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Simulation & Correlation of Blast-Induced, Early-Time Intracranial Wave Physics with Traumatic Brain Injury

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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 [2]
  - As of June 2007, 3294 US war fighters sustained TBI
  - 69% as a result of blasts, most occurring in Iraq
  - *"TBI is the signature injury of the Iraq war"*

- Blast Injury categories:
  - Primary: direct exposure to explosion-produced air blast (shock)
  - Secondary: impact by flying objects thrown by air blast
  - Tertiary: impact into stationary object (soldier thrown by air blast)

[2] Fischer, H., 2007, United States Military Casualty Statistics: Operation Iraqi Freedom and Operation Enduring Freedom, Congressional Research Service Report RS22452.

Prior Investigation of *Blast-Induced* Brain Injury by means of Modeling & Simulation [3]

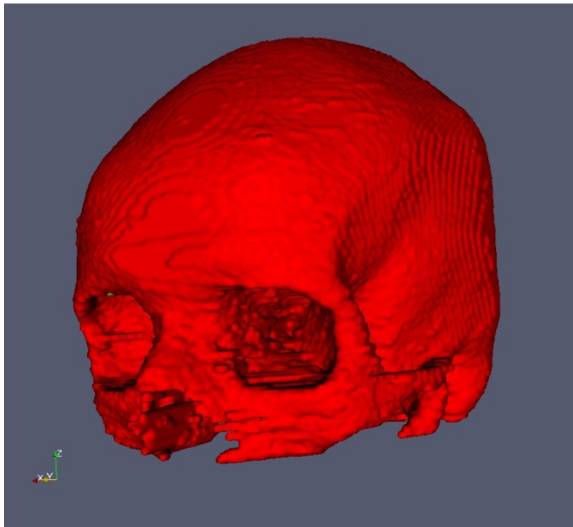
- Objective:
  - Investigate the effects of blast direction & strength on the resulting mechanical stress & wave energy distributions generated in the brain
- Tasks:
  - Construct high resolution, partial head model
    - Based on axial slice images from Visible Human Project
    - Images segmented into bone, white & gray brain matter, cerebral spinal fluid (CSF), & air (in sinuses)
    - 1 mm^3 voxel resolution (→6.85M computation cells for head model)
  - Construct constitutive models for biological materials comprising head
    - Brain: Distinct viscoelastic representations for white & gray matter
    - Bone: elastic-plastic response w/ strain-to-failure damage & fracture model
    - CSF: compressible equation-of-state (EOS) model for water
    - Air: compressible EOS model for Ni_2(78%)-O_2(22%)-Ar(<1%) mixture
  - Modify Eulerian shock physics code CTH for blast simulations
    - Modified to calculate specific wave physics variables that may correlate with clinical assessments of TBI (e.g., stress wave energy and power)
    - Typical Simulation: 32 hours on parallel cluster using 32 nodes (each node consists of Dual 3.6 GHz Intel EM64T processors sharing 6 GB RAM)

[3] Taylor, P. & Ford, C., 2009, J. Biomech. Engr. **131**, June 2009.

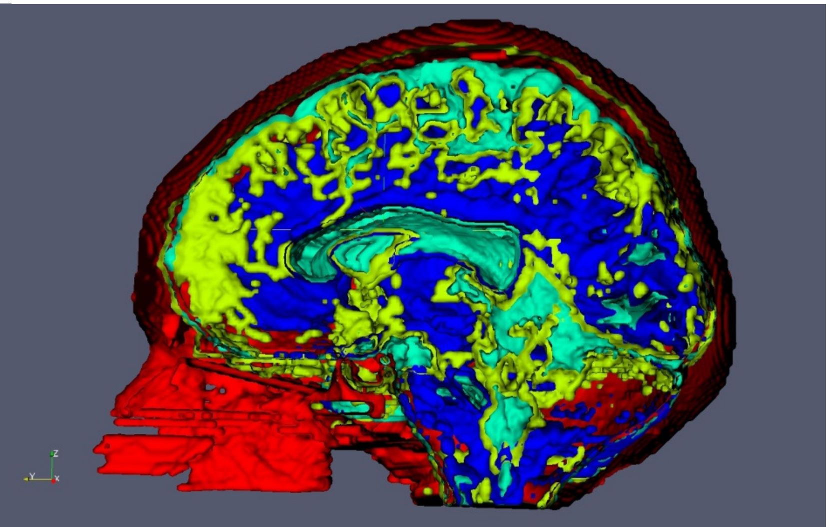
Prior M&S of *Blast-Induced* Brain Injury

Head Model and Blast Wave Structure

Oblique View

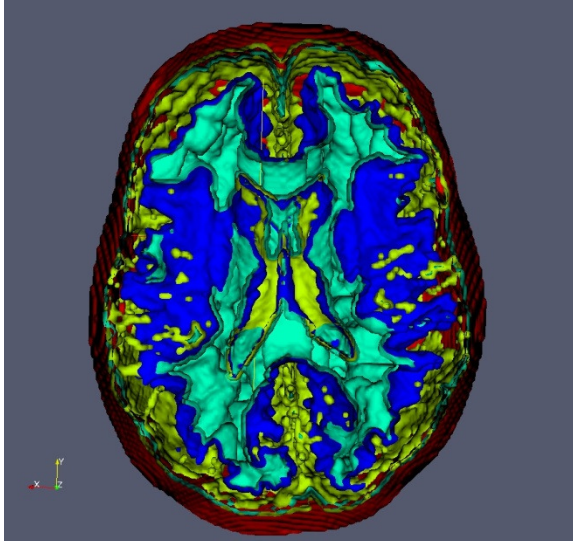


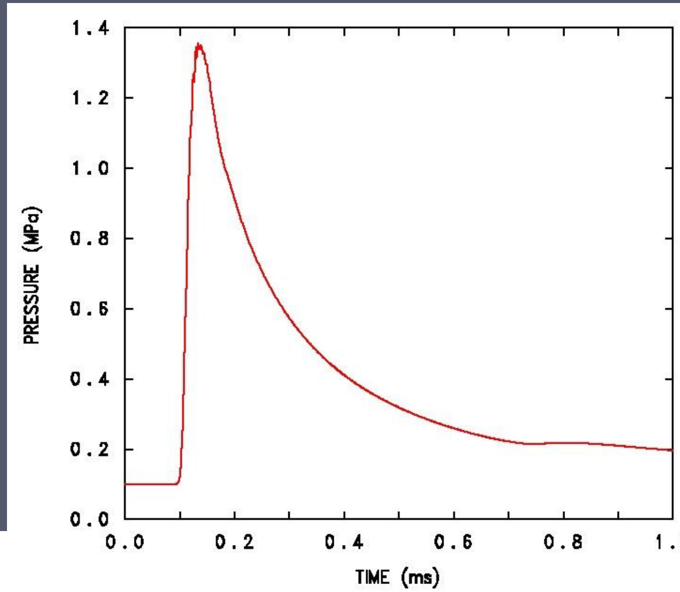
Sagittal Cut



Skull: red
WM: light blue
GM: dark blue
CSF: yellow

Axial Cut





Blast Wave Structure (=13 bars)

~ IED blast at 3m range

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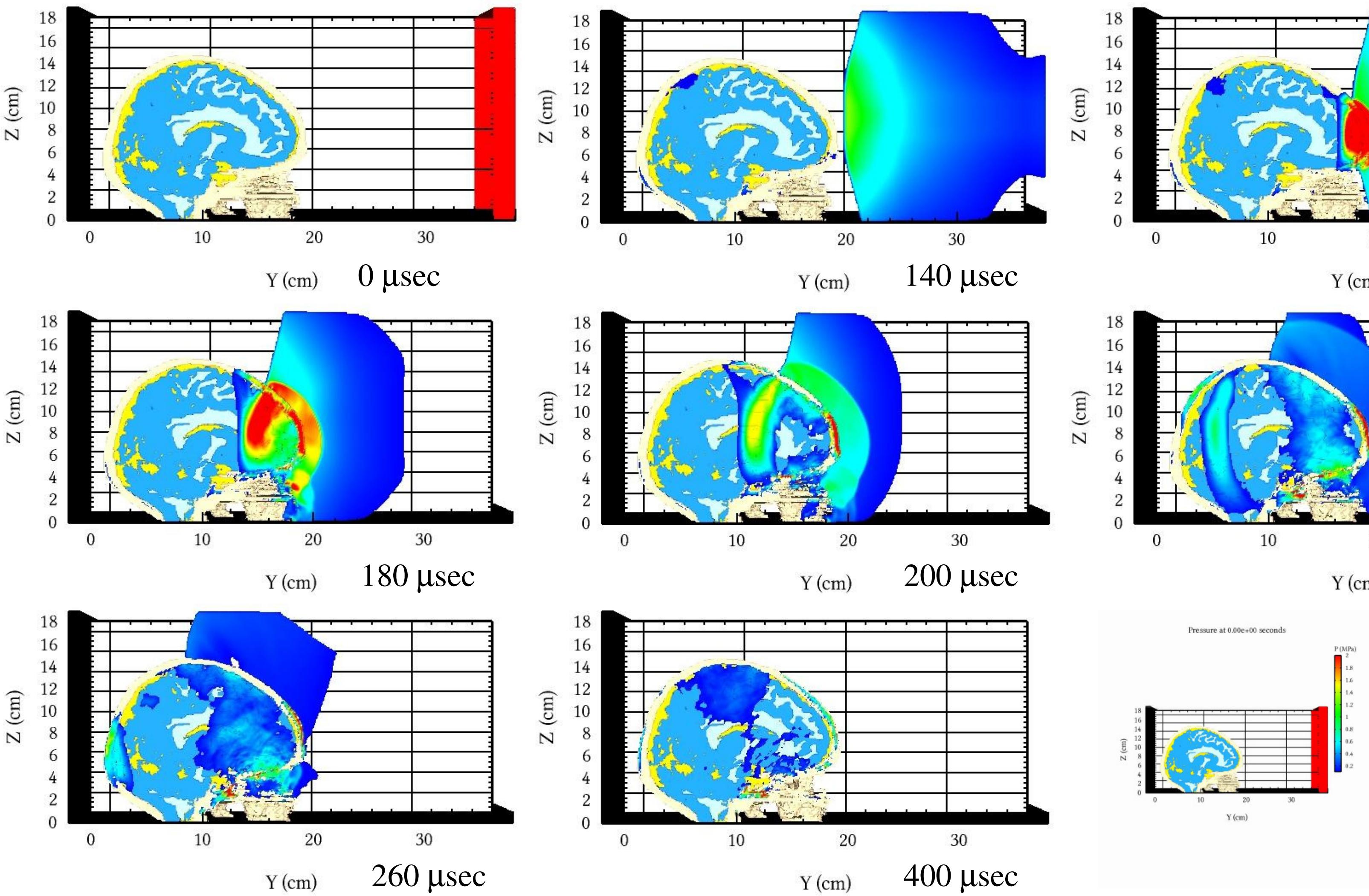
Prior M&S of *Blast-Induced* Brain Injury

13 bar (1.3 MPa) Blast Simulation: Pressure History



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Prior M&S of *Blast-Induced* Brain Injury
Summary

- Significance of Results
  - Predict intracranial stress wave motion occurring on time scales significantly shorter (~2 msec) than those calculated in other investigations (10-20 msec) [4] of impulse loading to the head
    - Current results due solely to mechanical wave interaction between surrounding air and head model
    - Other investigations predict intracranial stresses due to later-time head motion & the resulting brain tissue accelerations & rotations
  - Predict intracranial shear stress levels on same order of magnitude as those associated with concussive injury & mild TBI [4]
    - 3.1 KPa – 6.4 KPa in Thalamus (Mean = 4.5 KPa)
- Conclusion
  - Stress levels generated by early-time wave motion alone may be sufficient to induce traumatic brain injury
    - ***Primary Blast Injury* may be a direct cause of TBI in humans**

[4] Zhang, L., Yang, K., and King, A., (2004). A Proposed Injury Threshold for Mild Traumatic Brain Injury, J. Biomech. Engr. **126**(2), pp.226-236.

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Current Investigation of Traumatic Brain Injury

General Description

- Correlate M&S predictions with clinical assessment of TBI
  - Create high resolution full head-neck model for blast & impact simulations
  - Conduct clinical assessments of blast & blunt impact victims
    - Neuropsychological testing
    - DTI analyses

    } In collaboration with Corey Ford, MD, PhD, UNM Health Sciences Center
  - Perform simulations of blast & impact scenarios that mimic conditions experienced by TBI case history 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 & impact loading conditions leading to TBI
    - Current military head protection gear is designed to protect against ballistic fragments & debris
    - Offers little protection against blast leading to *Primary Blast Injury*

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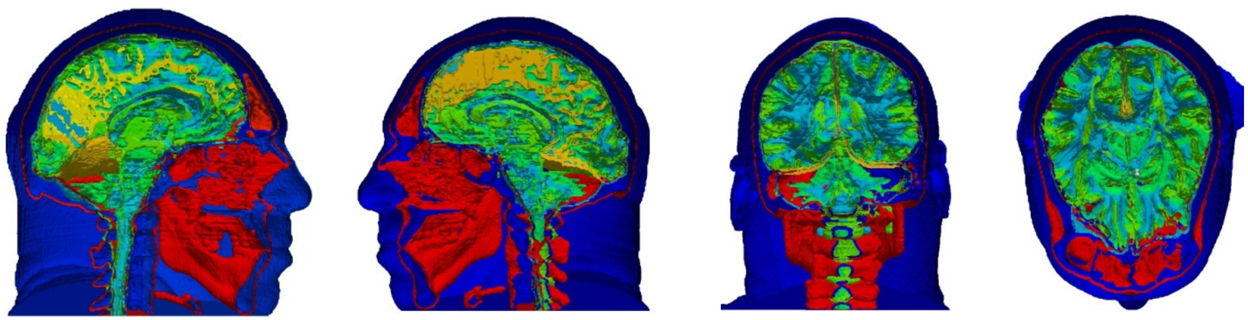
Current Investigation of Traumatic Brain Injury

Development of high resolution head-neck model

- Current model based on data from Visible Human Project [5]
  - Constructed from 255 1mm-thick, axial slices of anatomical sections of human male from the VHP
  - Anatomically correct distributions of white & gray brain matter, cerebral spinal fluid/blood, bone, falx & tentorium membranes, muscle/scalp

Sagittal, Coronal, & Axial Cuts:



Full Model Images:

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

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Current Investigation of Traumatic Brain Injury

Development of high resolution head-neck model

- Selection/Implementation of constitutive models
  - Biological Materials
    - Finite Elastic, Linear Viscoelastic models for White & Gray Matter
    - Linear Elastic model w/ Fracture for Bone
    - Finite Elastic models for Muscle, Scalp, Falx, & Tentorium
    - Linear Compressible model for Cerebral Spinal Fluid (CSF)
    - Non-linear Compressible model for Sinus Air (and surrounding air)
  - Head Protection Equipment
    - Composite model for helmet shell
    - Finite Elastic, Linear Viscoelastic foam model for helmet padding

Current Investigation of Traumatic Brain Injury

Perform clinical assessments on blast & blunt impact victims

- Blast & blunt impact victims recruited
  - 8 Subjects recruited to date
    - 4 blast exposure
    - 4 blunt impact
  - Subjects Undergo Clinical Assessment:
    - Detailed history of insult event recorded
    - Neuropsychological 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
    - Magnetic Resonance Imaging (MRI)
    - Diffusion Tensor Imaging (DTI)

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Clinical Diagnostic to Quantitatively Assess TBI

Diffusion Tensor Imaging (DTI)

- What is it?
  - DTI is an Magnetic Resonance-based imaging technique
  - Detects microscopic Brownian motion of water through brain tissue
    - Fluid displacement occurs over distances comparable to cell dimensions
    - Diffusion motion of water is impeded by tissue structures
      - Such as: cell membranes, myelin sheaths, intracellular microtubules, etc.
      - Diffusion parallel to axons or myelin sheaths is greater than diffusion in perpendicular directions
      - → Diffusion Anisotropy
- What does it do?
  - Measures diffusion anisotropy in vivo (within living subject)
    - Works well for white matter, due to its anisotropic structure (displaying elongated, fibrous network tracks)
- How does it detect white matter damage?
  - Water motion (diffusion) along white matter fiber tracks is reduced as a result of axonal damage
    - Axonal Damage is indicated by a *reduction* in diffusion anisotropy

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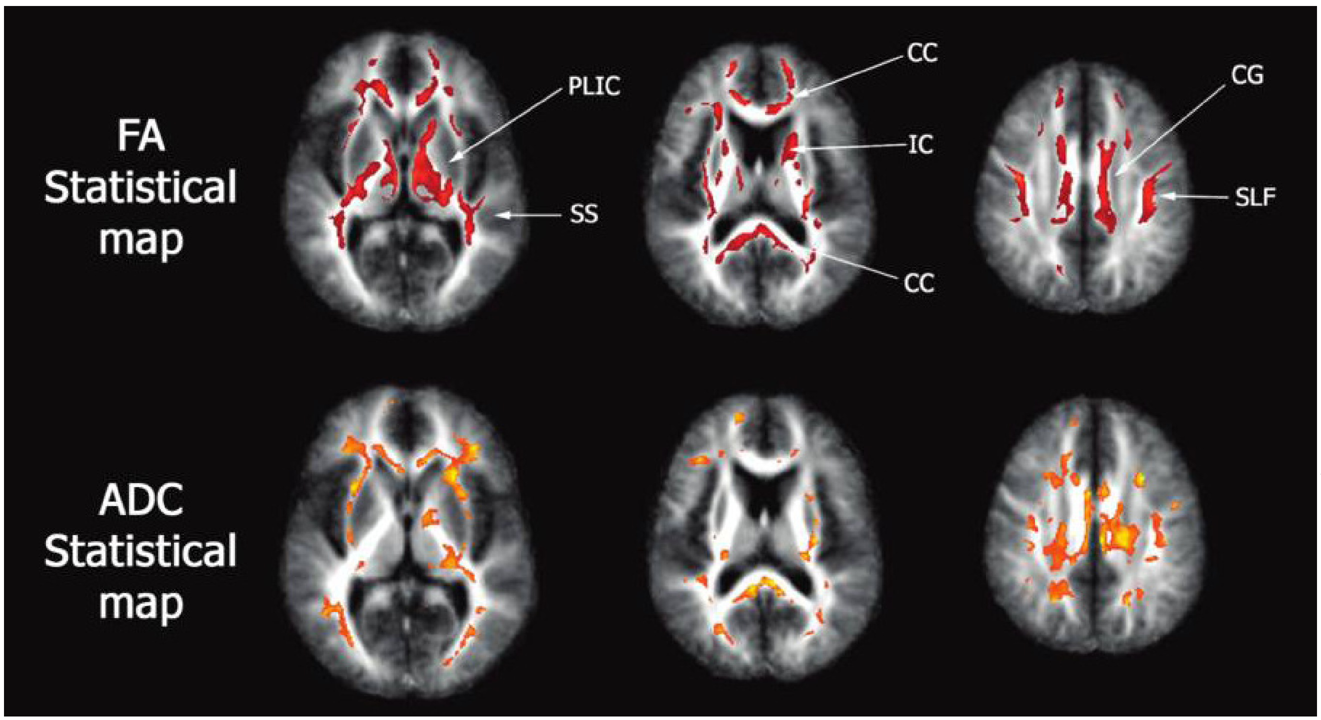
Clinical Diagnostic of TBI

Diffusion Tensor Imaging (DTI)

- Severity of TBI correlates with quantified DTI metrics:
  - Reduction in Fractional Anisotropy (FA) of White Matter
  - Increase in Apparent Diffusion Coefficient (ADC) of fluid in White Matter

DTI mapping of Axial Slice in TBI Patients



Regions of significantly lower Fractional Anisotropy

Regions of significantly higher Apparent Diffusion Coefficient

PLIC – Posterior Limb of Internal Capsula
CC – Corpus Callosum
IC – Internal Capsule
CG - Cingulum
SLF – Superior Longitudinal Fascicle

Xu J., et al., 2007, J. Neurotrauma, **24**(5), pp.753-765.

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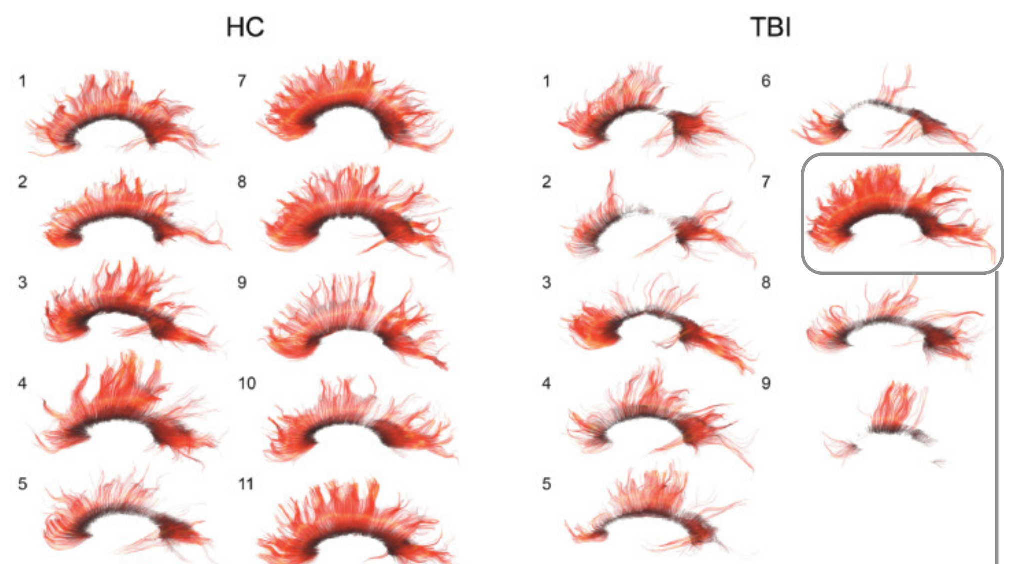
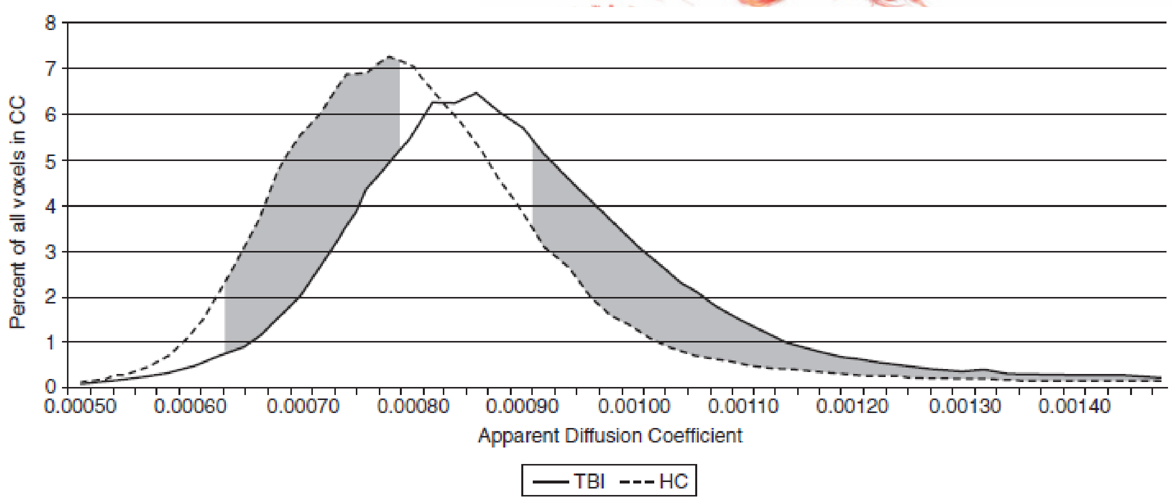
Clinical Diagnostic of TBI

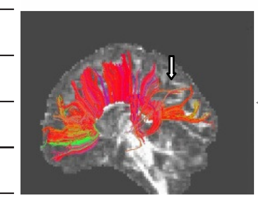
Corpus Callosum (CC) Tractography in TBI Subjects & Healthy Controls

- TBI subjects on right show early termination of CC fibers compared to healthy controls on left
- Damage to callosal fibers is heterogeneous
- Variability in tract damage likely explains cognitive and behavioral outcomes



Increase in ADC
In Corpus Callosum
(note curve shift to
right for TBI subjects)



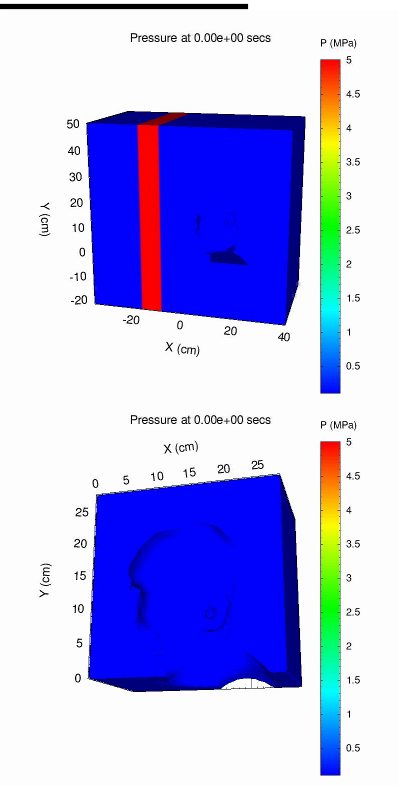


Xu J., et al., 2007, J. Neurotrauma, **24**(5), pp.753-765.

Current Investigation of Traumatic Brain Injury

Current Activities (2010)

- Testing Simulation Methods
  - Eulerian methods using CTH (finite volume / difference)
  - Lagrangian-Eulerian coupled methods using Presto/CTH (finite element / finite volume)
    - Loose coupling (1-way passing of node pressure histories to FEA)
    - Tight coupling (2-way interaction between Eulerian & Lagrangian analyses)
- Validation of Head/Neck Model
  - Compare M&S predictions with laboratory data
    - Laboratory blast data on physical head model courtesy of Dr. Roshdy Barsoum & Philip Dudt, NSWC-CD, Bethesda, MD
    - Magnetic Resonance Elastography & Tagging data on human heads (in vivo) courtesy of Dr. Philip Bayly and team, Washington University at St. Louis, MO



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Current Investigation of Traumatic Brain Injury

Year 2011 Activities

- Perform simulations of impact & blast scenarios that mimic conditions experienced by TBI case history 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 & impact loading conditions leading to TBI
  - Example: Blast exposure of head/neck model wearing various experimental helmet designs

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Questions?

Additional Background Slides

Traumatic Brain Injury (TBI)

Severity

- Severity Categories:
  - Mild
  - Moderate
  - Severe
- GCS: Glasgow Coma Scale [6]
  - Universal system for classifying severity of TBI
  - Scored by sum of 3 tests:
    - Eye response test
    - Verbal response test
    - Motor response test
  - GCS=3: Deep coma or death
  - GCS=15: fully awake person
- PTA: Post-Traumatic Amnesia
- LOC: Loss of Consciousness

TBI Severity	GCS	PTA	LOC
Mild	13-15	<1 hr	<30 min
Moderate	9-12	30 min – 24 hrs	1-24 hrs
Severe	3-8	> 1 day	>24 hrs

[6] http://en.wikipedia.org/wiki/Glasgow_Coma_Scale