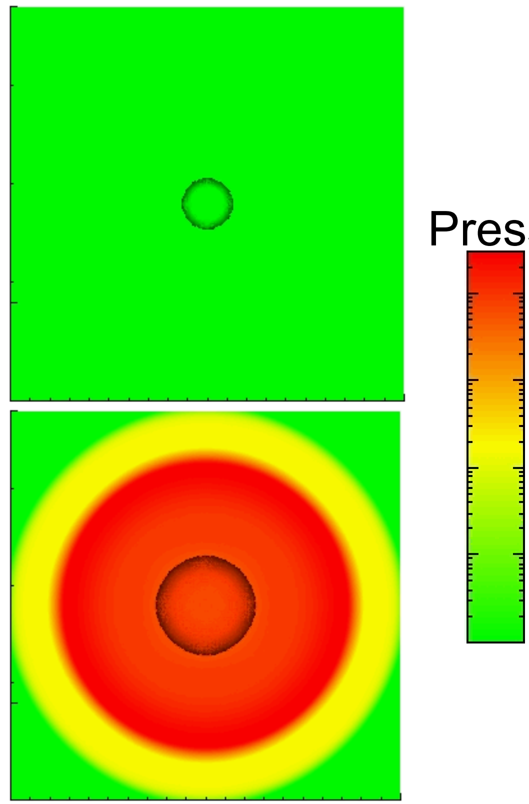
[4] Brundage, A.L., Implementation of Tillotson Equation of State for Hypervelocity Impact of Metals, Geologic Materials, and Liquids, Sandia National Laboratories, The 12th Hypervelocity Impact Symposium, 2013.

Analysis Code

- CTH - Sandia Eulerian Hydrocode[5]
  - Initially developed in the 80's – High velocity, large energy impacts
  - Capabilities added over the years – Generalized

High Velocity Impacts





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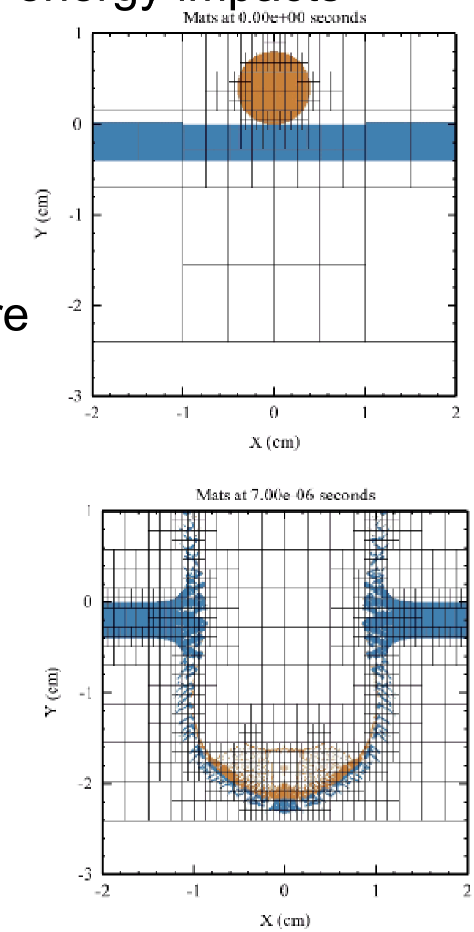
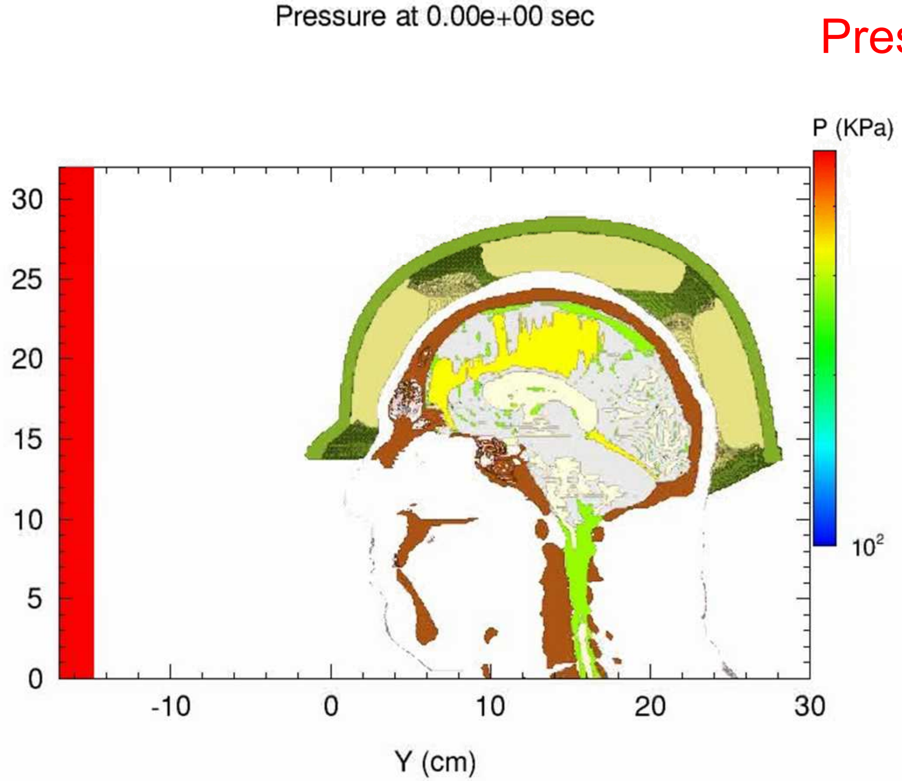


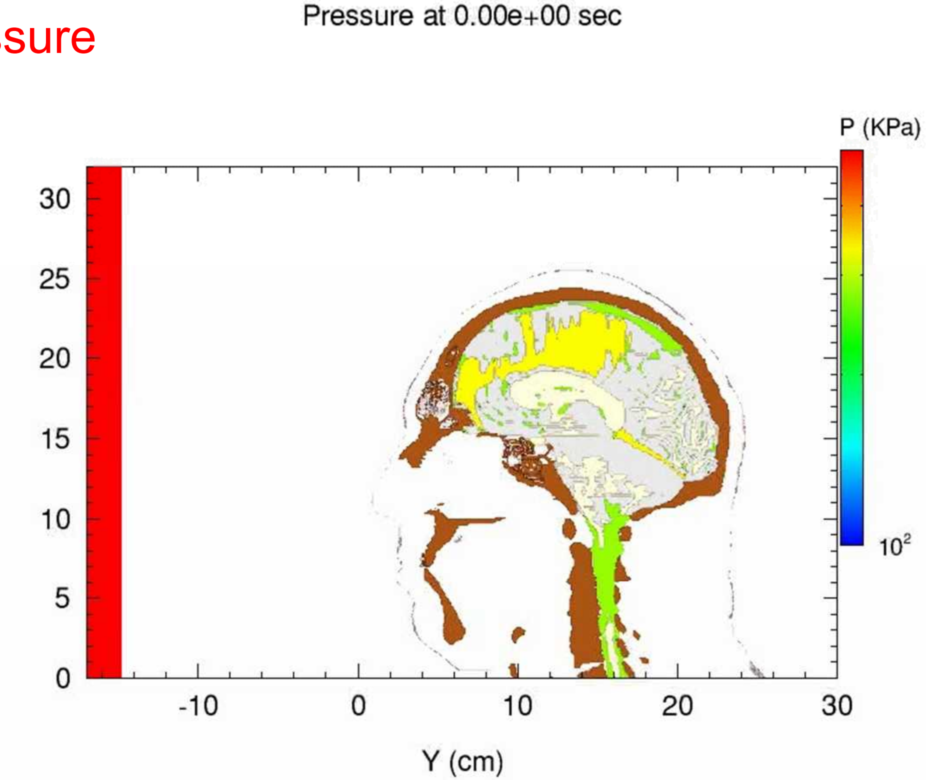
[5] Crawford et al., *CTH User's Manual and Input Instructions*. Sandia National Laboratories. January 26, 2012.

Relative Merit Helmet Protection Simulation

260 kPa Frontal Blast: mid-Sagittal Plane

Pressure





Note: Run Videos Simultaneously

Relative Merit Helmet Protection Simulation

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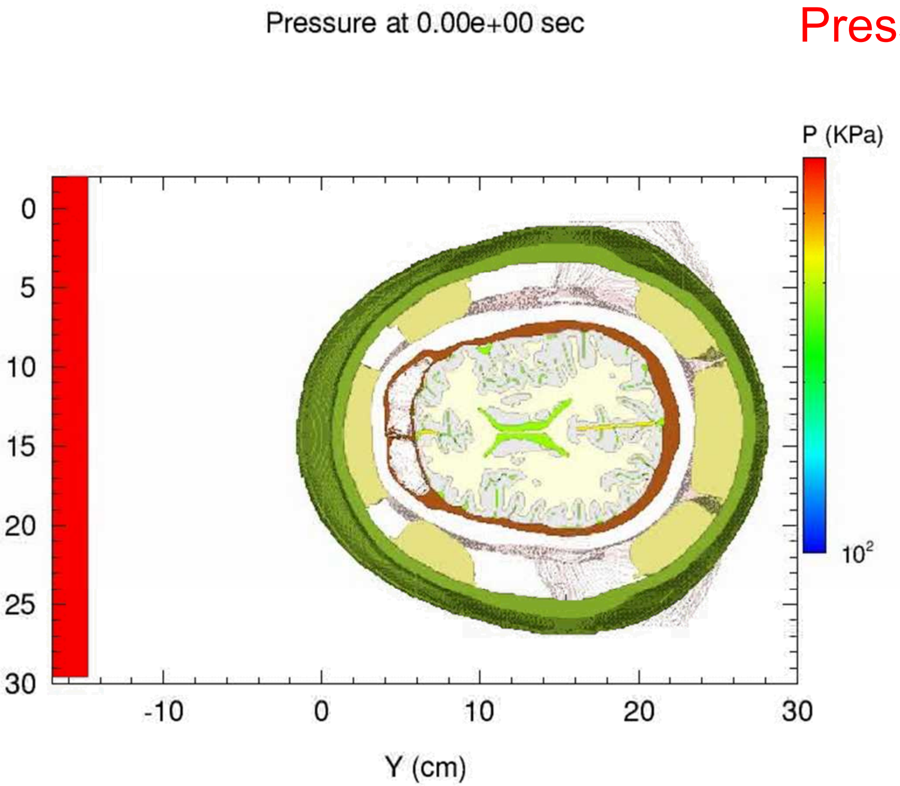
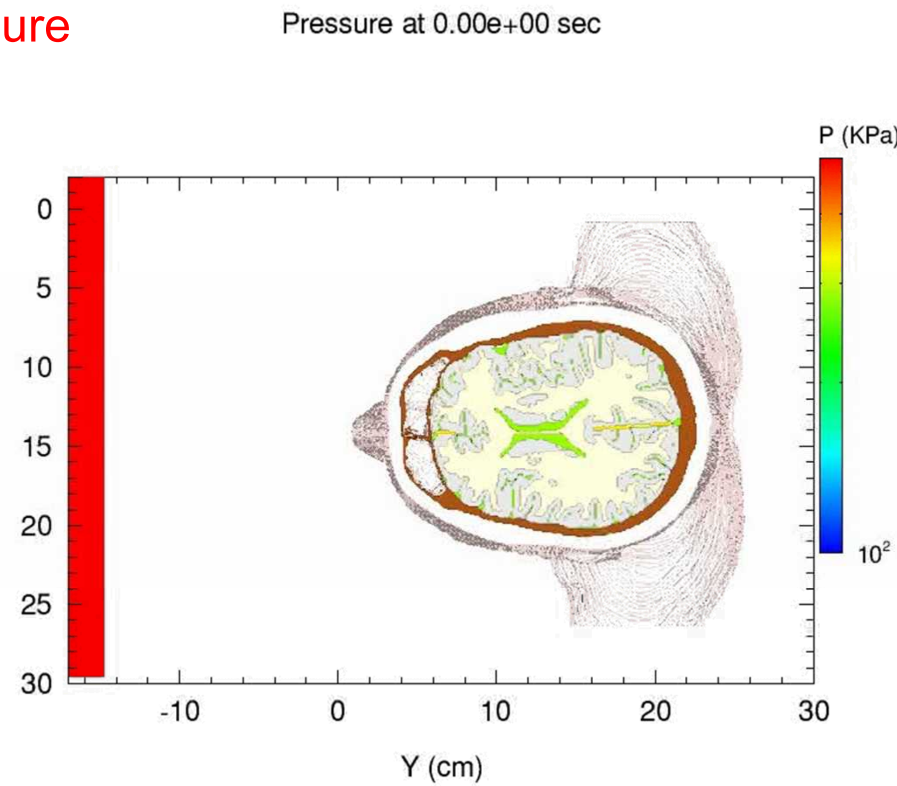
260 kPa Frontal Blast : Axial Plane above Eyes

Pressure





Note: Run Videos Simultaneously

Blast Mitigation Effects of Helmet Protection

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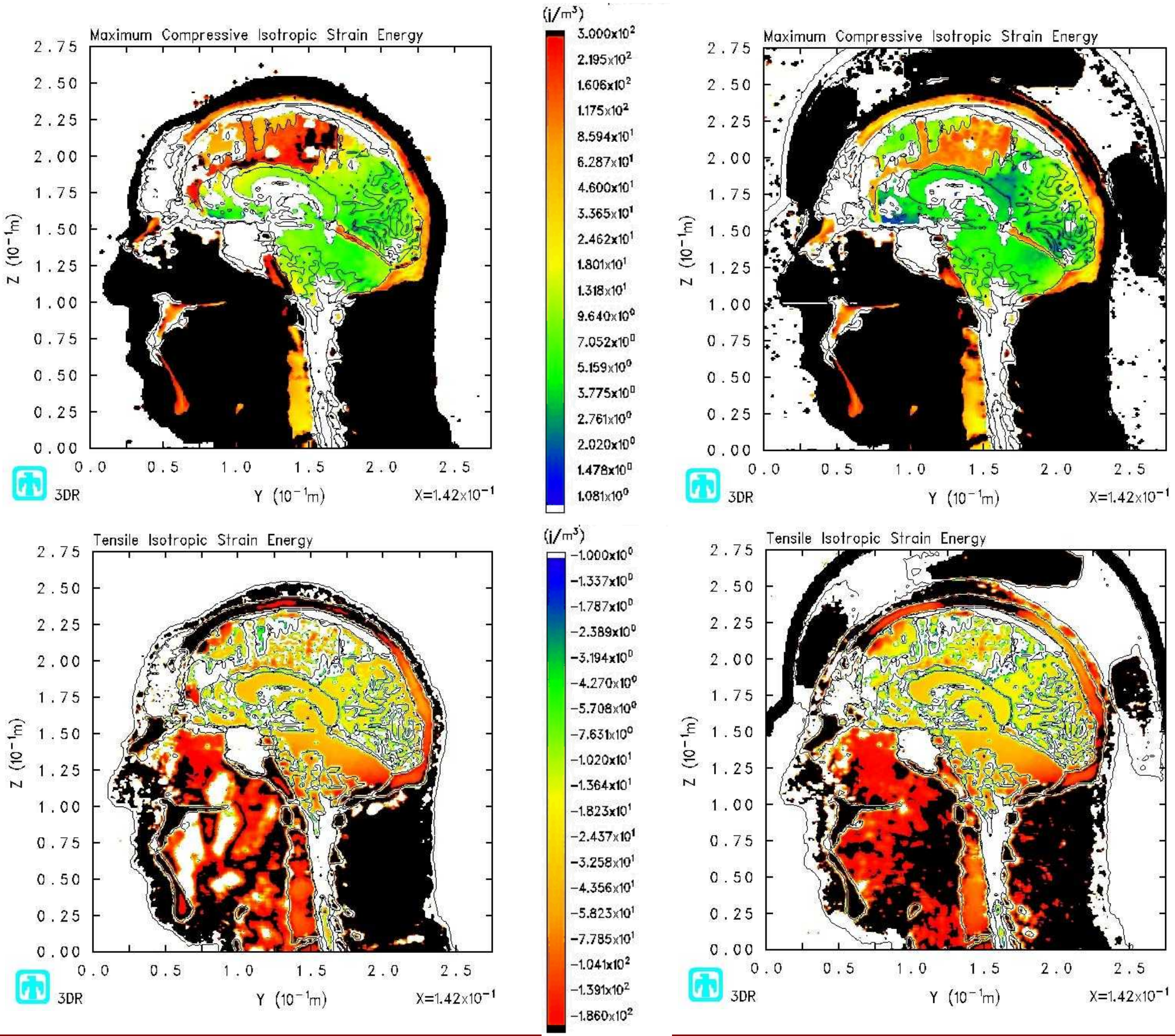
260 kPa Frontal Blast Exposure: Isotropic Strain Energy Maxima

Compressive Isotropic Strain Energy

Tensile Isotropic Strain Energy



Personal Armor Assessment

Rear Impact Scenario: V=370 m/s

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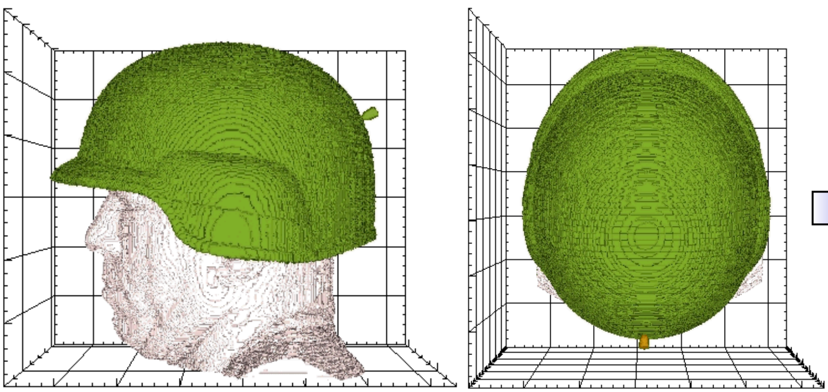
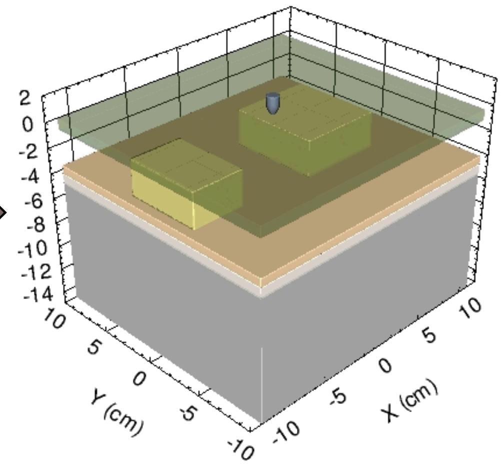
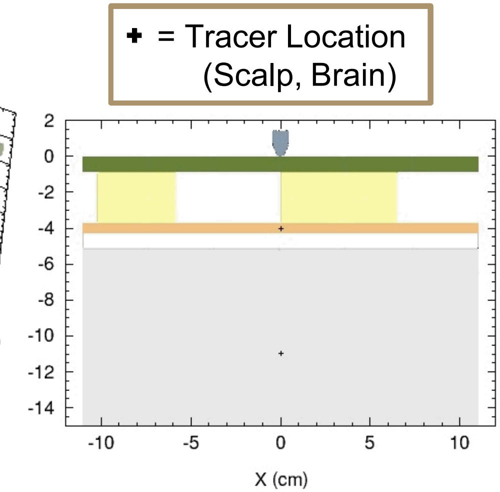


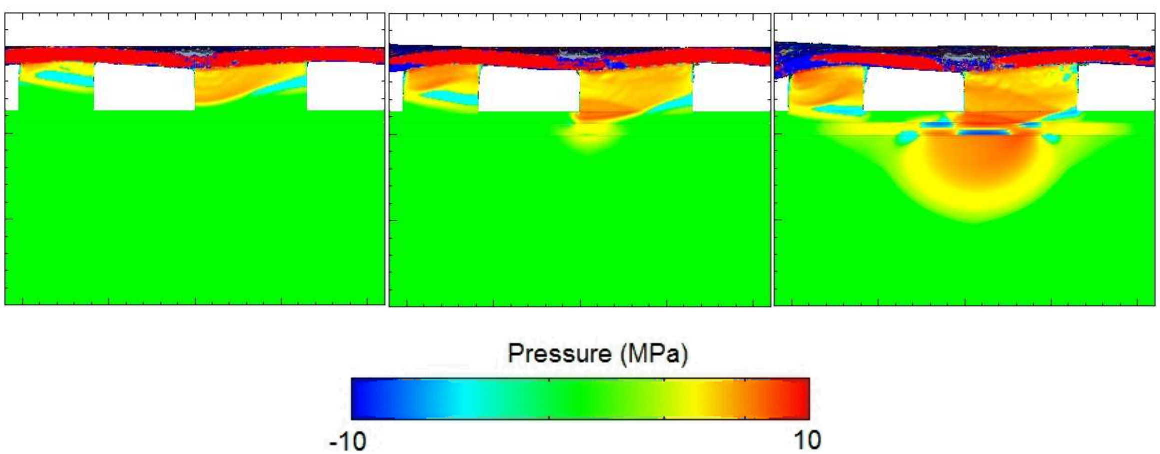


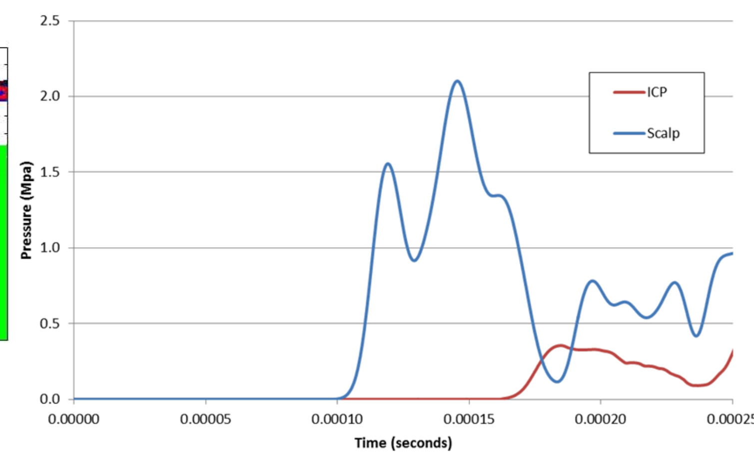


Pressure at 8.00e-05 secs.

Pressure at 1.20e-04 secs.

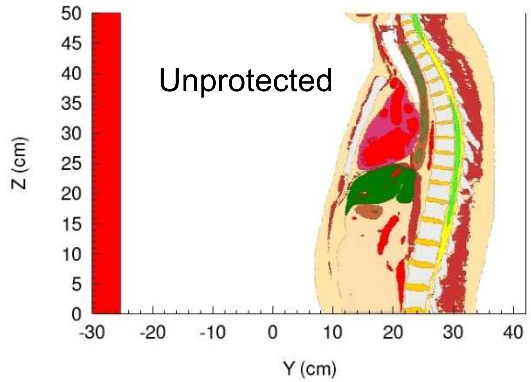
Pressure at 1.50e-04 secs.



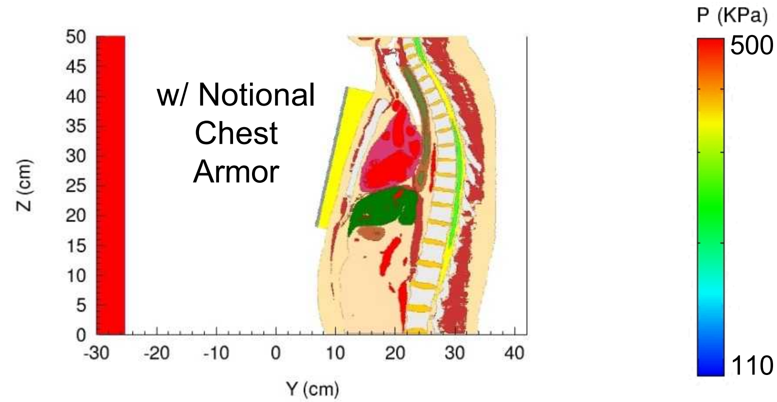


Personal Armor Assessment

Blast Protection of Torso



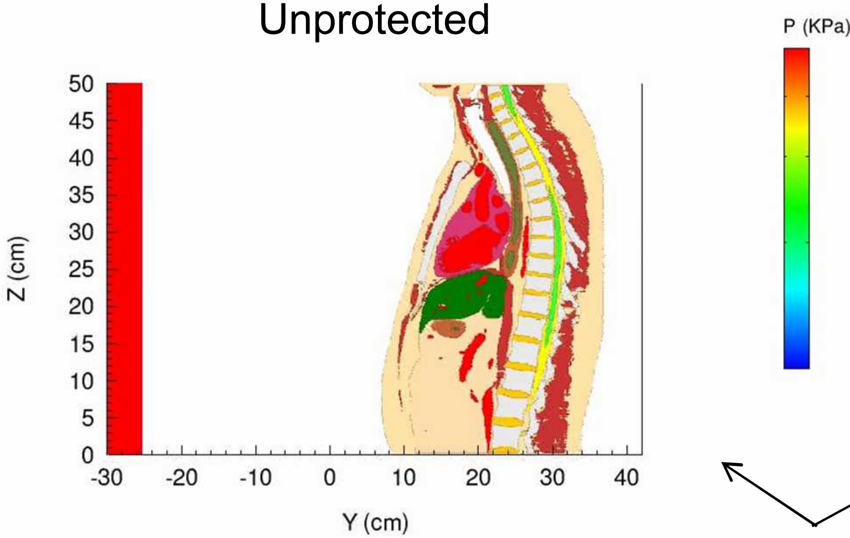
Initial Condition: Explosive Blast (260 kPa)



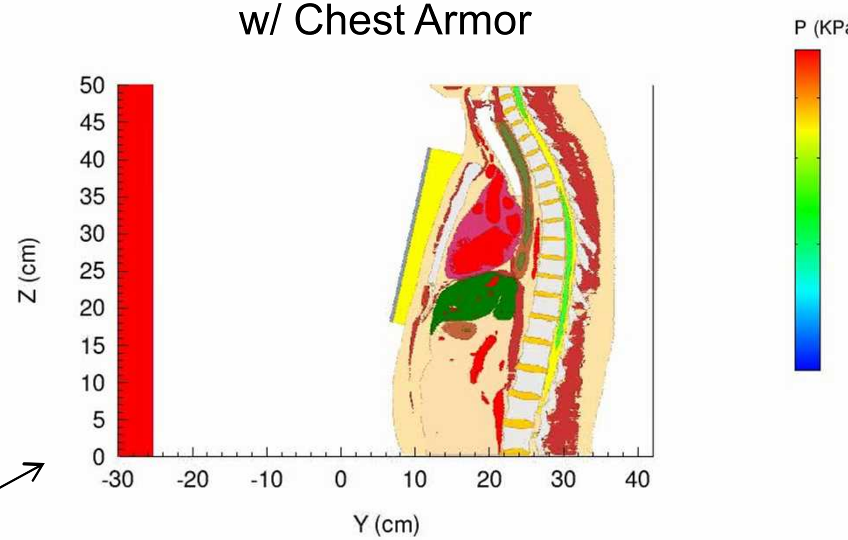
Pressure at 0.00e+00 sec

Pressure at 0.00e+00 sec

Unprotected



w/ Chest Armor

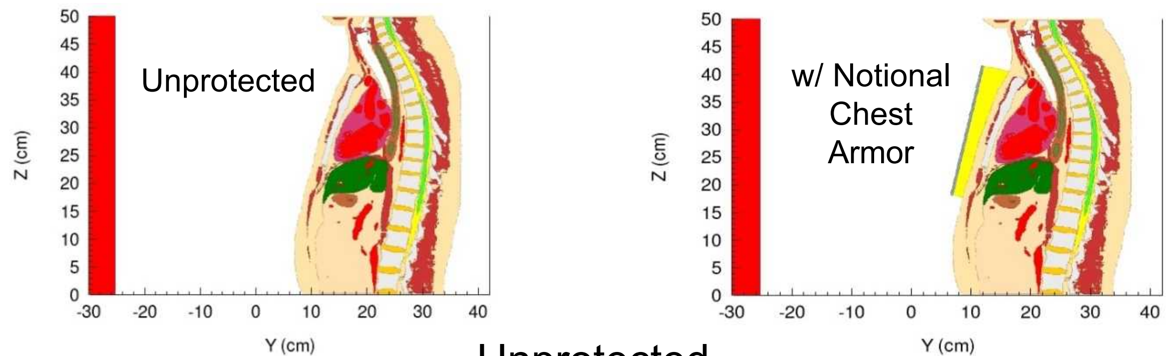


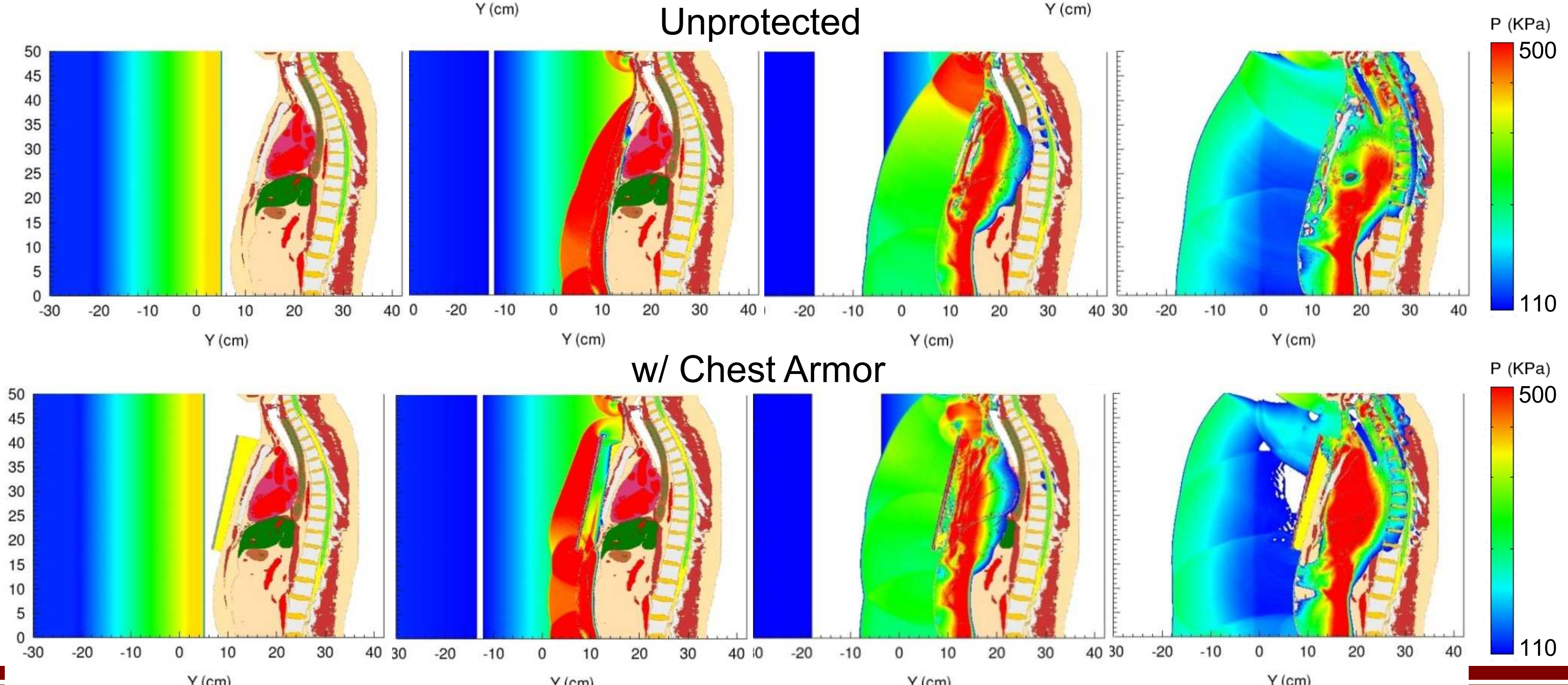
Run Videos Simultaneously

Personal Armor Assessment

Blast Protection of Torso

Initial Condition: Explosive Blast (260 kPa)

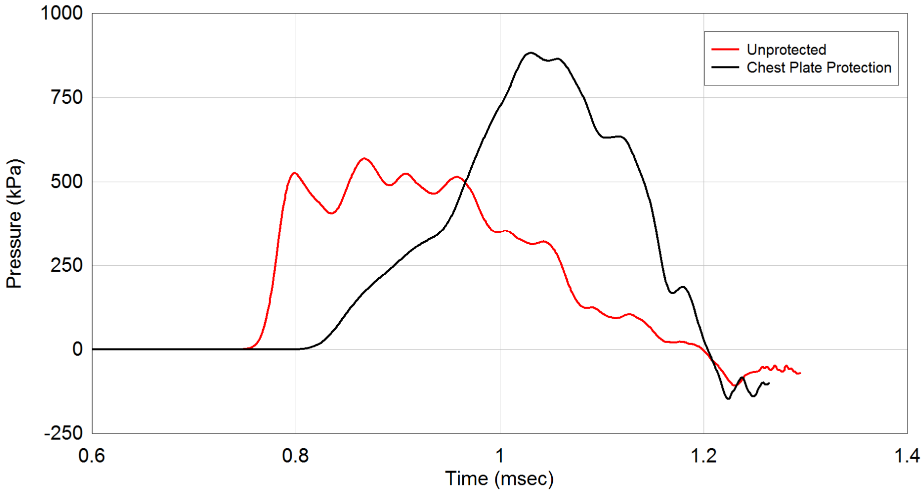




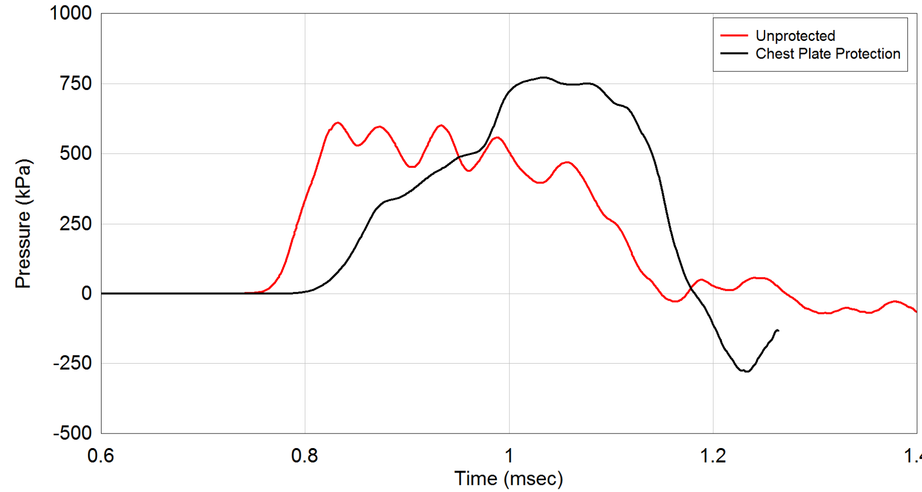
Personal Armor Assessment

Blast Protection of Torso

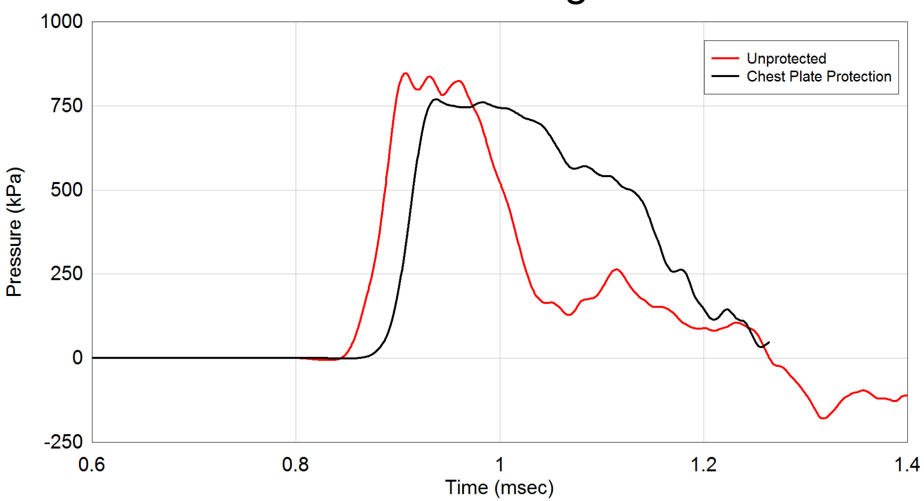
Heart



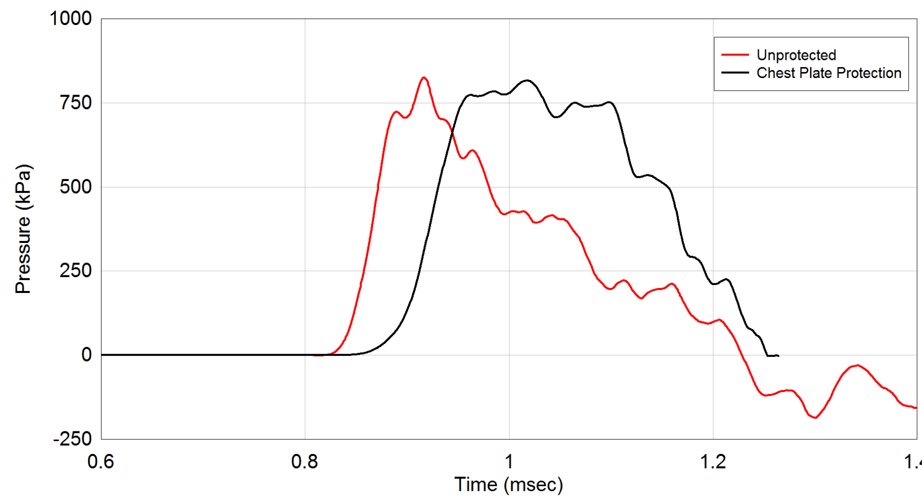
Liver



Left Lung



Right Lung

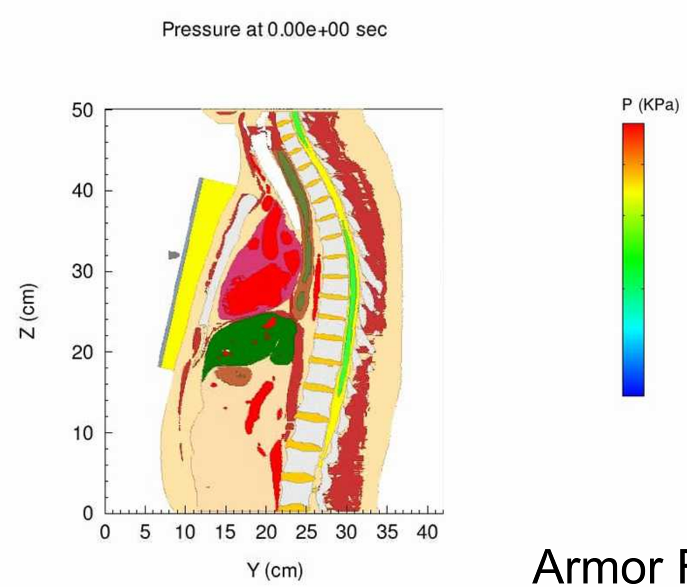


Personal Armor Assessment

Ballistic Impact Protection of Torso

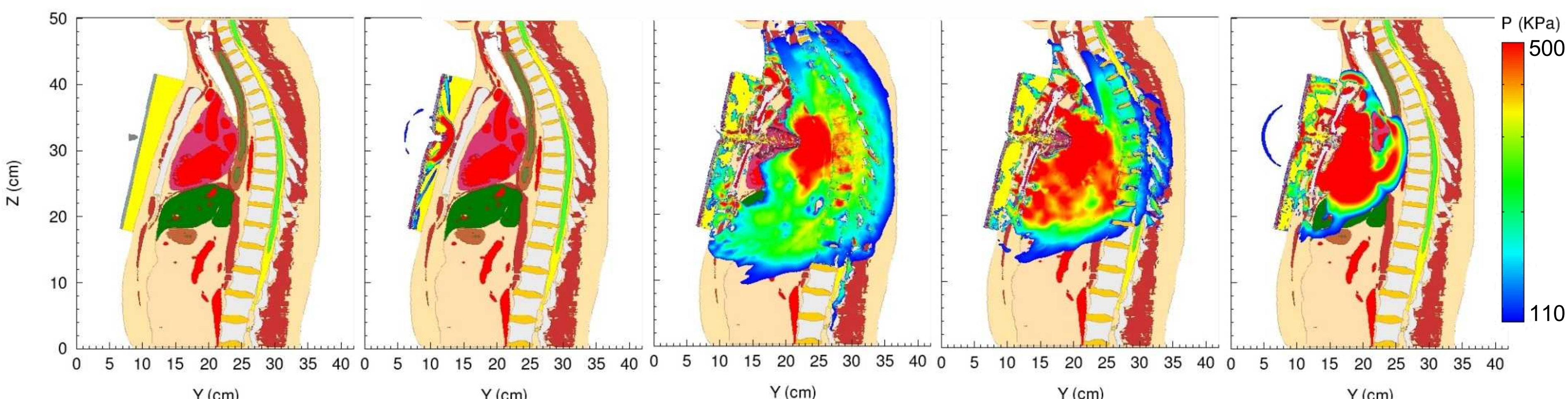
Initial Condition:

Ballistic Impact of 9 mm FMJ Projectile (427 m/sec) onto Torso w/ Notional Chest Armor



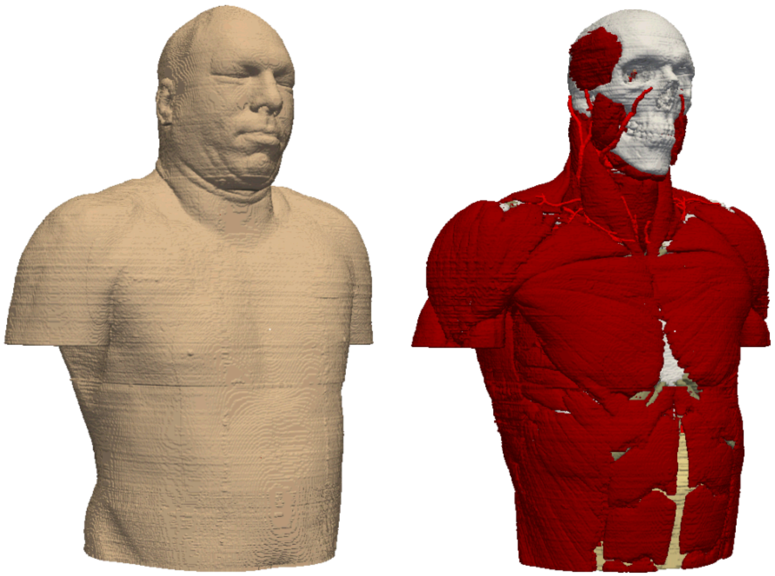
Click on Video ←

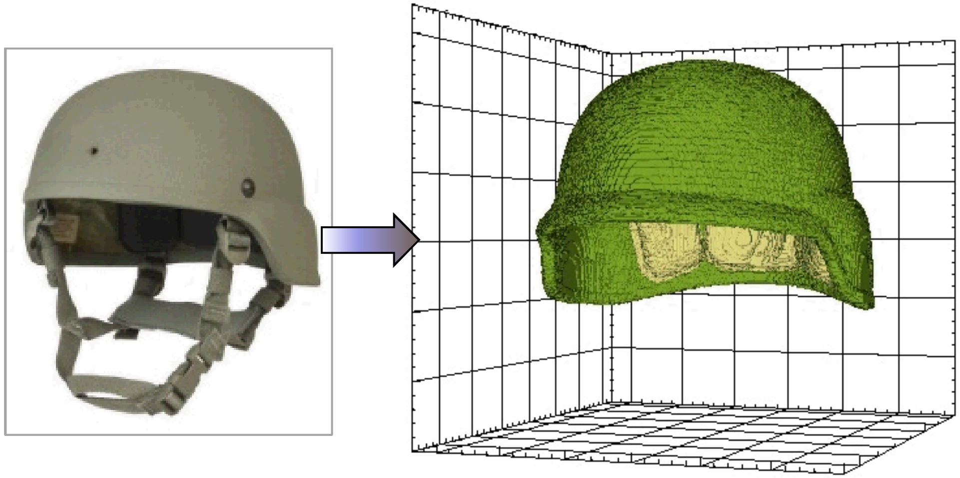
Armor Fails to Arrest Projectile



Summary

- **GOAL:** Develop tools to assist in better protecting the warfighter
- Constructed anatomically accurate digital models of the head/neck/torso region
  - Constitutive models fitted, but always in search of more data
- Digitized models of conceptual and prototype armor





Summary

- Conducted relative comparisons with both blast and blunt trauma insult scenarios
  - Advantages:
    - Injury scenario simulations can be conducted ad infinitum
    - Inexpensive! Replaces significant amount of physical testing
      - Reduces need for human cadavers or expensive physical surrogates
  - Disadvantages:
    - Accuracy of simulation results only as good as the equations-of-state (EOS) and constitutive models describing the various materials
    - Simulations can be computationally expensive
      - Blast simulation to head-neck requires ~30 cpu-core-hours per millisecond of simulation time using 96 cpu-cores; Torso simulations use 640 cpu-cores
      - *Good News:* Large simulations can be partitioned into smaller problems solved in fraction of time required for full-scale simulations
- Assessed armor capabilities and weaknesses
  - Provided feedback to designers

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Path Forward

Where to go from here?

- Validation of material models, macroscale models
  - Challenging with biomaterials
  - Lots of simplifications necessary in physical testing → how to compare to high fidelity numerical model?

- Primary goal still to correlate simulation results with real world injuries
  - Collaborating with University of New Mexico Medical Center
  - In the process of investigating data from Diffusion Tensor Imaging (DTI) of TBI patients
  - Develop injury threshold criteria to aid in armor design and assessment

- Construct micromechanical models of "hot spots" identified from macroscale models

TBI Macroscale Modeling & Simulation

260 KPa Blast Exposure: Cavitation Vapor Volume Fraction

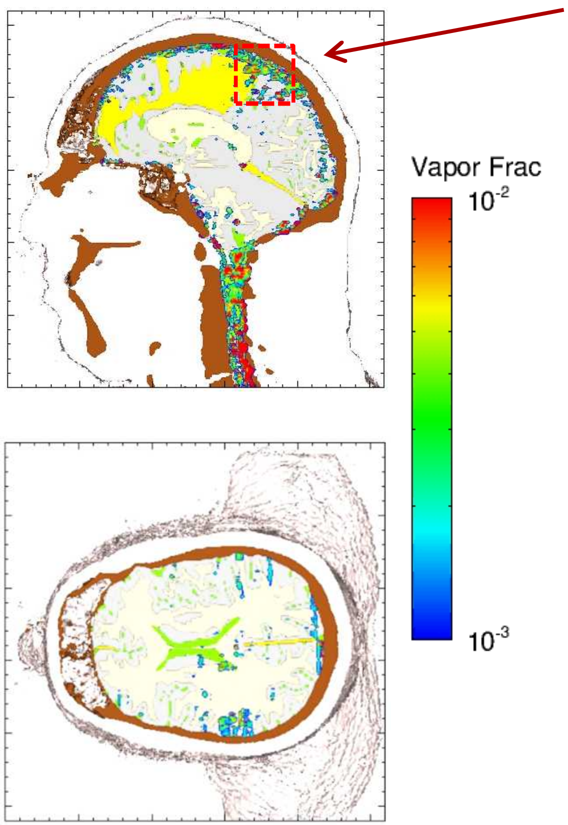
Frontal Blast

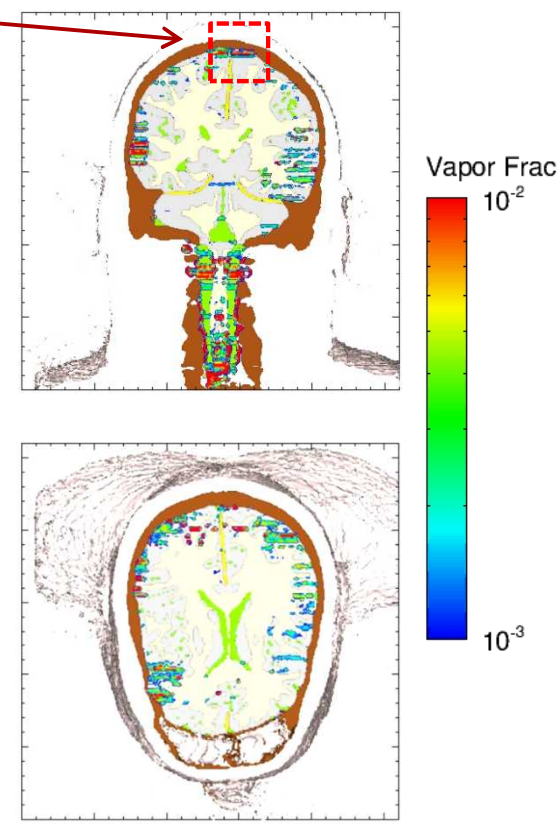
Blast Direction

Note cavitation occurrence in Superior Sagittal Sinus

Side Blast

Blast Direction





TBI Microscale Modeling

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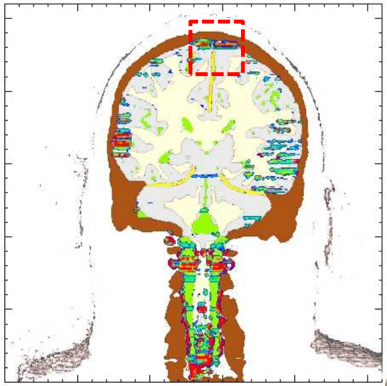
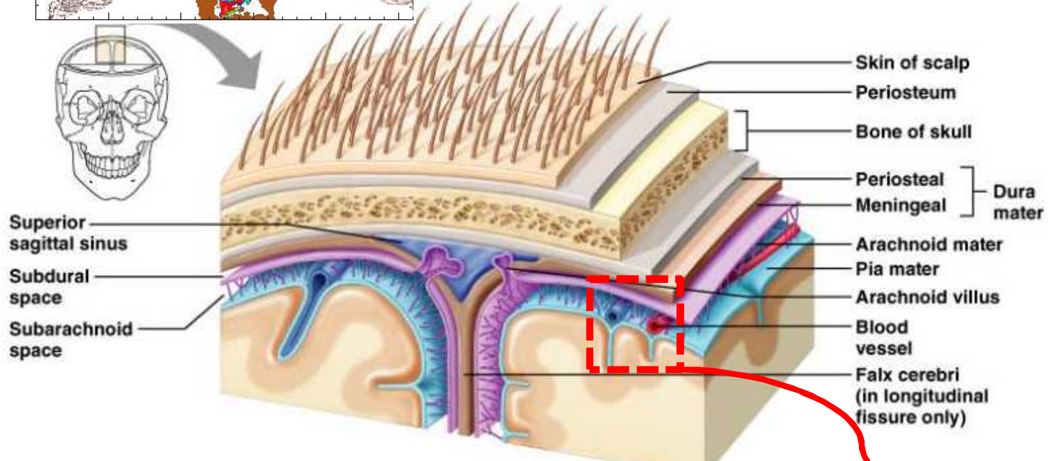
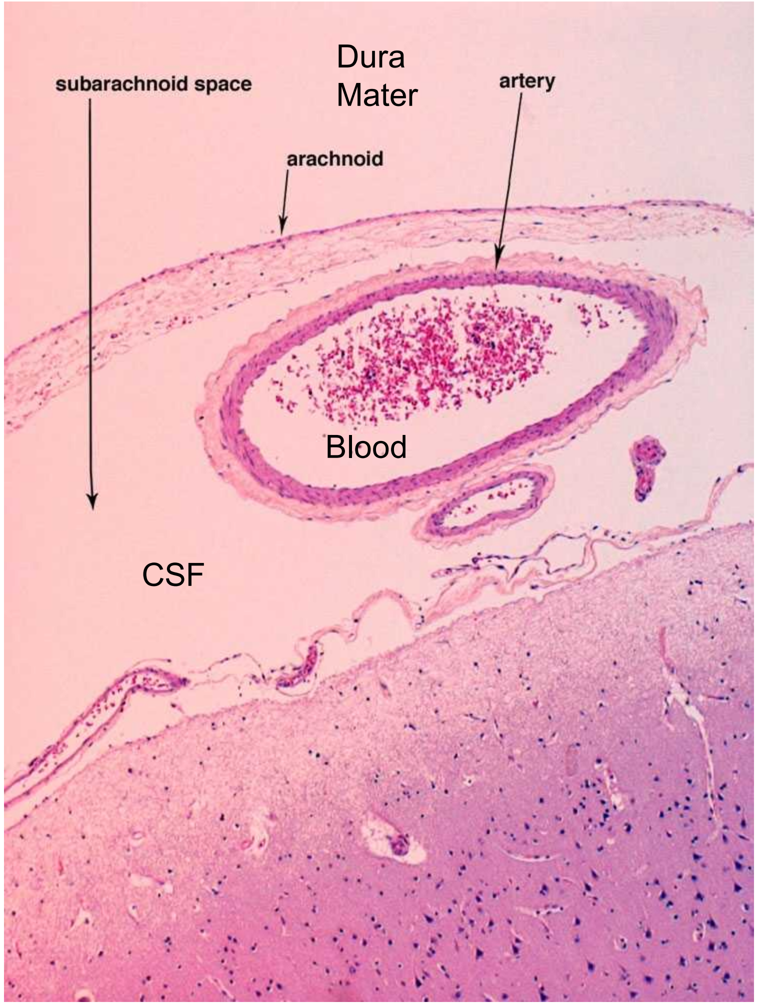
Cavitation in Superior Sagittal Sinus





Marieb, E. N., & Hoehn, K. (2007). Human Anatomy & Physiology (7th ed.). San Francisco: Pearson Benjamin Cummings

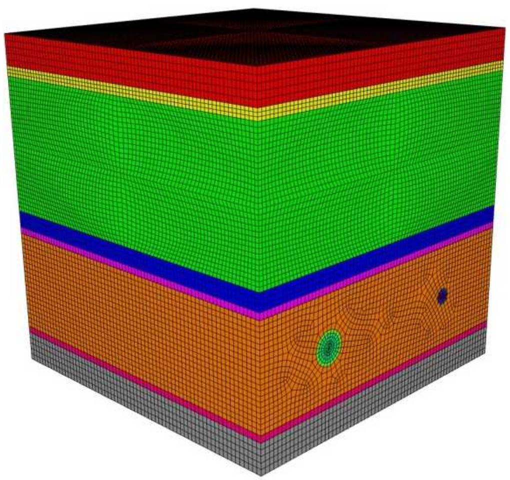


- Representative Volume Element
  Brain-Skull Interface
  - Focus on regions containing fluid
    - Subarachnoid Spacing
    - Sagittal Sinus
    - Arteries & Veins
  - Potential damage to Arachnoid Villi, blood cells, blood platelets (stroke potential)

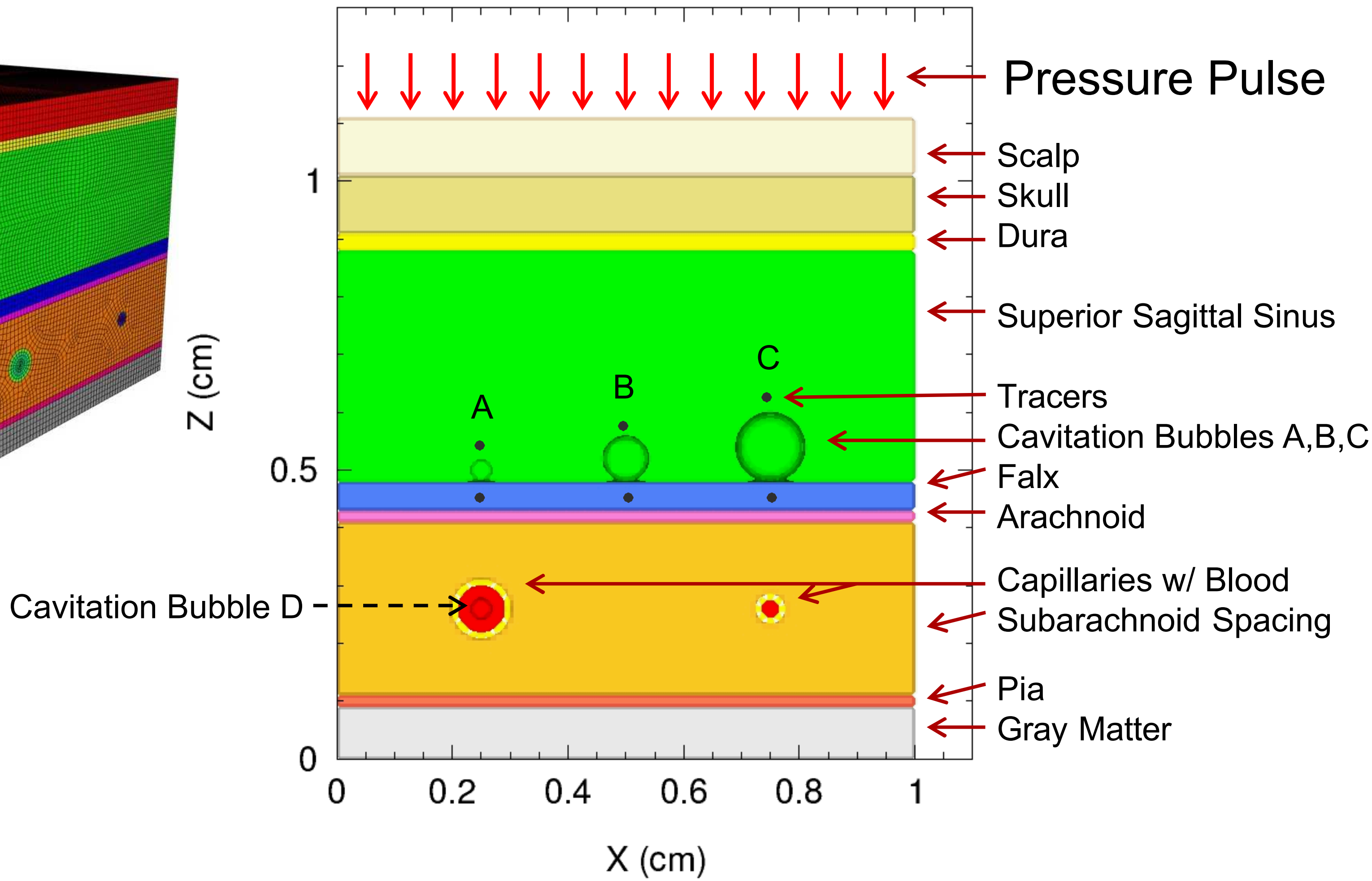
http://www.stonybrookmedicalcenter.org/pathology/neuropathology/chapter1

TBI Microscale Modeling

Superior Sagittal Sinus



Initial Configuration



Bubble Radii:
A: 0.2 mm
B: 0.4 mm
C: 0.6 mm
D: 0.2 mm

Parietal Superior Sagittal Sinus Microscale Model Intracranial Stress Wave caused by 260 KPa Side Blast

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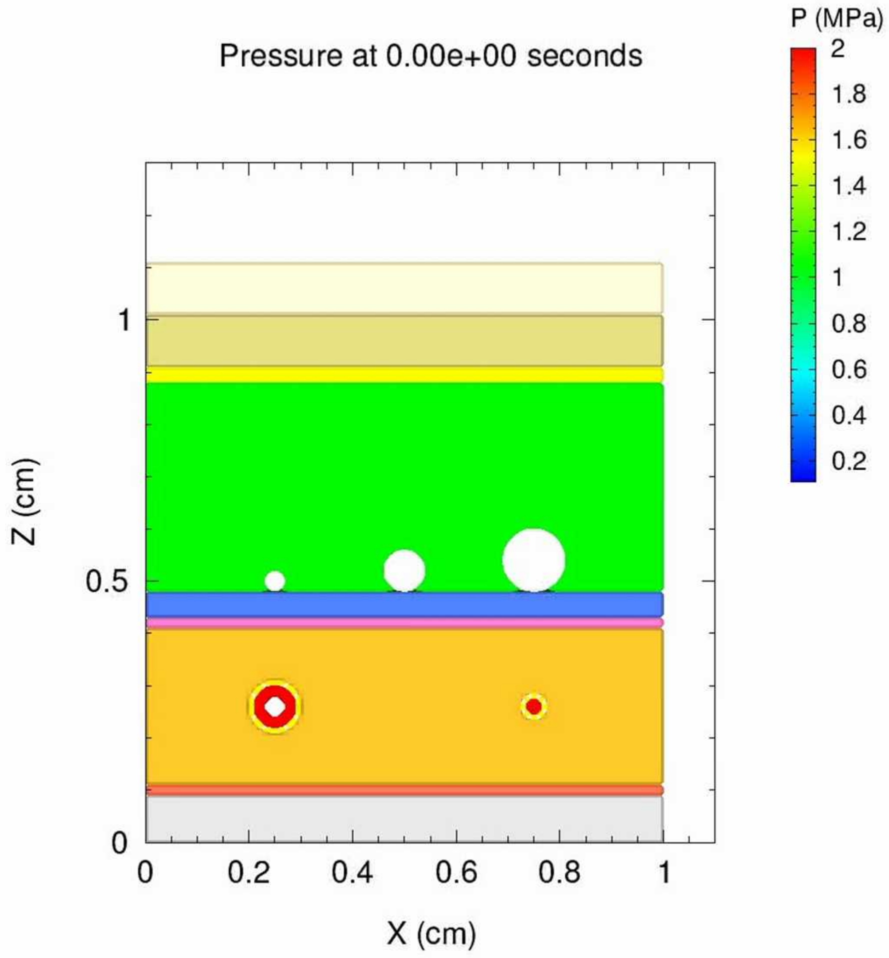

Results of Study:

- Effects of cavitation bubble collapse:
  - Generation of high pressure region around bubble site
  - Microjetting of fluid surrounding bubble in downstream direction
  - Significant levels of shear stress downstream from bubble
  - → Shearing of tissue downstream
- These effects dependent on:
  - Strength of intracranial stress wave (related to blast strength)
  - Bubble diameter
  - Internal bubble pressure
- Results of this microscale study published in paper to appear in Proceedings of the 2015 IMECE Conference, Houston, TX, 2015

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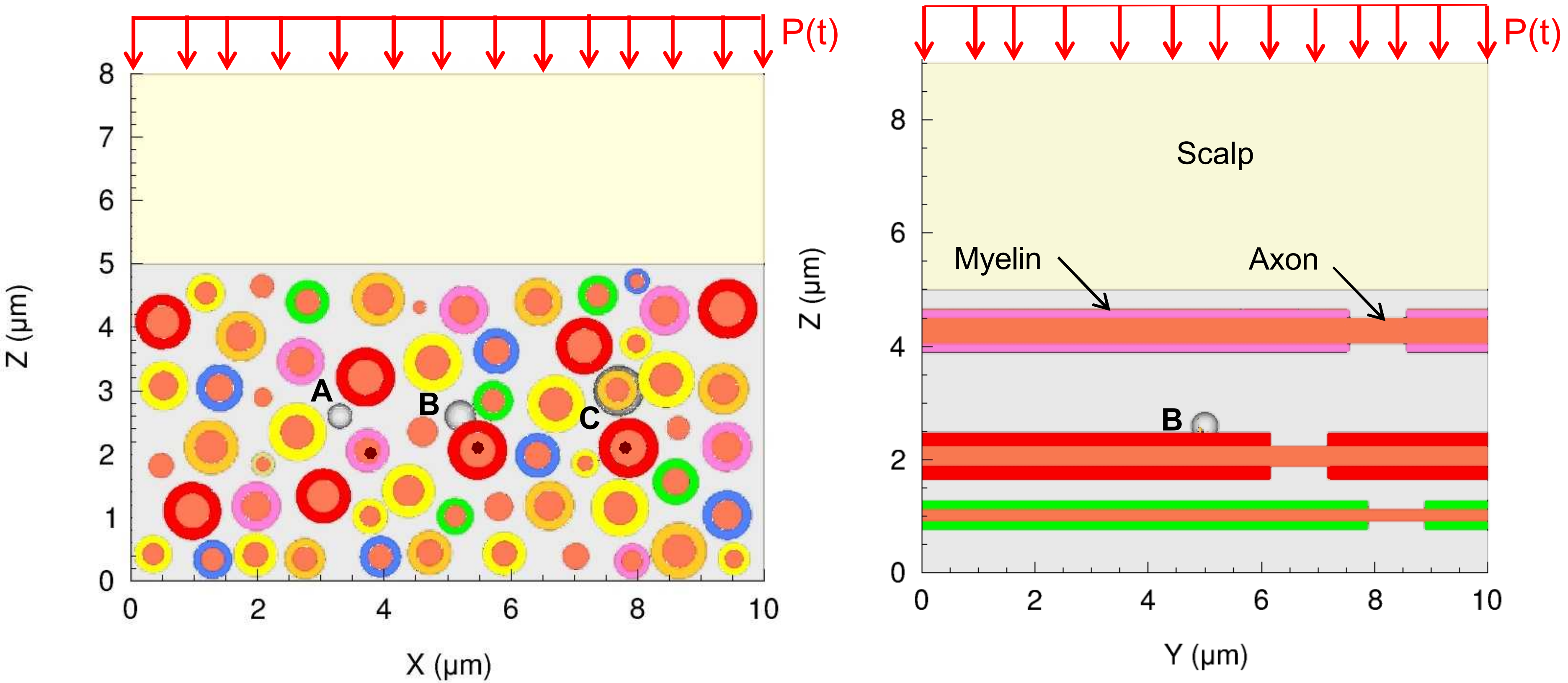
Thank You!

Backup Slides

Microscale model of the White Matter Axonal Fiber Bundle

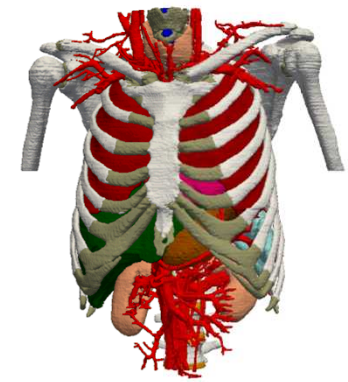


- Axon Statistics: volume fraction = 52%, average diameter = 1 μm
- 3 Cavitation bubbles (A, B, & C) demonstrating different scenarios:
    1. Bubble A (0.4 μm dia.) in CSF not touching axons
    2. Bubble B (0.5 μm dia.) adjacent to an axon
    3. Bubble C (0.8 μm dia.) fully encapsulating axon

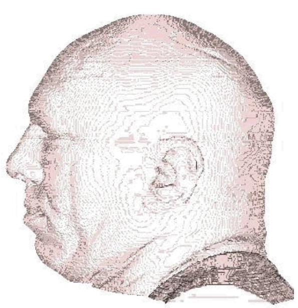
Background

- 2008-2009 Early blast modeling using partial head model
- Current Head/Neck Model Developed
- Prototype Helmet Digitized

- Torso Model Developed



2012 **2014** **2015**



- Blast Modeling
- Blunt Trauma Modeling
- Combined Head/Neck/Torso Modeling (Blast and Blunt Trauma)
- Micromechanical Models In Development