Terminal Ballistics Technology
TBT
Target Protect
Target Defeat

SAND2012-0751C

SAND2012-0751C

# Simulation of Blast-Induced, Early-Time Intracranial Wave Physics leading to Traumatic Brain Injury & its Mitigation by Various Helmet Designs

Paul Taylor, Ph.D.
Terminal Ballistics Technology Department
Sandia National Laboratories

Collaborators:

John Ludwigsen, Ph.D.
Terminal Ballistics Technology Department
Sandia National Laboratories

Corey C. Ford, M.D., Ph.D.
Andrei Vakhtin, B.A.
Neurology Department
University of New Mexico Health Sciences Center

This work funded through the U.S. Naval Health Research Center, Office of Naval Research
Mr. James MacKiewicz, project funding manager

NNSA
National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Terminal Ballistics Technology
TBT
Target Protect
Target Defeat

# Traumatic Brain Injury (TBI)
## Sandia Focus: Military Relevance

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

- Blast Injury categories:
  - Primary: direct exposure to explosion-produced air blast
  - Secondary: impact by flying objects thrown by air blast
  - Tertiary: impact into stationary object (soldier thrown by air blast)
- Our focus is on Primary Blast Injury and investigating mechanisms associated with brain injury
  - Once know, want to mitigate blast mechanisms through helmet 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.

Sandia National Laboratories

# Overall Project
## Tasks & Goals

- Correlate M&S predictions with clinical assessment of TBI
  - Create high resolution full head-neck model for blast & impact simulations (SNL)
  - Conduct clinical assessments of blast TBI subjects (UNM)
    - Neuropsychological testing
    - Magnetic resonance analyses

    } In collaboration with Corey Ford, MD, PhD
    UNM Health Sciences Center
  - Perform simulations of blast scenarios that mimic conditions experienced by TBI subjects
  - Establish correlation between simulation predictions of intracranial wave mechanics & localized brain injury observed in TBI case histories
    - → *Brain Injury Threshold Criterion* (BITC)
- Employ BITC and M&S tools to aid in design of head protection gear to mitigate blast loading conditions leading to TBI
  - BITC provides threshold conditions leading to TBI in *absolute terms*
- However, we can assess protective merits of helmet design in *relative terms*

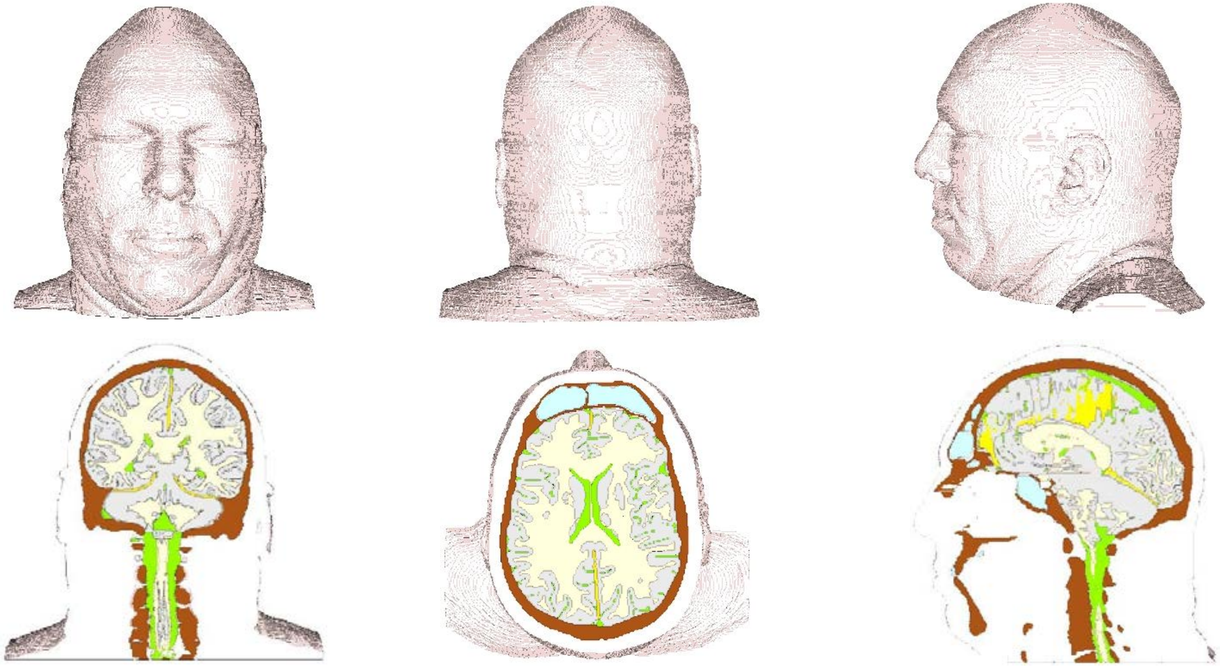
# Modeling & Simulation

## Development of Head-Neck Model

- Constructed 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:

Coronal, Axial, & Sagittal Cuts:



Model Size: 5.9M Cells

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

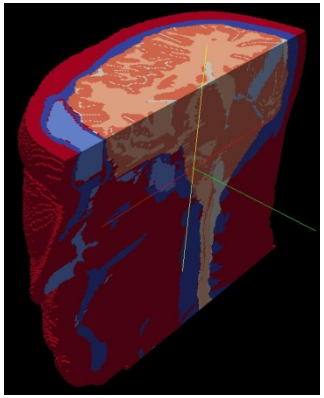
Terminal Ballistics Technology

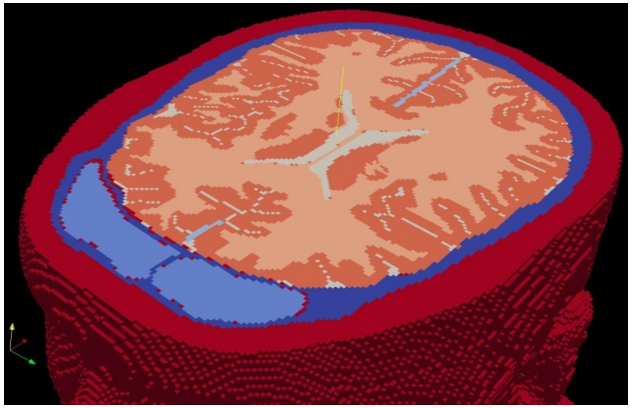
TBT Target Protect Target Defeat

# Modeling & Simulation

## Development of Head-Neck Model

- Constructed Finite element version of head-neck model
  - Possesses anatomically correct distributions of white & gray brain matter, cerebral spinal fluid/blood, bone, falx & tentorium membranes, muscle/scalp
  - 5.9 million hex elements
    - Brain: 1.4M elements (1.4 L)
      - GM: 794K
      - WM: 509K
      - Falx/Tentorium: 21K
      - CSF/Blood: 89K
    - Sinus: 98K elements (0.098 L)
    - Bone: 749K elements (0.75 L)
    - Scalp/Muscle: 3.6M elements (3.6 L)
  - For use in Lagrangian finite element simulations and coupled Eulerian-Lagrangian simulations

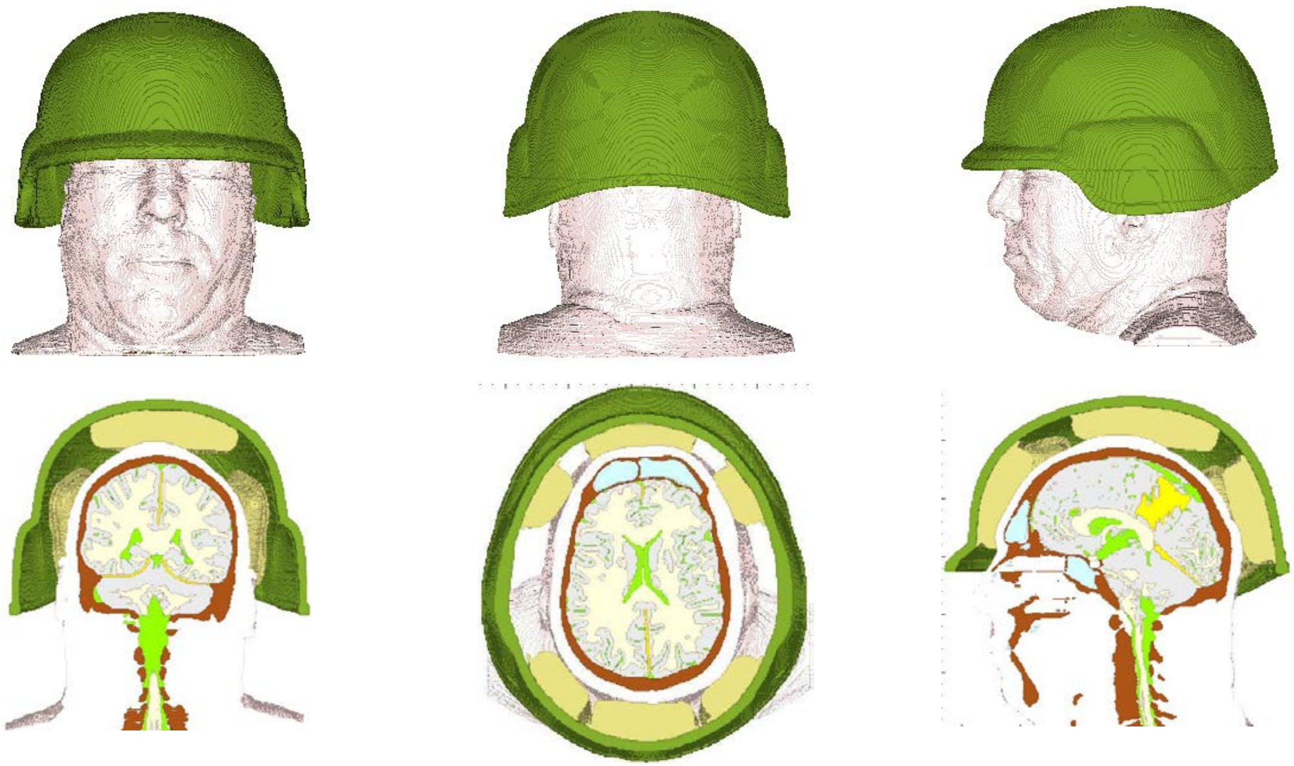


Sandia National Laboratories

# Modeling & Simulation

## Development of Helmet Model

- Constructed representation of military helmet
  - Helmet shell: Kevlar Composite
  - Pads: Polyurethane Foam Pads
  - Strapping removed; Not necessary in timeframe of interest (3-4 ms)
    - Helmet moves only 3-4 mm during course of our simulations



# Modeling & Simulation

## Model Development

- Selection/Implementation of constitutive models
  - Biological Materials
    - White & Gray Matter - Finite Elastic, Linear Viscoelastic models [4]
    - Bone - Linear Elastic model w/ Fracture [4,5]
    - Falx & Tentorium (membranes) – Finite Elastic models [4]
    - Muscle & Scalp - Finite Elastic models [4,6]
    - Cerebral Spinal Fluid (CSF) – Non-Linear Compressible model (EOS)
    - Sinus Air (and surrounding air) - Non-linear Compressible model (EOS)
  - Military Helmet
    - Helmet Shell - Composite model [7]
    - Helmet Pads - Finite Elastic foam model [7]

[4] Zhang, L., Yang, K.H., & King, A.I., 2001, "Comparison of Brain Responses between Frontal and Lateral Impacts by Finite Element Modeling," J. Neurotrauma **18**(1), pp. 21-30.
[5] Carter, D.R., 1985, "Biomechanics of Bone," Biomechanics of Trauma, Appleton-Century-Crofts, Norwalk, CT, pp. 135-165.
[6] Mak, A.F.T. & Zhang, M., 1998, "Skin and Muscle," in Handbook of Biomaterial Properties, ed. J. Black & G. Hastings, Chapman & Hall, London, pp. 66-69.
[7] Nyein, M.K., Jason, A.M., Yu, L., Pita, C.M., Joannopoulos, J.D., Moore, D.F., & Radovitzky, R.A., 2010, "In silico investigation of intracranial blast mitigation with relevance to military traumatic brain injury," Proc. Nat. Acad. Sci. **107**(48), pp. 20703-20708.

# Modeling & Simulation

## Simulation Methodology & Validation

- Simulation Methods
  - Eulerian methods using CTH (w/ finite volume model)
  - Lagrangian-Eulerian coupled methods using Presto/CTH (w/ finite element model)
    - Loose coupling (1-way passing of node pressure histories to Finite Element Analysis)
    - Tight coupling (2-way interaction between Eulerian & Lagrangian analyses)
- Head/Neck Model Validation
  - Compared Simulation predictions with laboratory data
    - Magnetic Resonance Elastography & Tagging data on the human head (in vivo) courtesy of Prof. Philip Bayly and team, Washington University at St. Louis, MO USA
    - Laboratory blast data on Human Surrogate Head Model courtesy of JHU Applied Physics Laboratory, PoC: Andrew Merkle

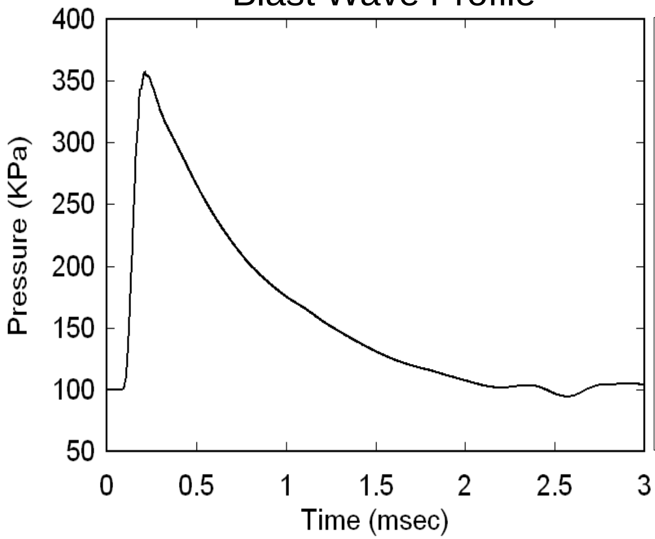
# Modeling & Simulation

## Example: 3.6 bar (360 KPa) Blast

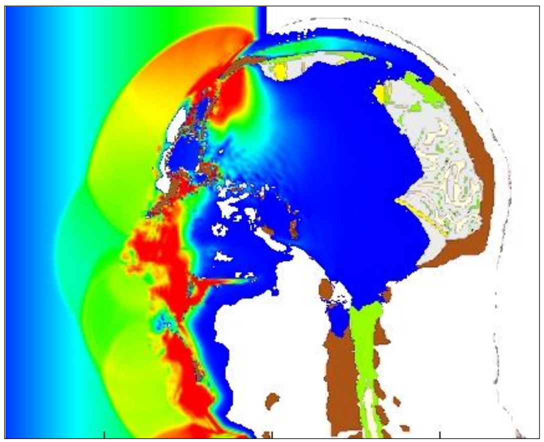
### Snap-Shot Images of Blast-Induced Pressure Wave Propagating through Head

Time ~ 130 μs after blast wave encounters head

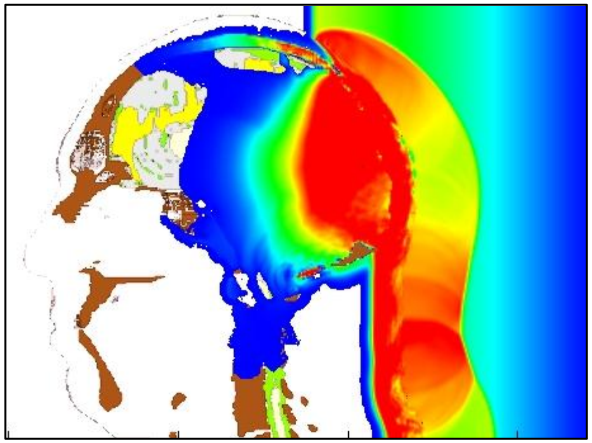
Blast Wave Profile



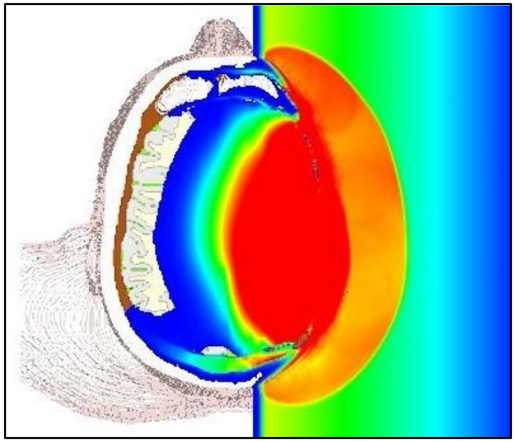

Frontal Blast

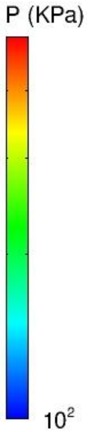


Rear Blast



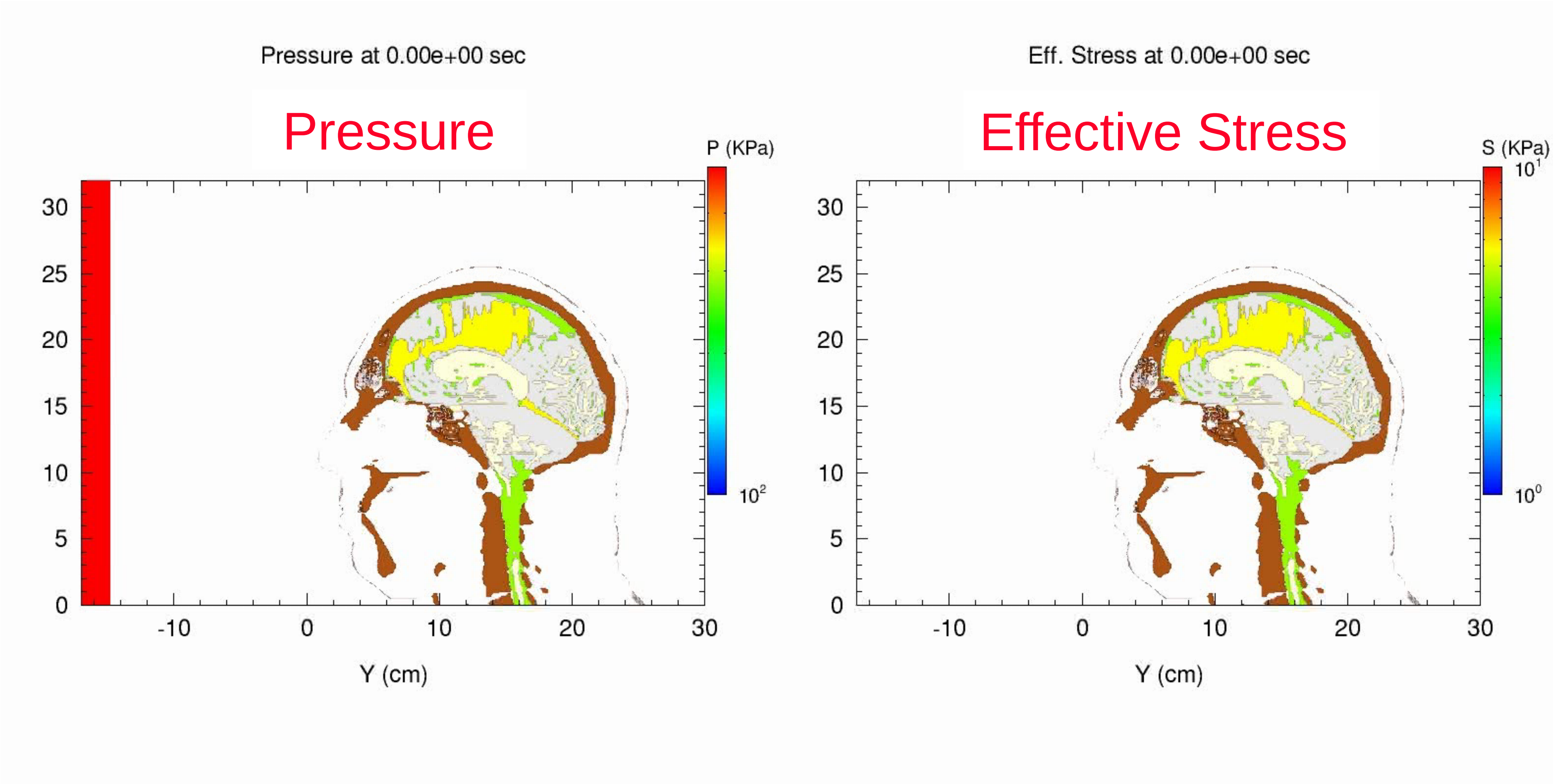
Side Blast





# Modeling & Simulation

## 3.6 bar Frontal Blast Exposure: mid-Sagittal Plane

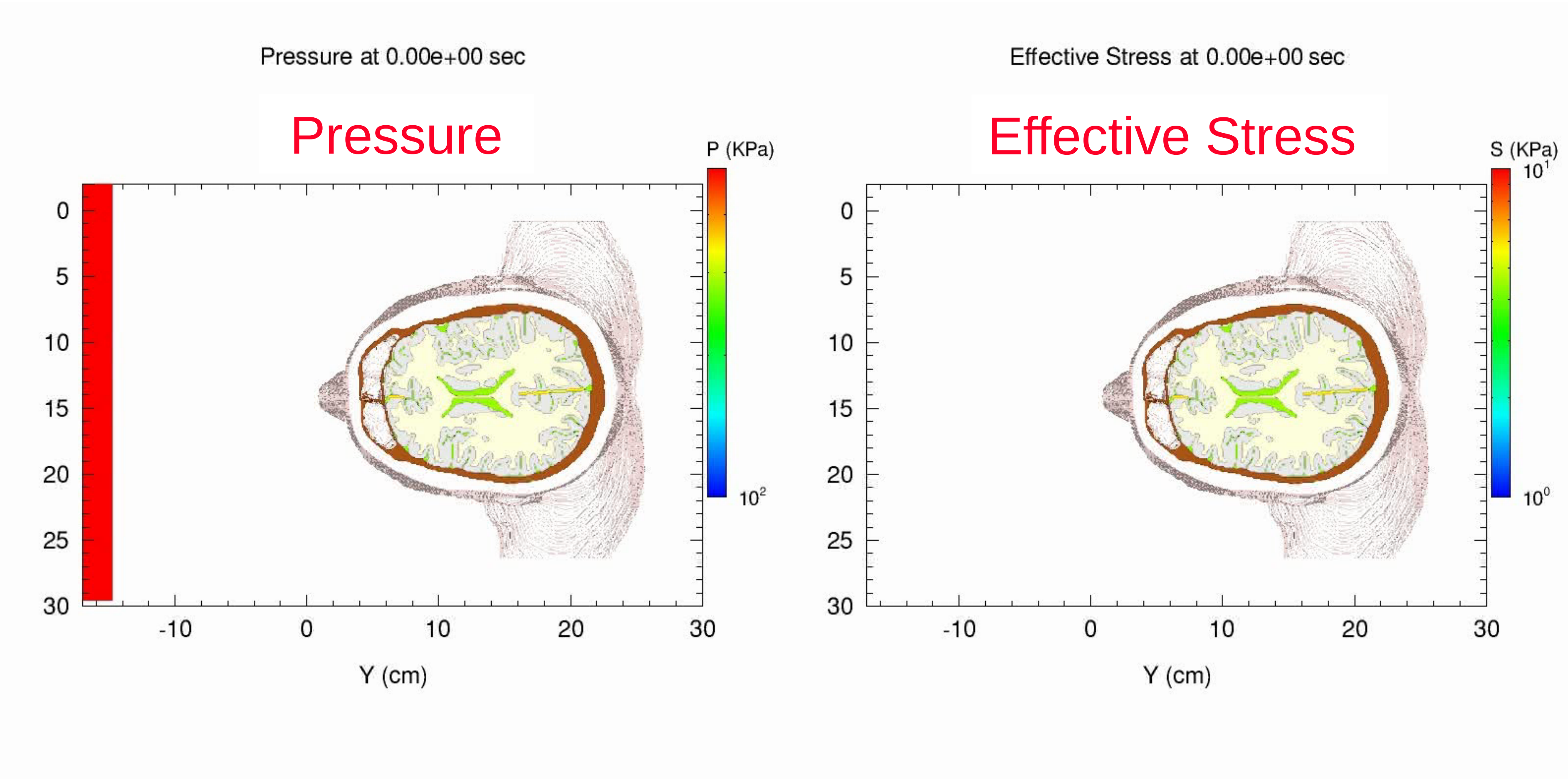



Note: Run Videos Simultaneously

Terminal Ballistics Technology

# Modeling & Simulation

## 3.6 bar Frontal Blast Exposure: Axial Plane above Eyes




Note: Run Videos Simultaneously

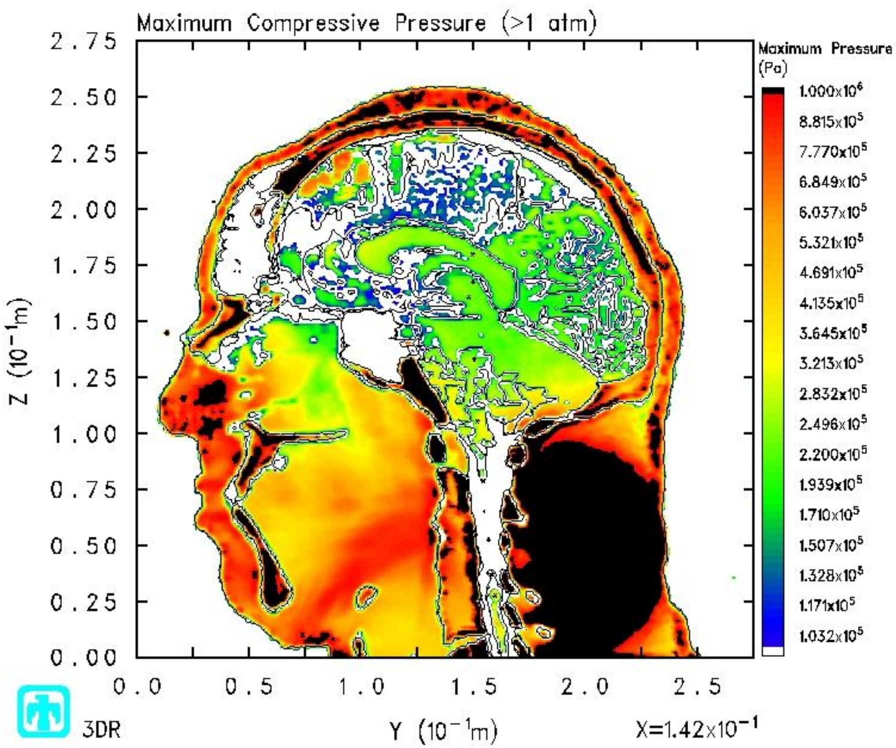
Sandia National Laboratories

# Modeling & Simulation

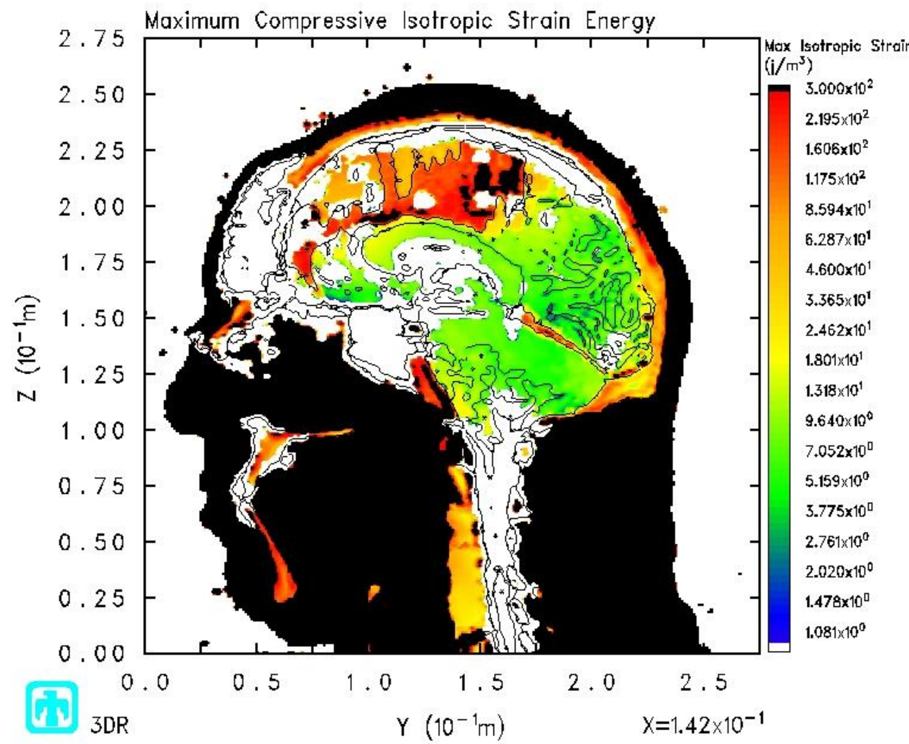
## 3.6 bar Frontal Blast Exposure: Energy vs. Pressure

Does Isotropic Energy display greater differentiation than Pressure?
-- Compressive Isotropic Energy associated with volumetric "Crush"

Maximum Compressive Pressure




Compressive Isotropic Energy



# Modeling & Simulation

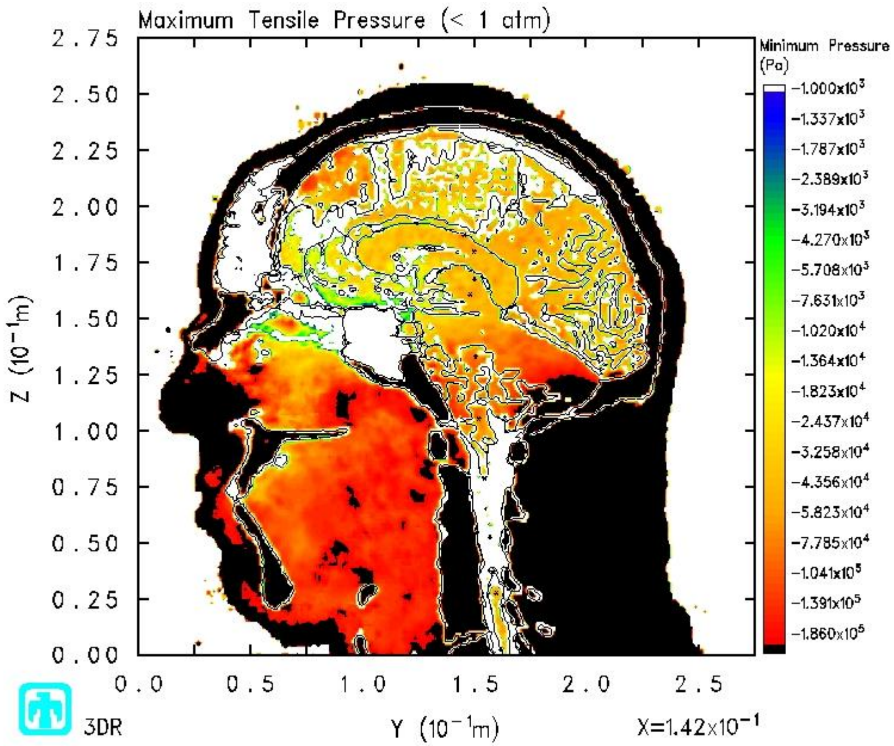
## 3.6 bar Frontal Blast Exposure: Energy vs. Pressure

Does Isotropic Energy display greater differentiation than Pressure?

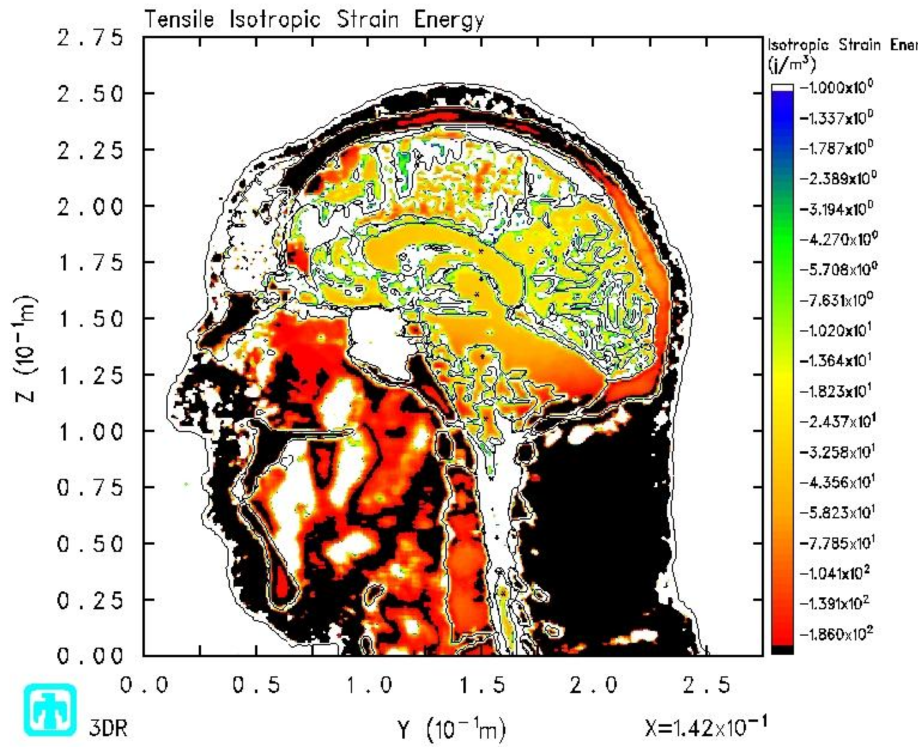
-- Tensile Isotropic Energy associated with volumetric "Dilatation"

- Dilatation gives rise to Cavitation

Maximum Tensile Pressure




Tensile Isotropic Energy

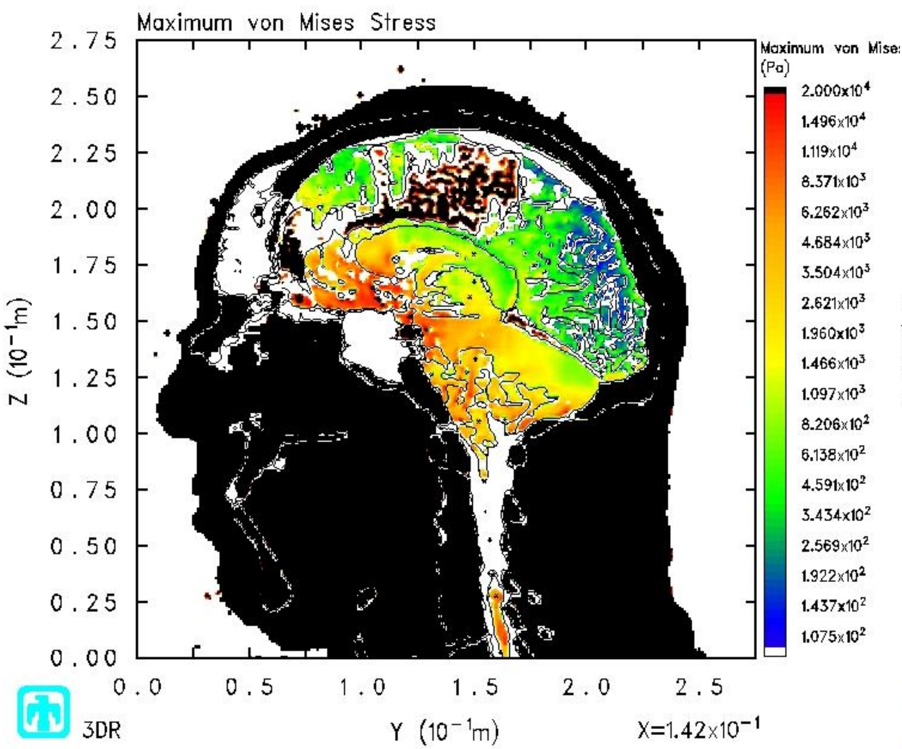


# Modeling & Simulation

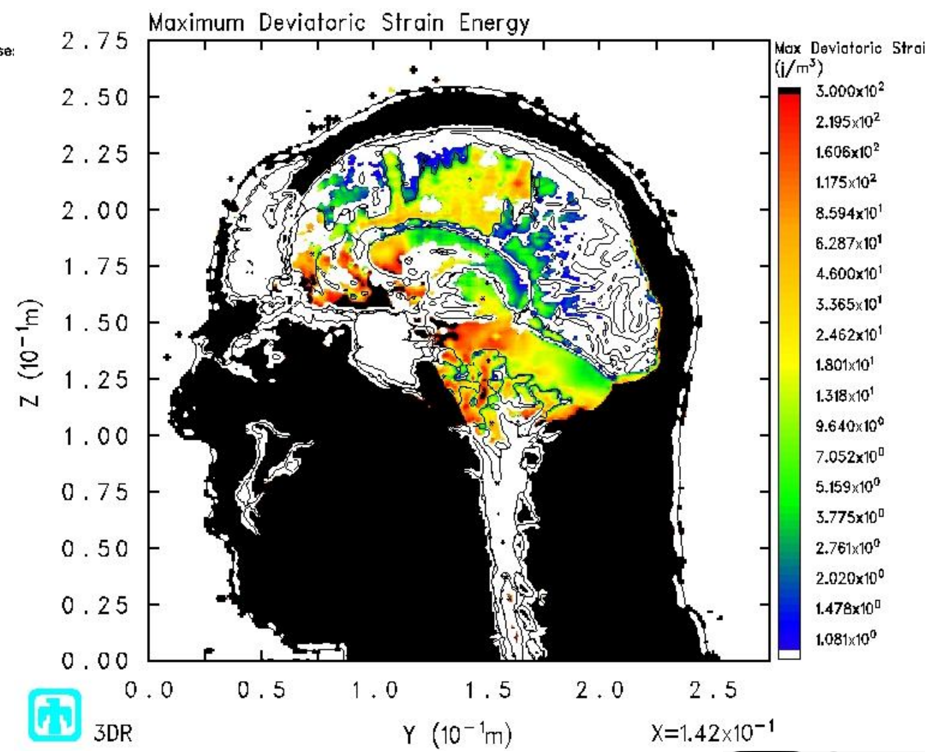
## 3.6 bar Frontal Blast Exposure: Deviatoric Energy vs. Stress

Does Deviatoric (Shear) Energy display greater differentiation than Shear Stress?
-- Deviatoric (Shear) Energy associated with “Tearing”

Maximum Deviatoric Stress




Maximum Deviatoric Energy



# Clinical Investigation of Traumatic Brain Injury

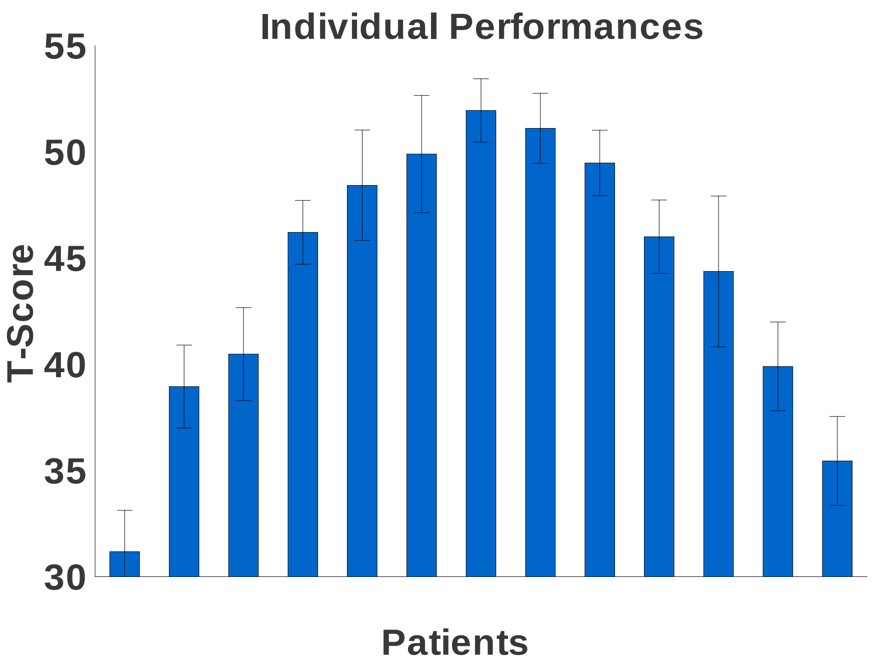
## Perform clinical assessments on blast & blunt impact victims

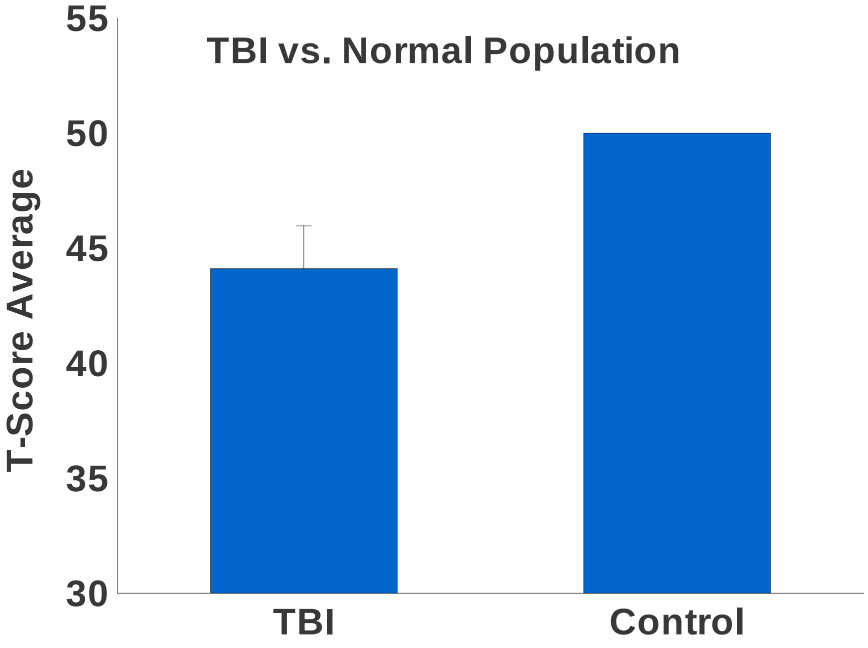
- Blast & blunt impact victims recruited
  - 17 Subjects w/ mild TBI
  - 13 blast exposure
    - 4 blunt impact
  - Subjects underwent Clinical Assessment:
    - Detailed history of insult event recorded
    - Neurocognitive assessment – 15 tests; examples include:
      - Wechsler Abbreviated Scale of Intelligence– Revised (WAIS)
        - Assesses Intelligence Quotient (IQ)
      - Paced Auditory Serial Addition Task (PASAT)
        - Tests memory, attention, information processing speed
      - Neurobehavioral Symptom Inventory & Checklist (NBI)
        - Asks about symptoms experienced since injury (e.g., dizziness and forgetfulness)
      - Beck Depression Inventory II (BDI-II)
        - Asks subject about feelings of sadness, frequency of crying
    - Functional Magnetic Resonance Imaging (fMRI) – shows promise
    - Diffusion Tensor Imaging (DTI) – no significant findings

# Neurocognitive Testing

## Comparison between Blast-Injured Subjects & Healthy Controls

- T-Scores averaged across all tests for 13 individual TBI subjects (left)
  - Gaussian distribution observed (min/max = 31.2/51.9, $\sigma$ = 6.5)
- Average TBI subjects' T-scores were lower than control population (right)



Terminal Ballistics Technology

# Clinical Diagnostic to Quantitatively Assess TBI

## Functional Magnetic Resonance Imaging (fMRI)

- What is it?
  - fMRI is an Magnetic Resonance-based imaging technique
- What does it do?
  - Measures Resting State Network (RSN) activity levels and connectivity between the RSN's
    - There are 28 independent RSN components divided into groups based on their anatomical and functional properties
    - Groups: Sensorimotor, Visual, Auditory, Attentional, Default-Model, Basal Ganglia, & Frontal Network

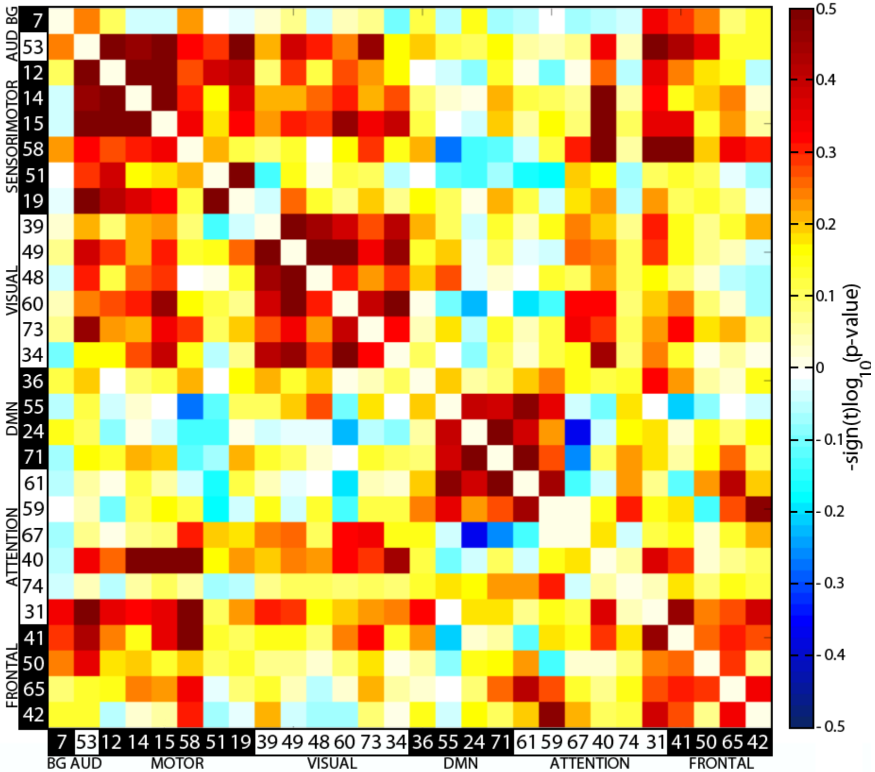
- How does one detect brain damage with fMRI?
- Identify significant differences in Resting State Network (RSN) activity and connectivity between TBI brain-injured subjects & a normal controls group
  - We identified the difference between 13 blast subjects and 50 age-matched healthy individuals from the normal controls group

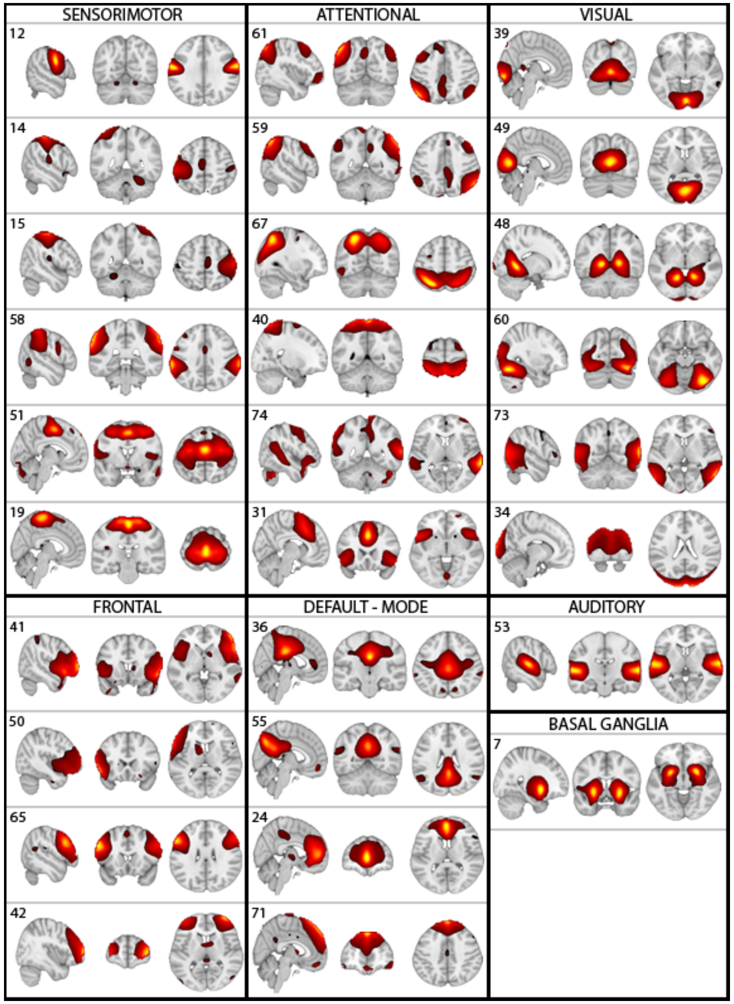
Sandia National Laboratories

# Functional MRI Results

## Independent Component Analysis (ICA) to measure RSN Activity & Connectivity

Identified 28 resting state networks and their functional connectivities across all 63 subjects



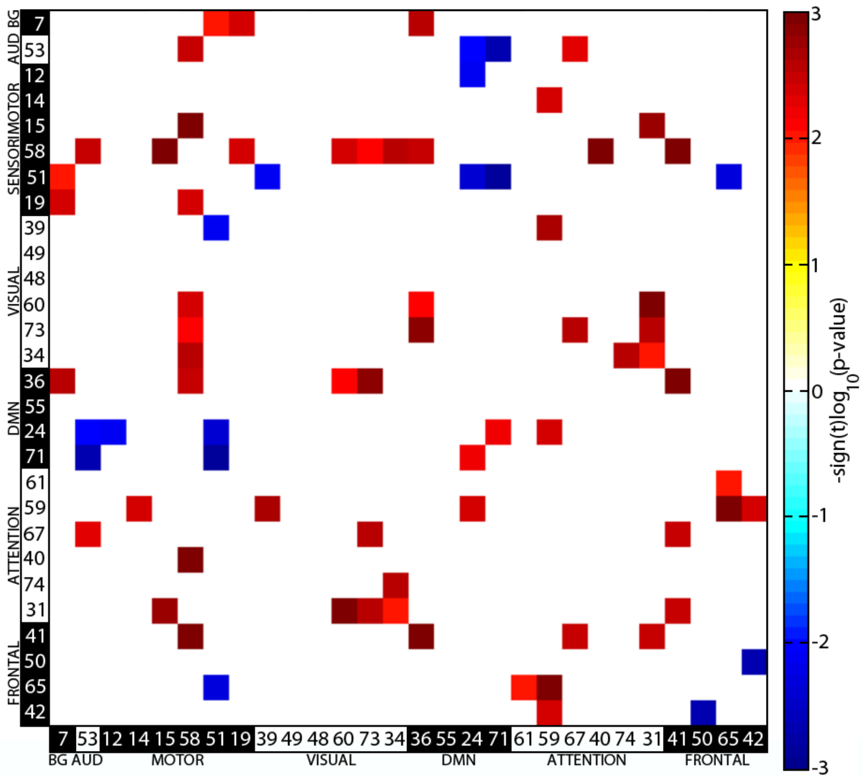



# fMRI Differences between TBI Subjects & Controls

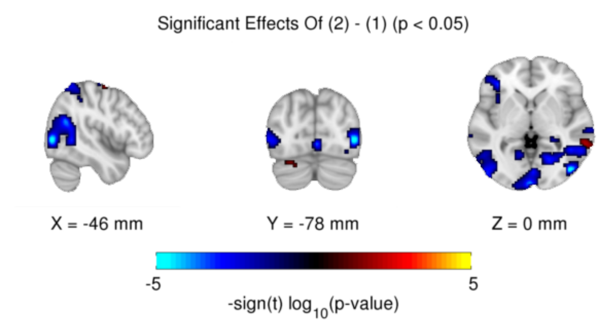
## Independent Component Analysis (ICA): Trending Results

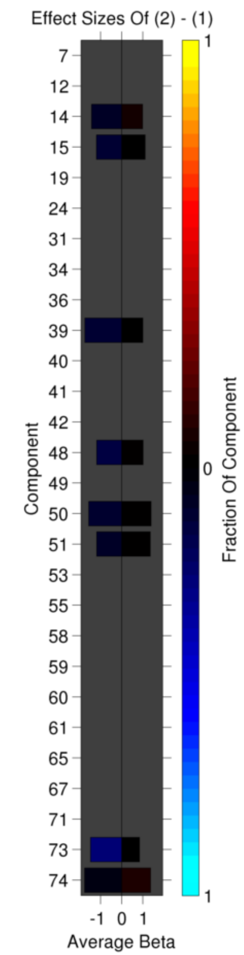
- Trending differences found in fractions of networks: Visual (73, 48, & 39), Attentional (74), Sensorimotor (14, 15, & 51), Frontal (50)

Trending FNC Differences (Controls minus TBI)




**Univariate Results (Spatial maps)**



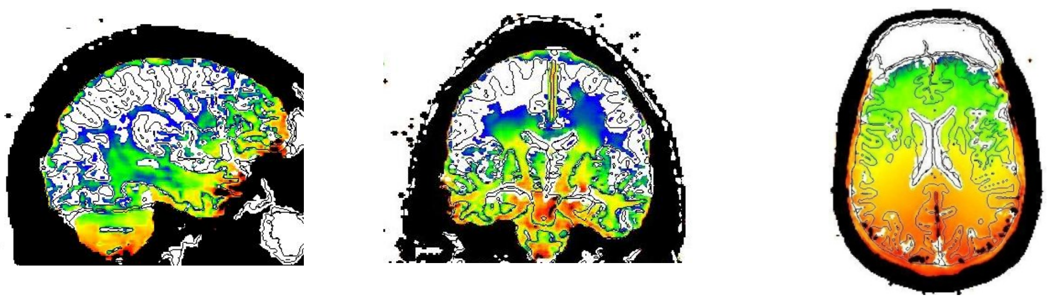
# Current Focus

## Correlate M&S Predictions with fMRI Data

- M&S: Conduct Blast Simulation sequence covering various conditions
  - Blast Direction
  - Blast Amplitude
- Clinical: Collect Averaged fMRI Data over all TBI subjects
  - Functional MRI (fMRI): to detect changes in brain associated w/ Sensorimotor, Visual, Auditory, Attention, Default Mode, etc.
- Goal: Correlate M&S Predictions w/ fMRI Data
  - Which variable(s) best correlate? Stress amplitude, Energy, Power?

Blast Simulations

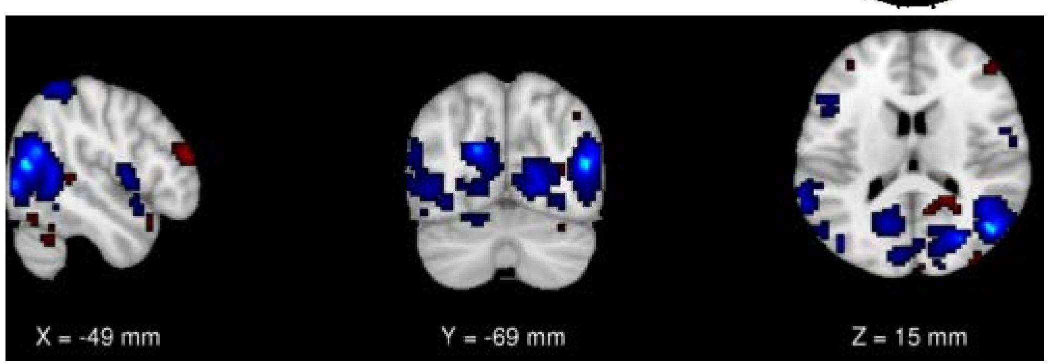
High Energy Deposition regions:



Possible Correlation?

fMRI Analysis of TBI subjects

Damaged regions:



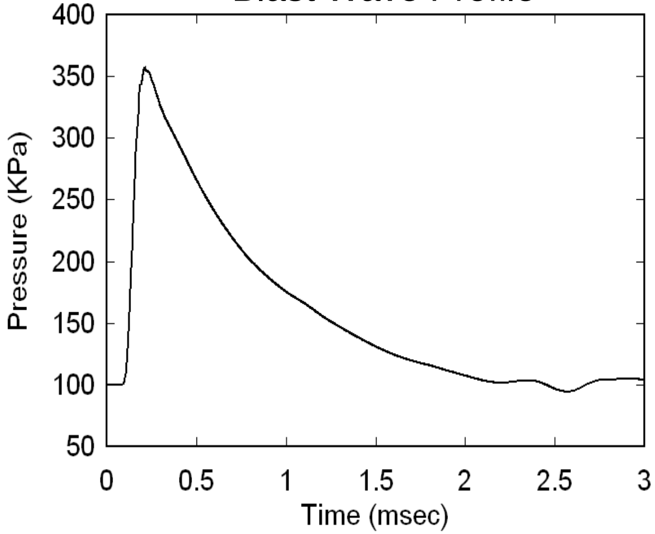
# Relative Merit Helmet Protection Simulation

## Helmet Protection from 3.6 bar (360 KPa) Blast

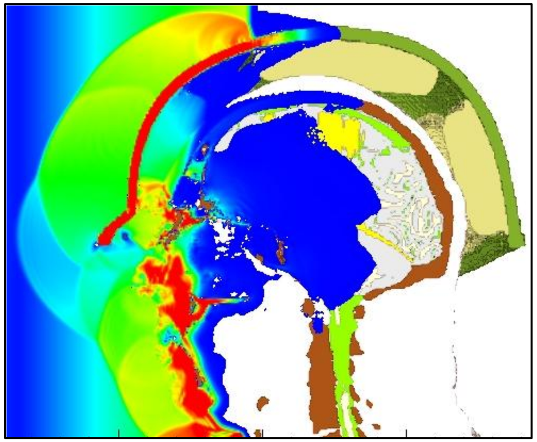
Snap-Shot Images of Blast-Induced Pressure Wave Propagating through Head

Time ~ 200 $\mu$s after blast wave encounters helmet

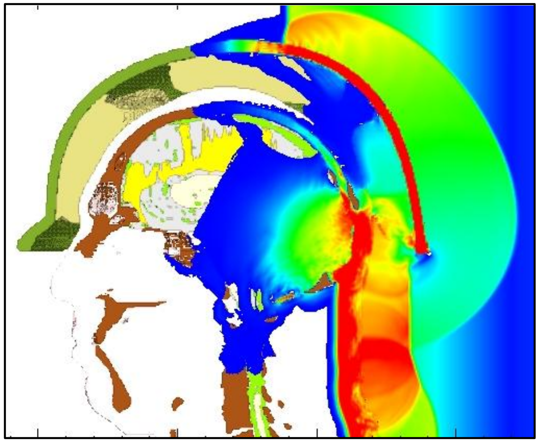
Blast Wave Profile



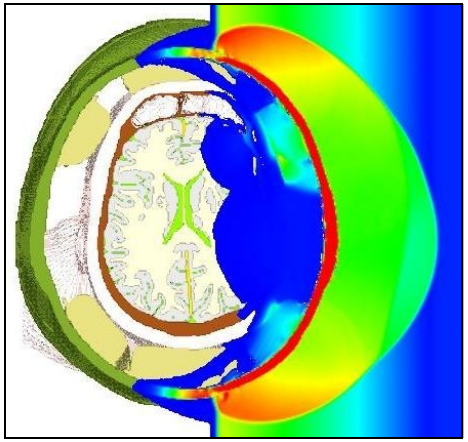

Frontal Blast

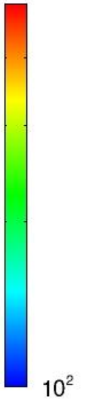


Rear Blast



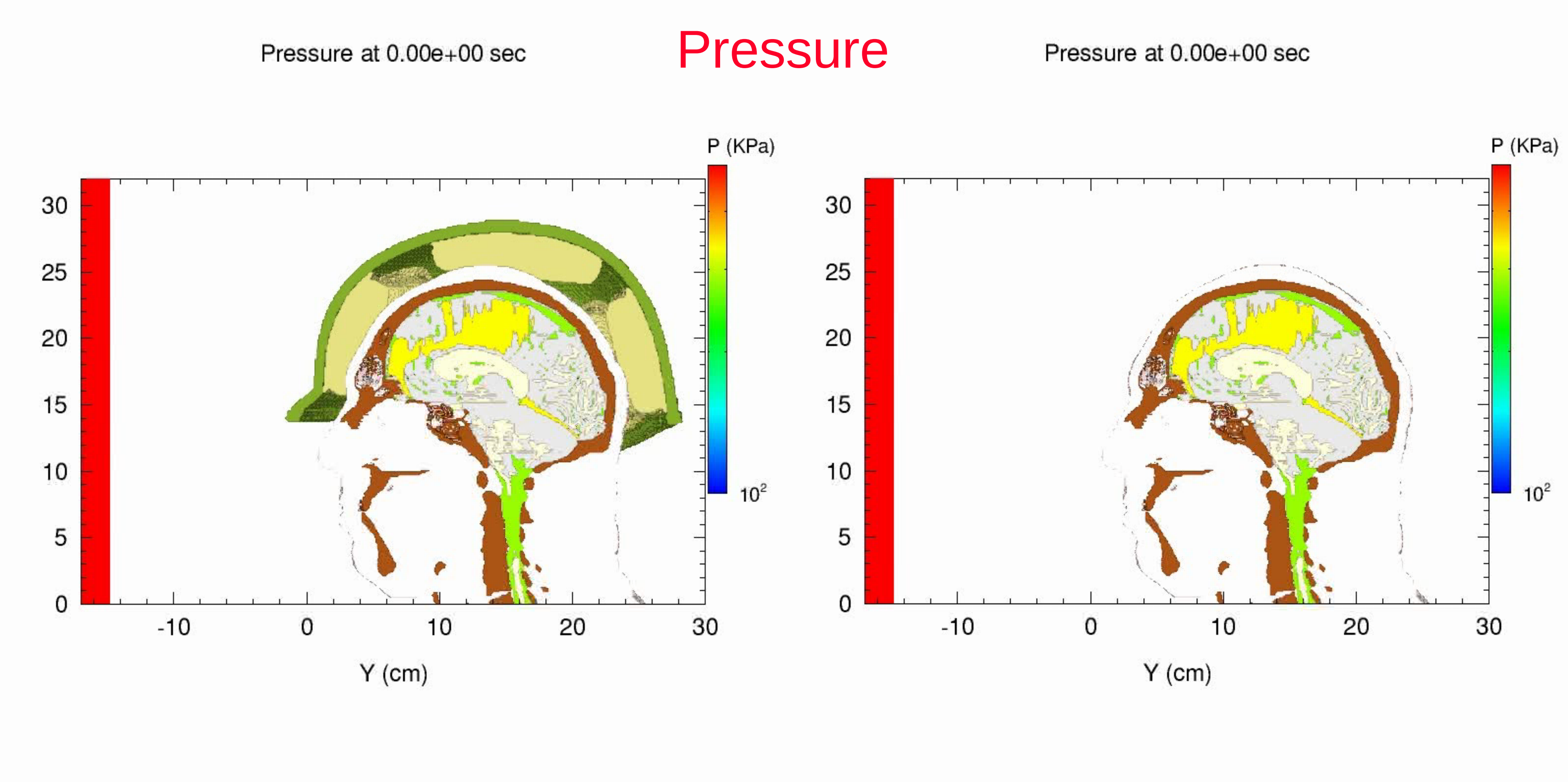
Side Blast





# Relative Merit Helmet Protection Simulation

## 3.6 bar Frontal Blast: mid-Sagittal Plane

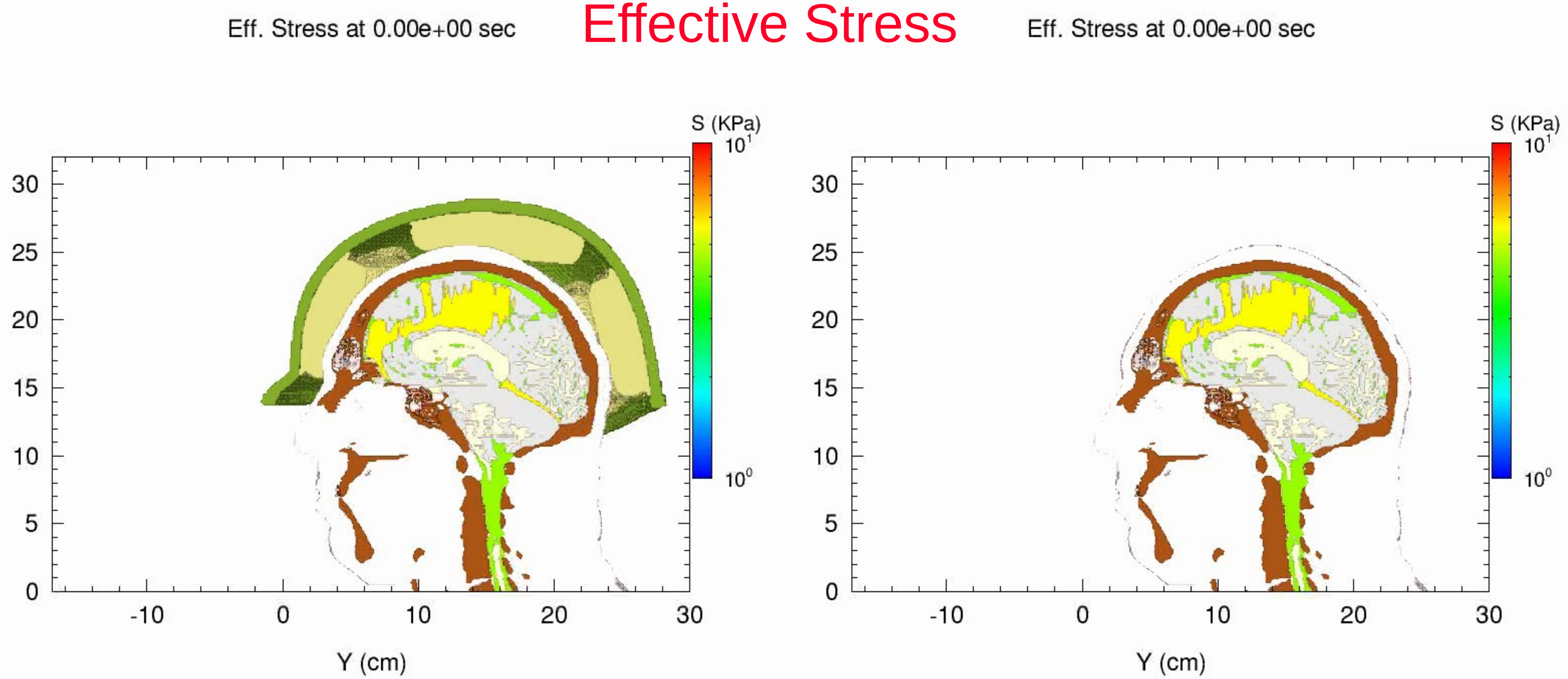



Note: Run Videos Simultaneously

# Relative Merit Helmet Protection Simulation

## 3.6 bar Frontal Blast: mid-Sagittal Plane

### Effective Stress



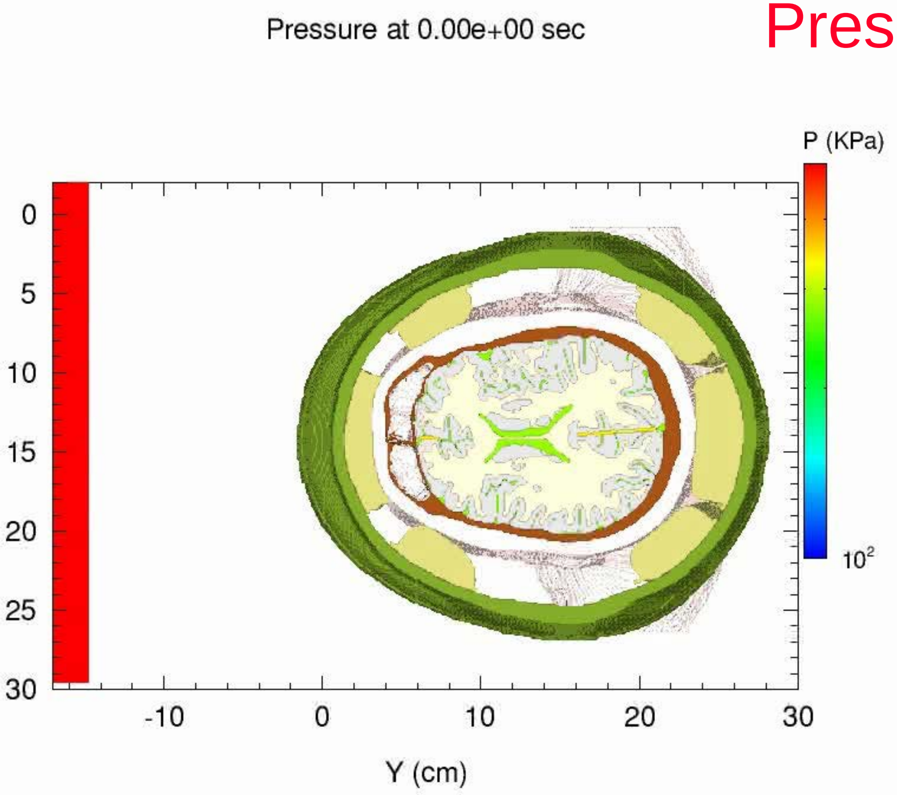

Note: Run Videos Simultaneously

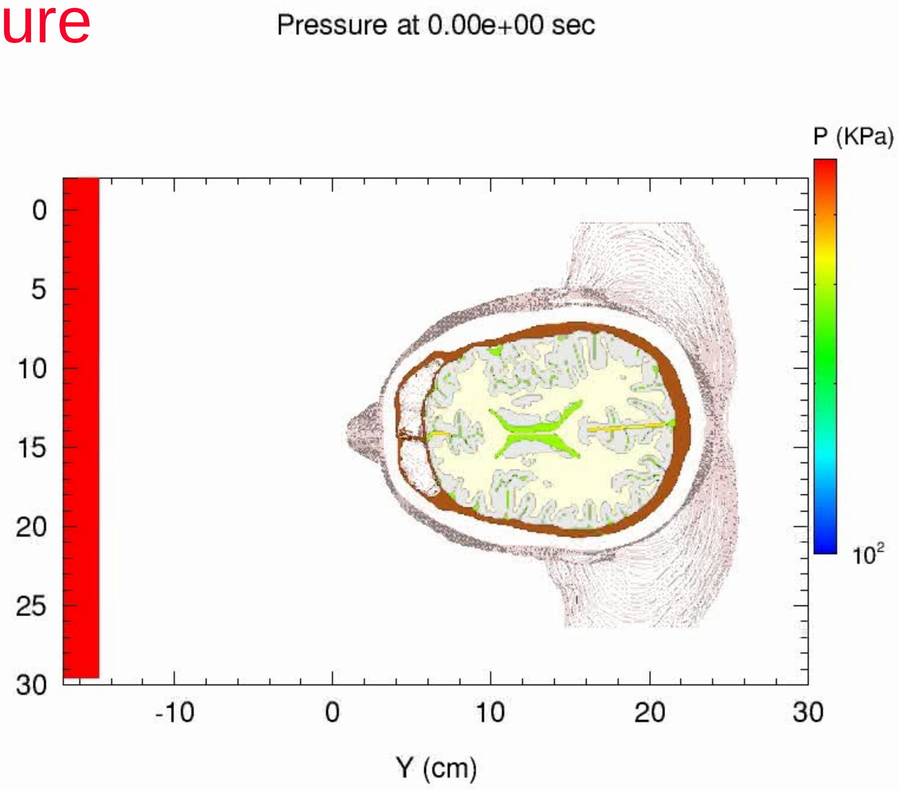
Terminal Ballistics Technology

# Relative Merit Helmet Protection Simulation

## 3.6 bar Frontal Blast : Axial Plane above Eyes

Pressure



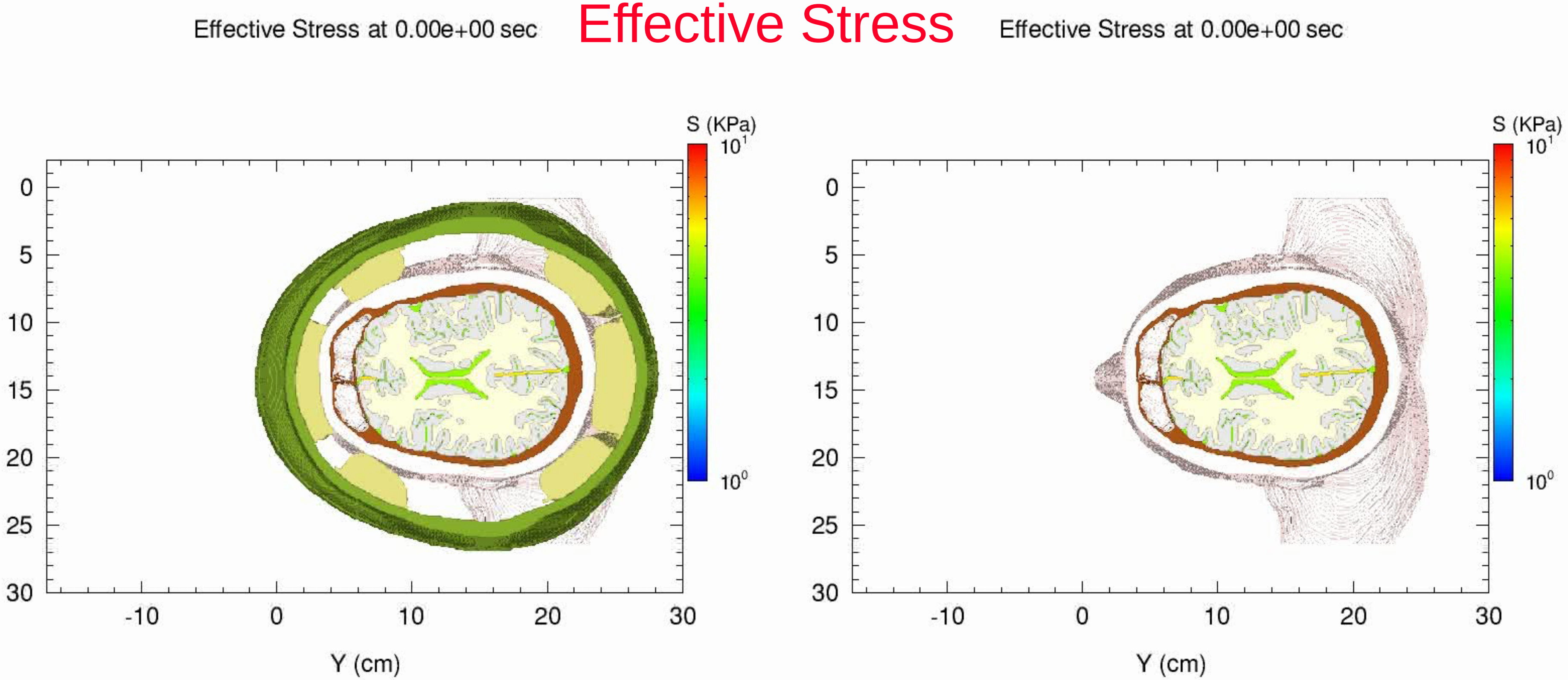

Note: Run Videos Simultaneously

Sandia National Laboratories

# Relative Merit Helmet Protection Simulation

## 3.6 bar Frontal Blast : Axial Plane above Eyes

### Effective Stress



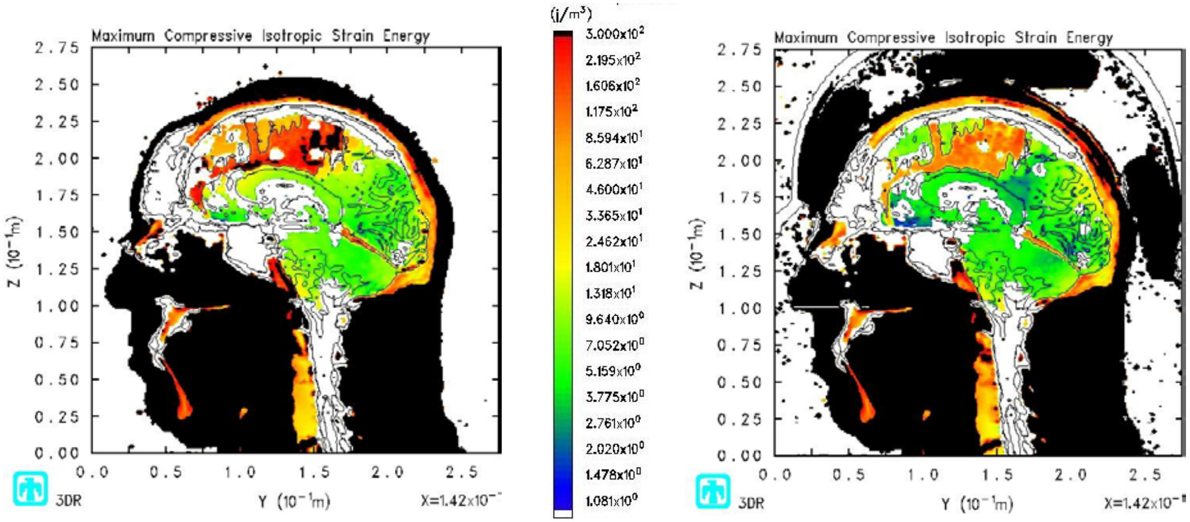

Note: Run Videos Simultaneously

# Blast Mitigation Effects of Helmet Protection

## 3.6 bar Frontal Blast Exposure: Isotropic Strain Energy Maxima

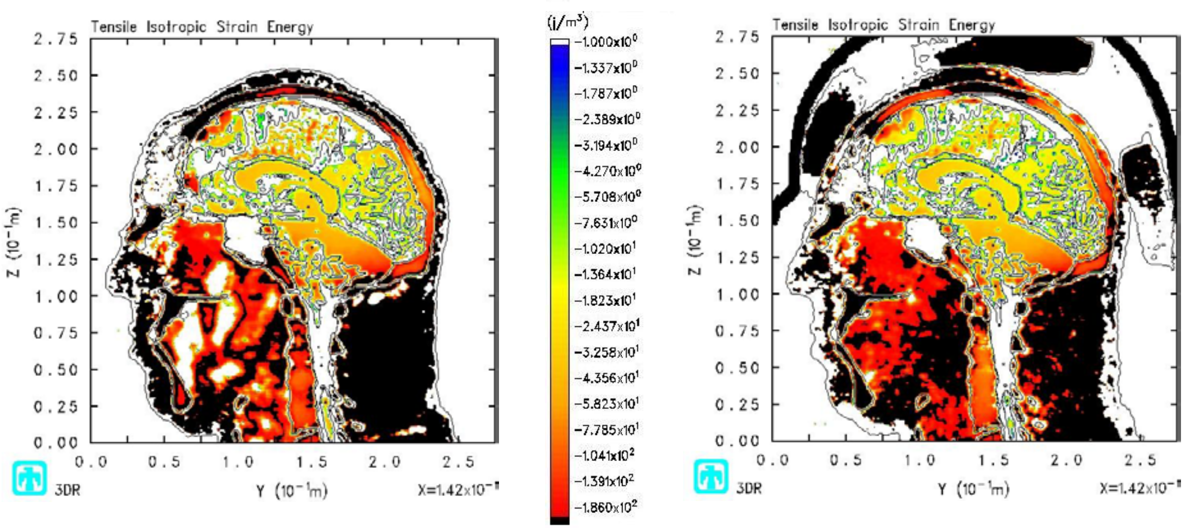
Compressive Isotropic Strain Energy

"Crush"




Tensile Isotropic Strain Energy

"Dilatation" (leads to Cavitation)

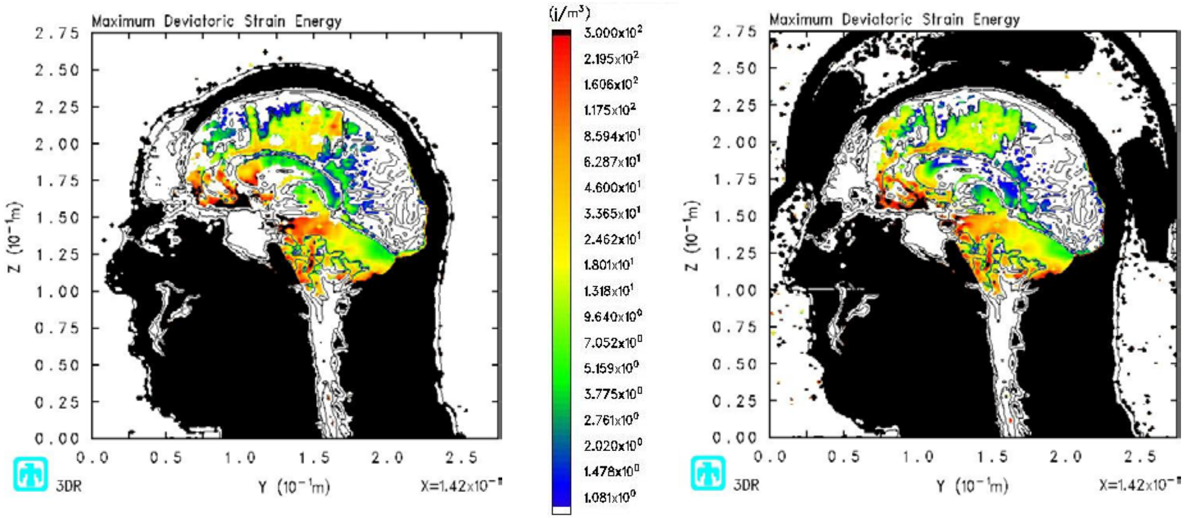


# Blast Mitigation Effects of Helmet Protection

## 3.6 bar Frontal Blast Exposure: Deviatoric Strain Energy Maxima

Deviatoric Strain Energy

"Tearing"




- For frontal blast, we predict Helmet:
  - Reduces compressive isotropic energy deposition (~50%)
  - Does not reduce tensile isotropic energy deposition
    - Slightly reduces compression-to-dilatation swing in frontal brain region
  - Does not significantly reduce deviatoric strain energy
    - Significant! Deviatoric stress & energy are associated with mild TBI outcomes [8]


[8] Zhang, L., Yang, K.H., & King, A.I., 2004, "A Proposed Injury Threshold for Mild Traumatic Brain Injury," ASME J. Biomech. Eng., 126(2), pp.226-236.

# Blast Mitigation Effects of Helmet Protection

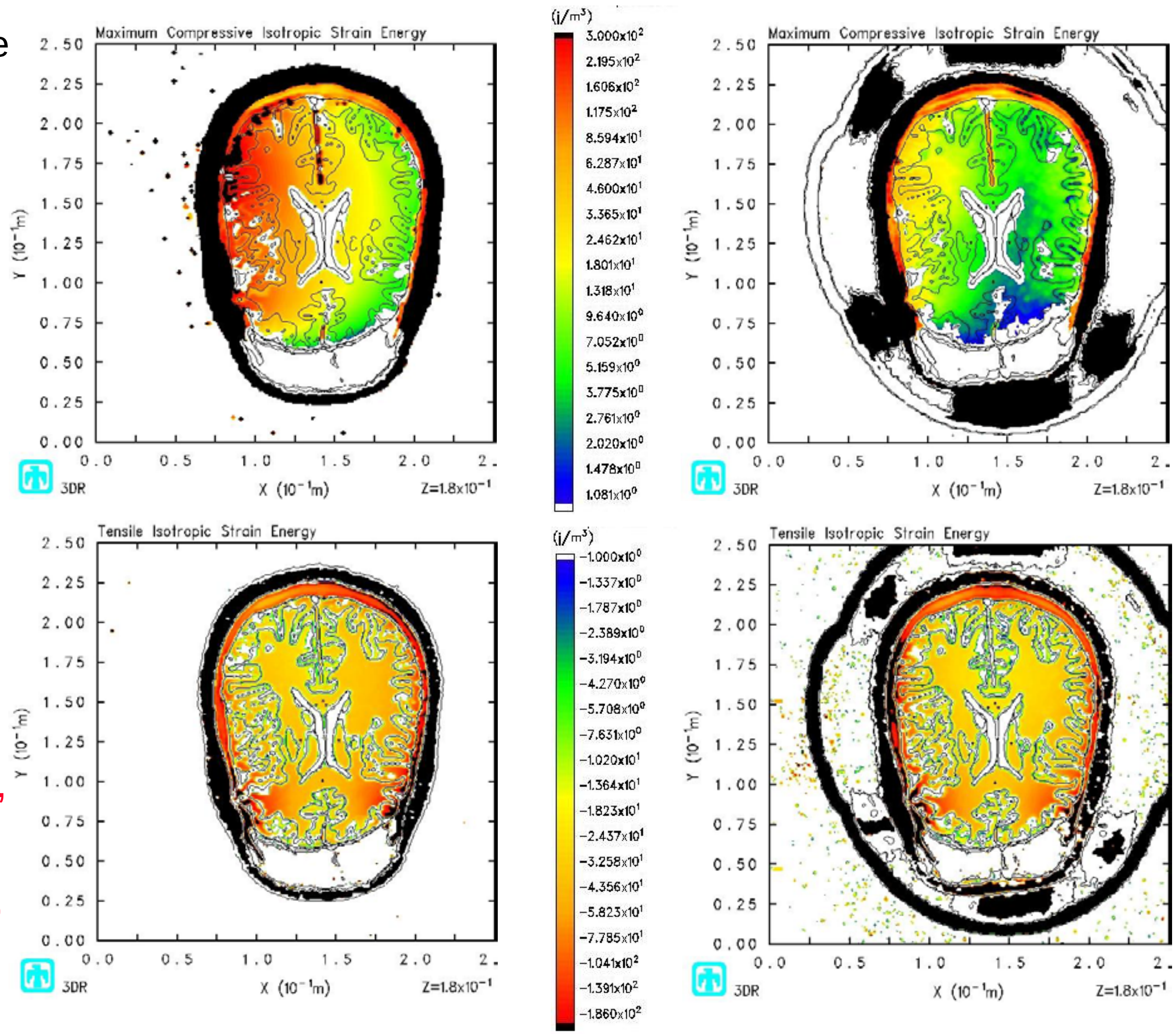
## 3.6 bar R-Side Blast Exposure: Isotropic Strain Energy Maxima

Compressive Isotropic Strain Energy

"Crush"

Tensile Isotropic Strain Energy

"Dilatation" (leads to Cavitation)



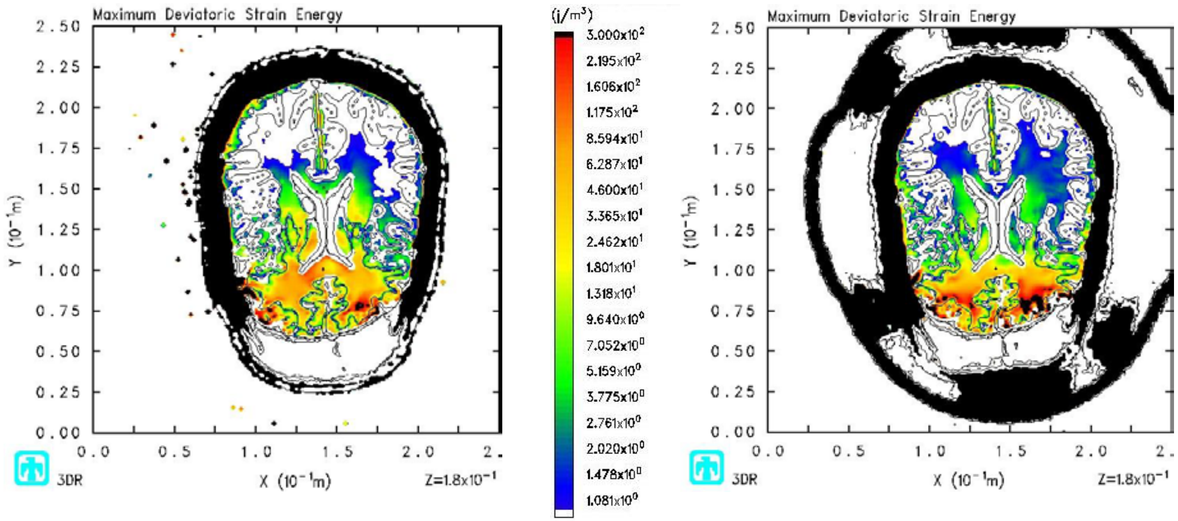
Terminal Ballistics Technology
TBT
Target Protect
Target Defeat

# Blast Mitigation Effects of Helmet Protection

## 3.6 bar R-Side Blast Exposure: Deviatoric Strain Energy Maxima

Deviatoric Strain Energy

"Tearing"




- In side blast, we predict Helmet:
  - Reduces compressive isotropic energy deposition (~50%)
  - Does not reduce tensile isotropic energy deposition
    - Slightly educes compression-to-dilatation swing in right temporal brain lobe region
  - Slightly enhances deviatoric strain energy
    - Significant! Deviatoric stress & energy are associated with mild TBI outcomes [8]


[8] Zhang, L., Yang, K.H., & King, A.I., 2004, "A Proposed Injury Threshold for Mild Traumatic Brain Injury," ASME J. Biomech. Eng., 126(2), pp.226-236.


Sandia National Laboratories

# Closure

## Summary

- Results to Date
  - Helmet Protection from 3.6 bar Blast
    - For blast pressures and associated isotropic strain energy deposition from front, side, & rear directions
      - 50% mitigation for compression but none for tensile isotropic energy
    - Does not reduce deviatoric (shear) stresses & associated strain energy
      - Slightly enhanced in side blast scenario
      - However, threshold levels leading to TBI are still unknown
        - Brain Injury Threshold Criterion (BITC) will help define these levels
    - Suggestion for improvement of Helmet
      - Modify pads and/or suspension system to further reduce shear stress & associated energy transmission into head
- Current Work
  - Assessing blast mitigation of experimental helmet designs
    - Studying additional (proprietary) prototypes
    - Establishing Brain Injury Threshold Criterion (BITC)
- Questions?