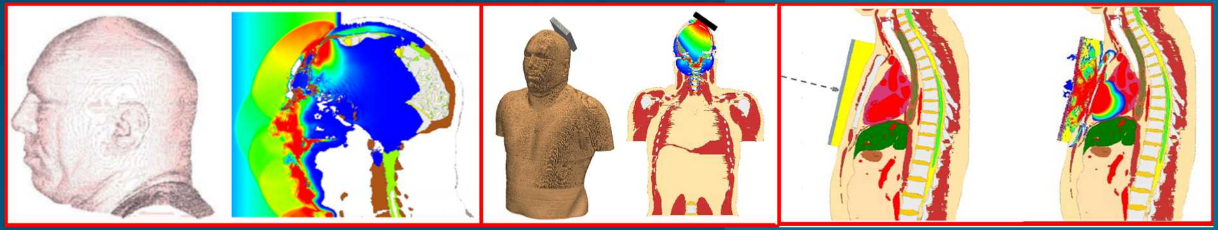
SAND2019-4002C

Computational Modeling of Blast-Induced Cavitation Bubble Collapse in the Brain



PRESENTED BY

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Cooper, Dederman, Hovey, Terpsma

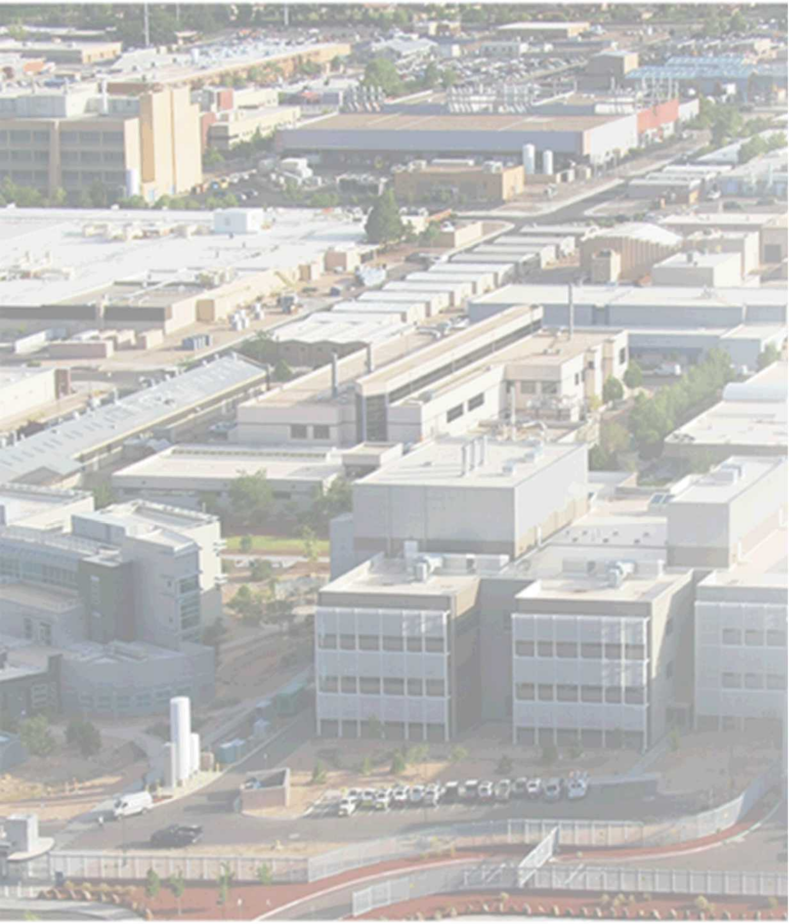
Terminal Ballistics Technology Department 5421

www.sandia.gov/biomechanics

April 11, 2019

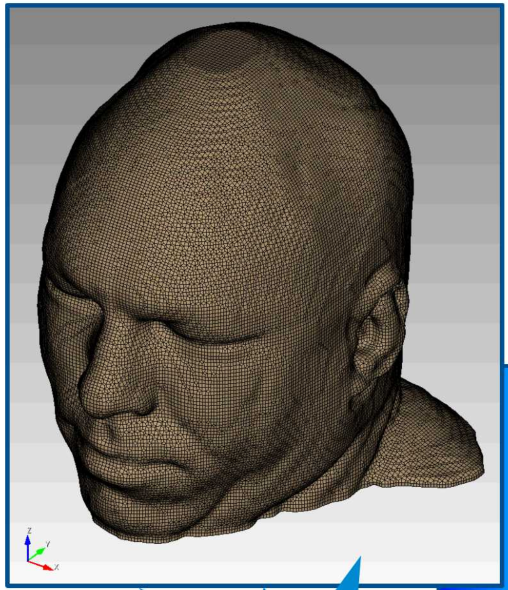
SAND2019-xxxx

SANDIA HAS FIVE MA
PROGRAM PORTFOL



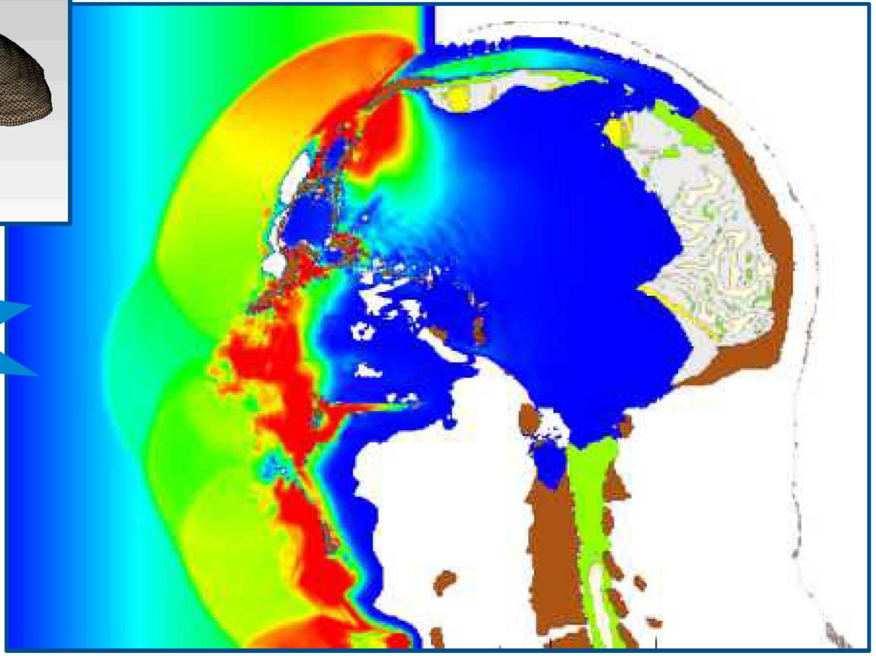
Sandia Injury Biomechanics Lab

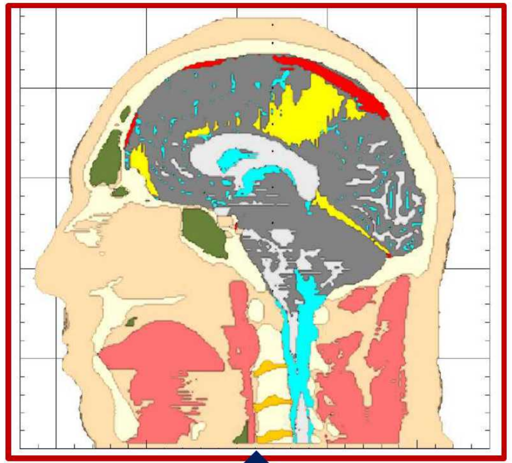
Sandia National Laboratories



Blast – C2B2

Blunt Impact - Panther





Understanding

Injury

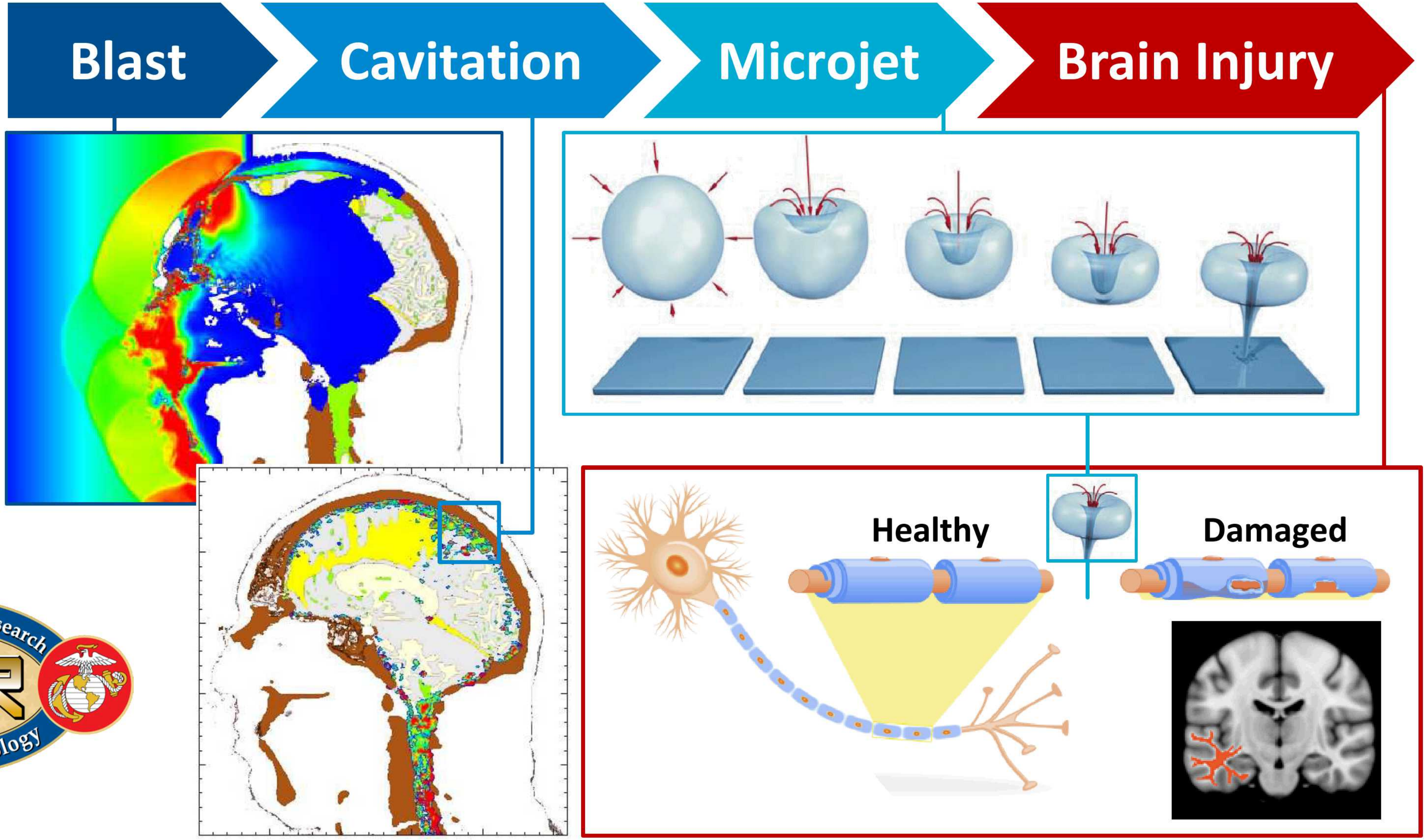
Risk

Office of Naval Research ONR Science & Technology

Protect the U.S. Warfighter

Multiscale Model of Cavitation Injury

Sandia National Laboratories



Office of Naval Research
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Science & Technology

Sandia Head Geometric Model

CT and digital photography scan entire body

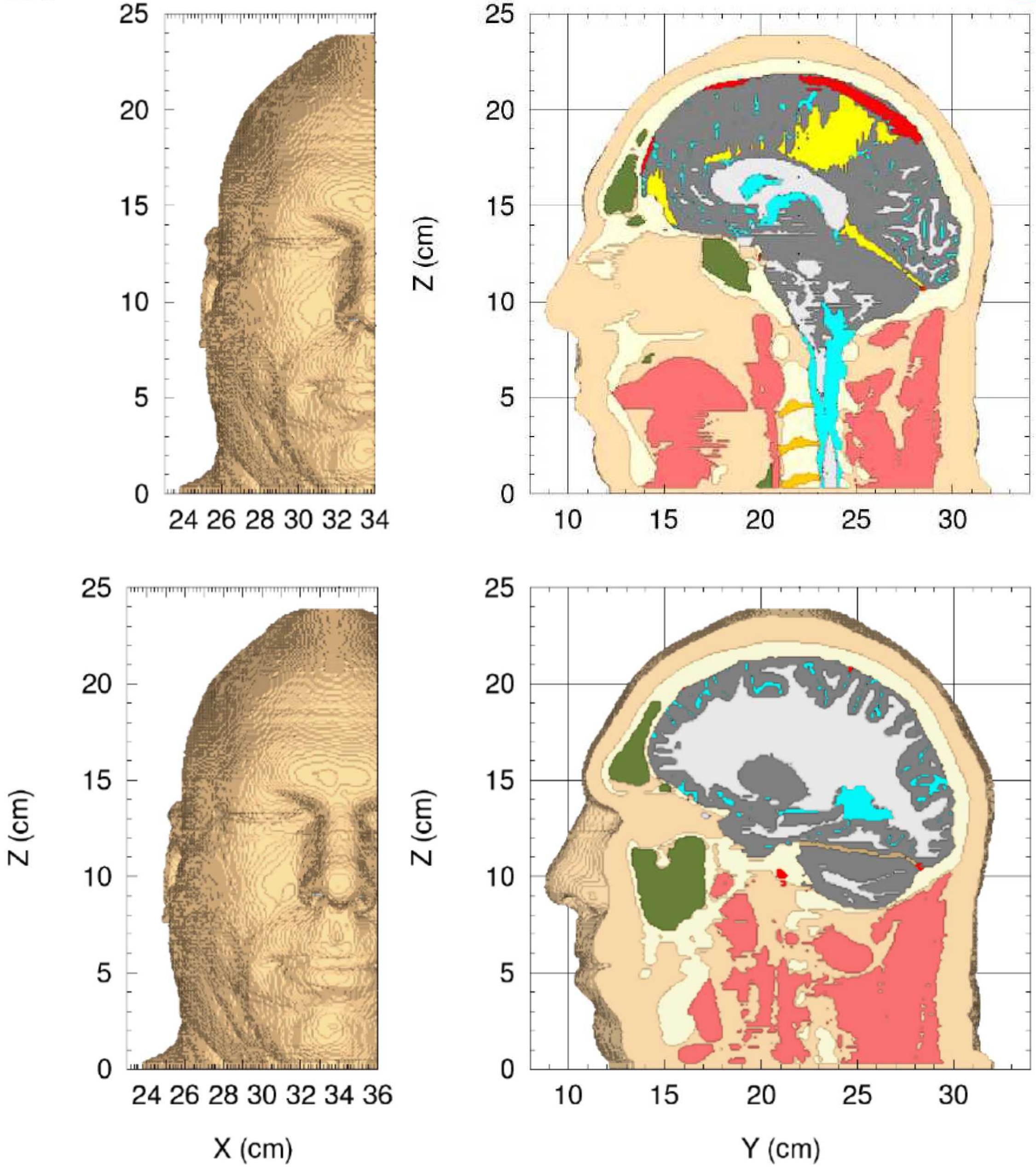
- full body 1,871 axial slices at 1 mm intervals
- CT: 512 x 512 pixels; 12 bit gray
- Photo: 4,096 x 2,700 pixels; 24 bit color

MR head and neck

- axial slices at 4 mm intervals
- 256 x 256 pixels; 12 bit gray

Mid-sagittal
X = 340 mm = 34.0 cm

Mid-sagittal + 2 cm offset
X = 360 mm = 36.0 cm

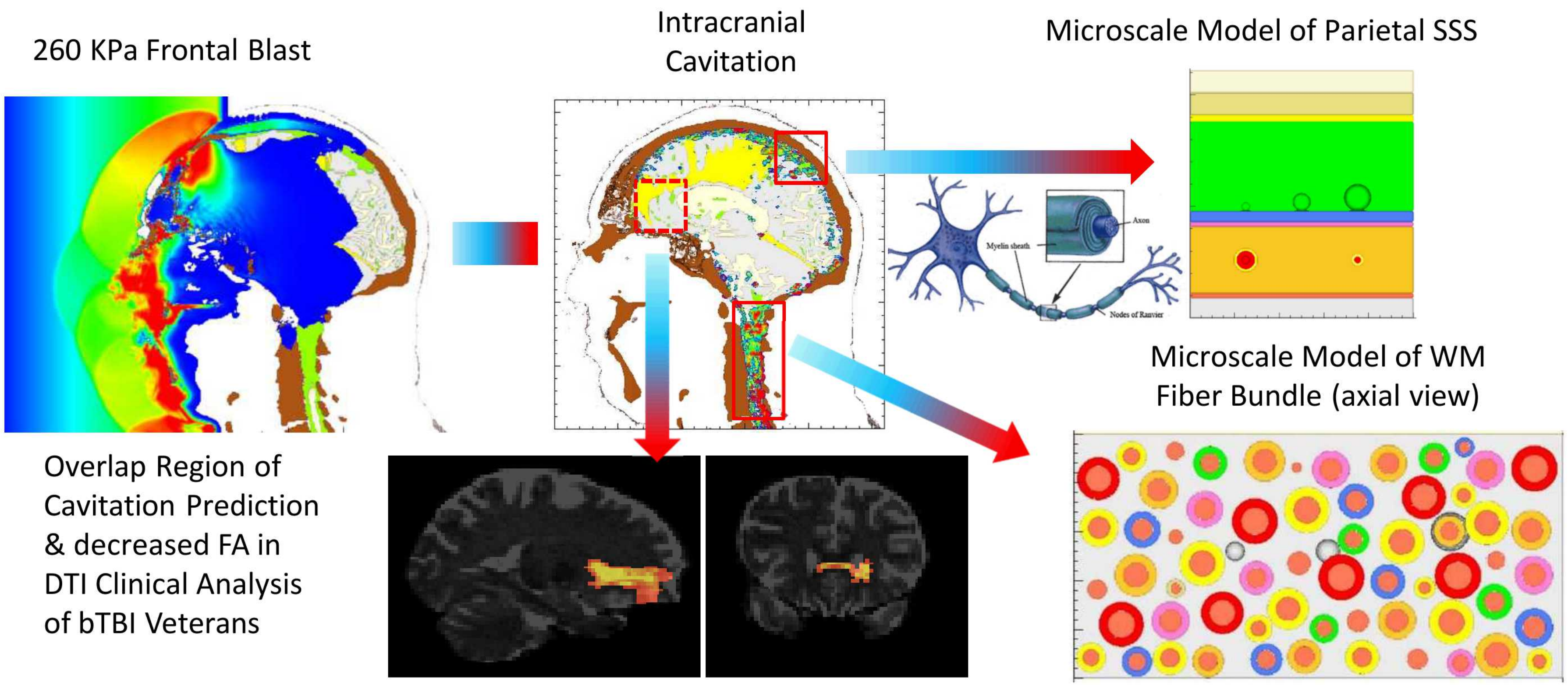


Micromechanical Modeling of Brain Injury from Blast-Induced Intracranial Cavitation

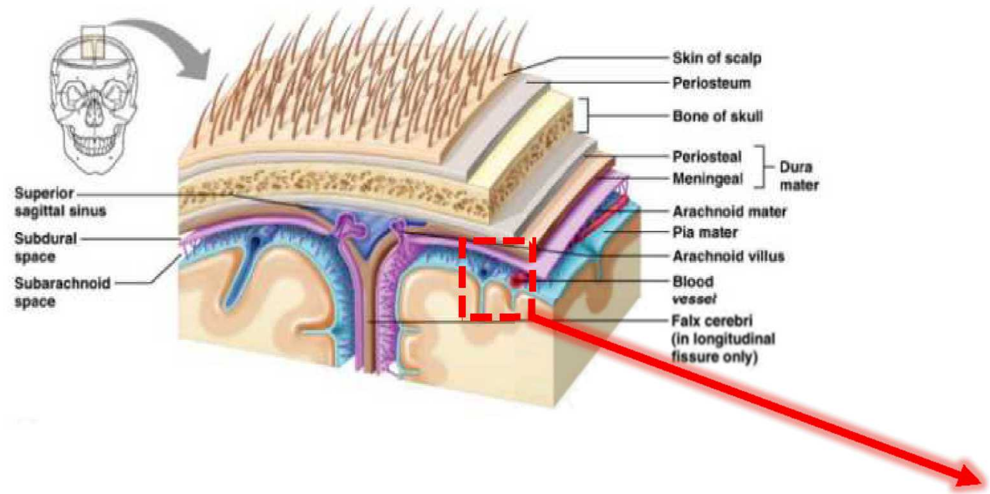
Objectives:

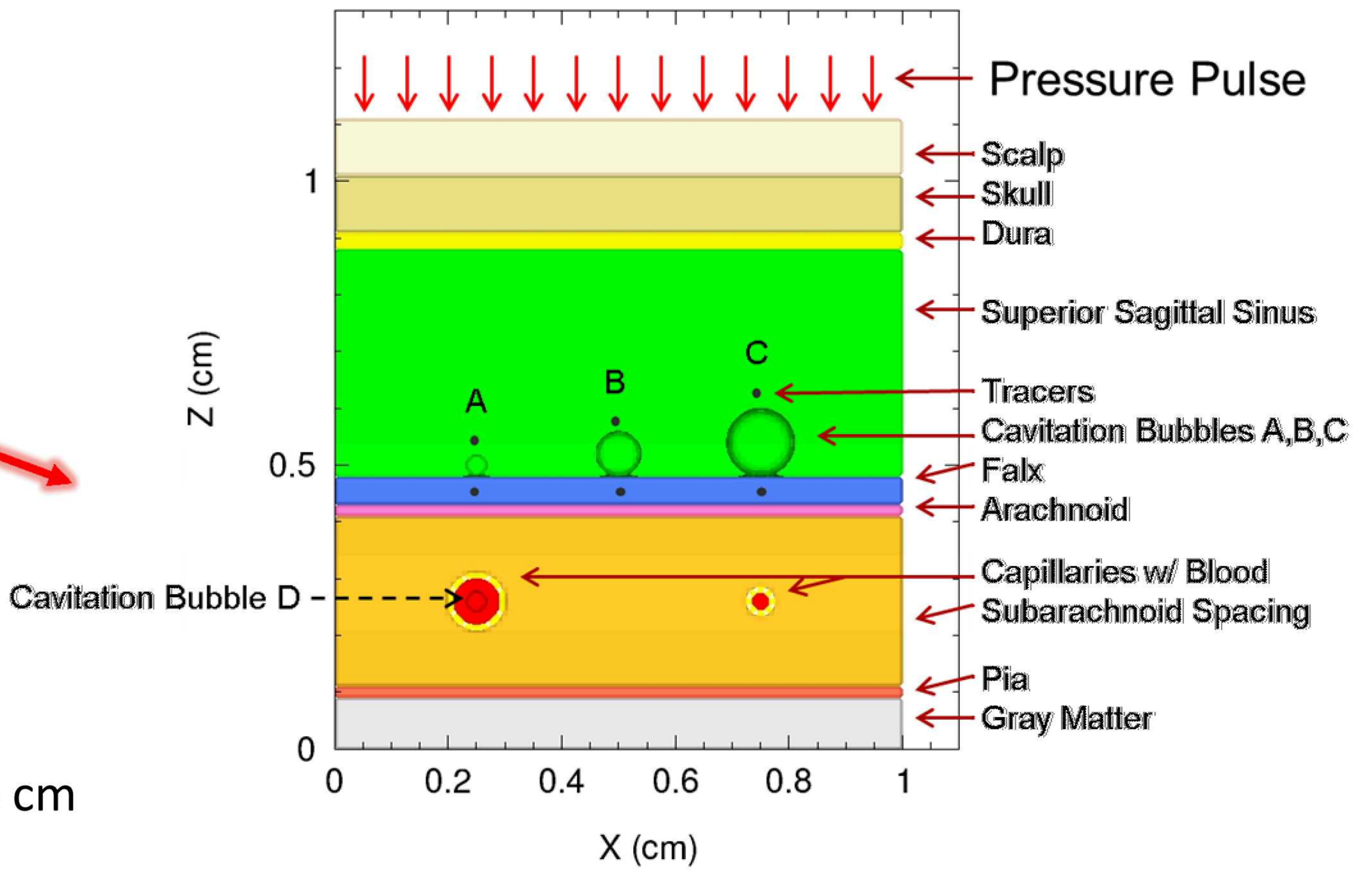
- Investigate mechanisms of cavitation-induced brain tissue damage on a microscale resulting from blast exposure to the warfighter
- Goal: correlate cavitation predictions w/ clinically measured brain damage

(If correlation is possible)



Superior Sagittal Sinus (SSS) Microscale Model



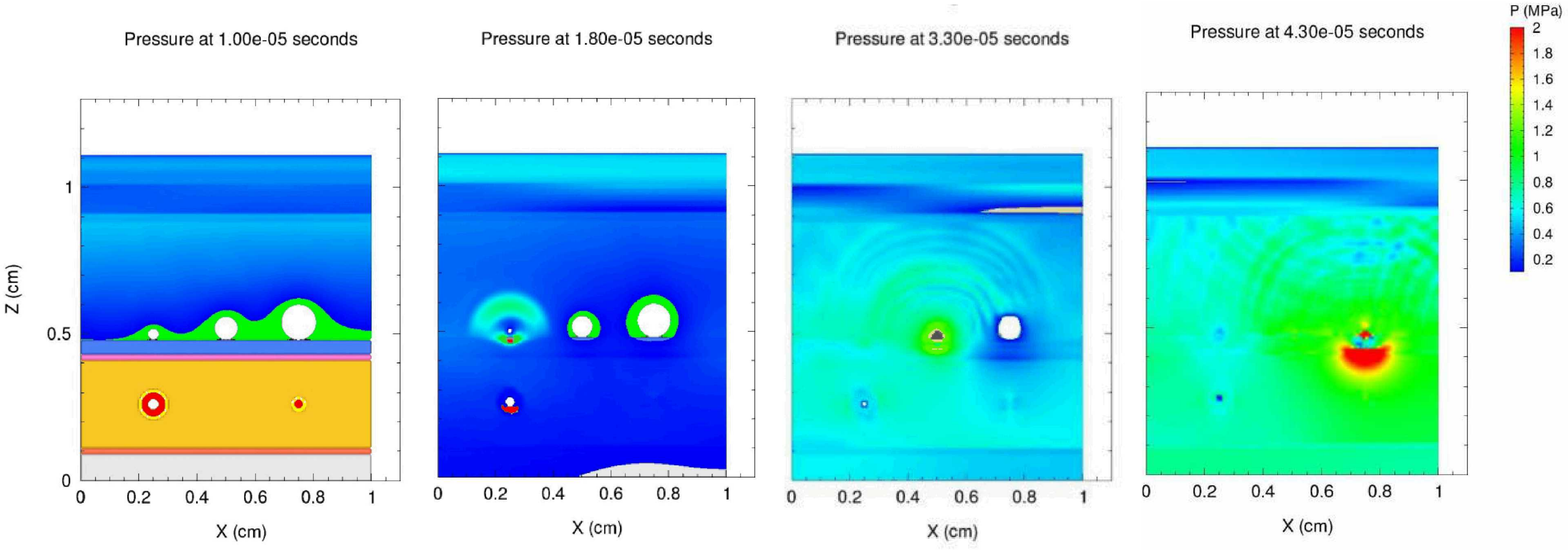


Bubble Diameter:
A: 0.4 mm
B: 0.8 mm
C: 1.2 mm
D: 0.4 mm

RVE: 1 cm x 0.5 cm x 1.25 cm

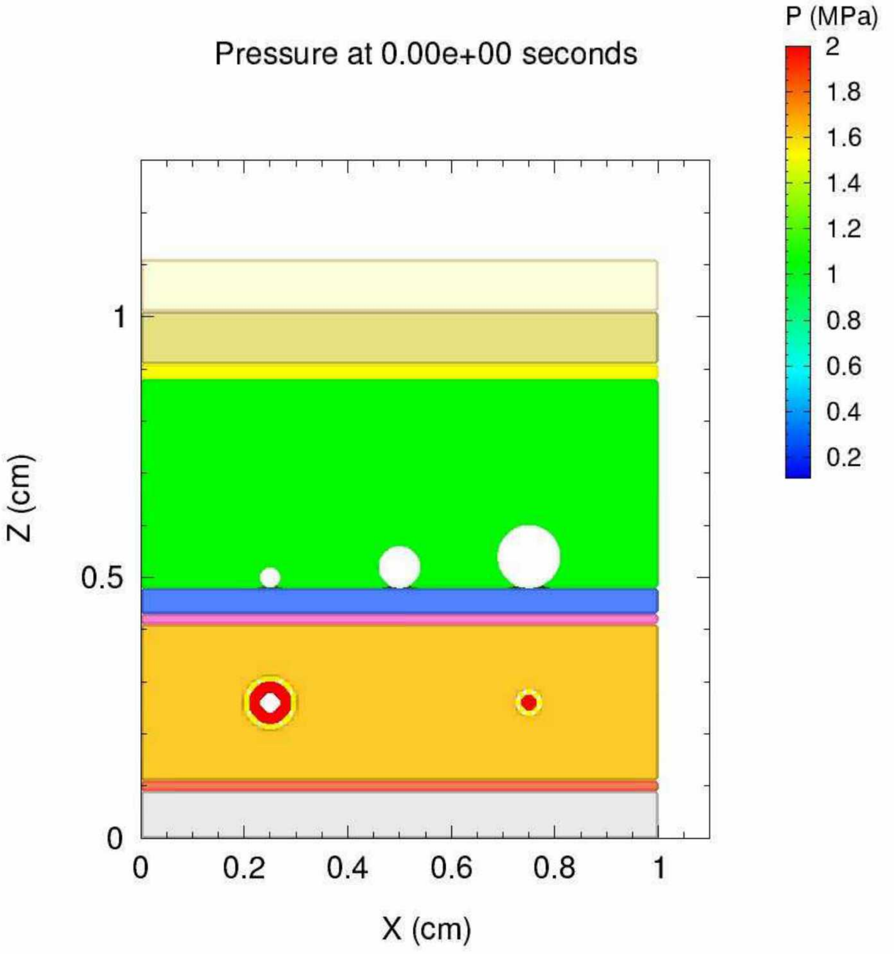
Haniff S, Taylor P, et al. Virtual Simulation of the Effects of Intracranial Fluid Cavitation in Blast-Induced Traumatic Brain Injury. ASME International Mechanical Engineering Congress and Exposition, *Volume 3: Biomedical and Biotechnology Engineering* ():V003T03A062. doi:10.1115/IMECE2015-52696.

SSS Microscale Model



- Observations:
  - Increases in bubble diameter cause delays in peak pressure arrival time
  - Bubble collapse microjetting observed at 18, 33, and 43 µs

SSS Microscale Model



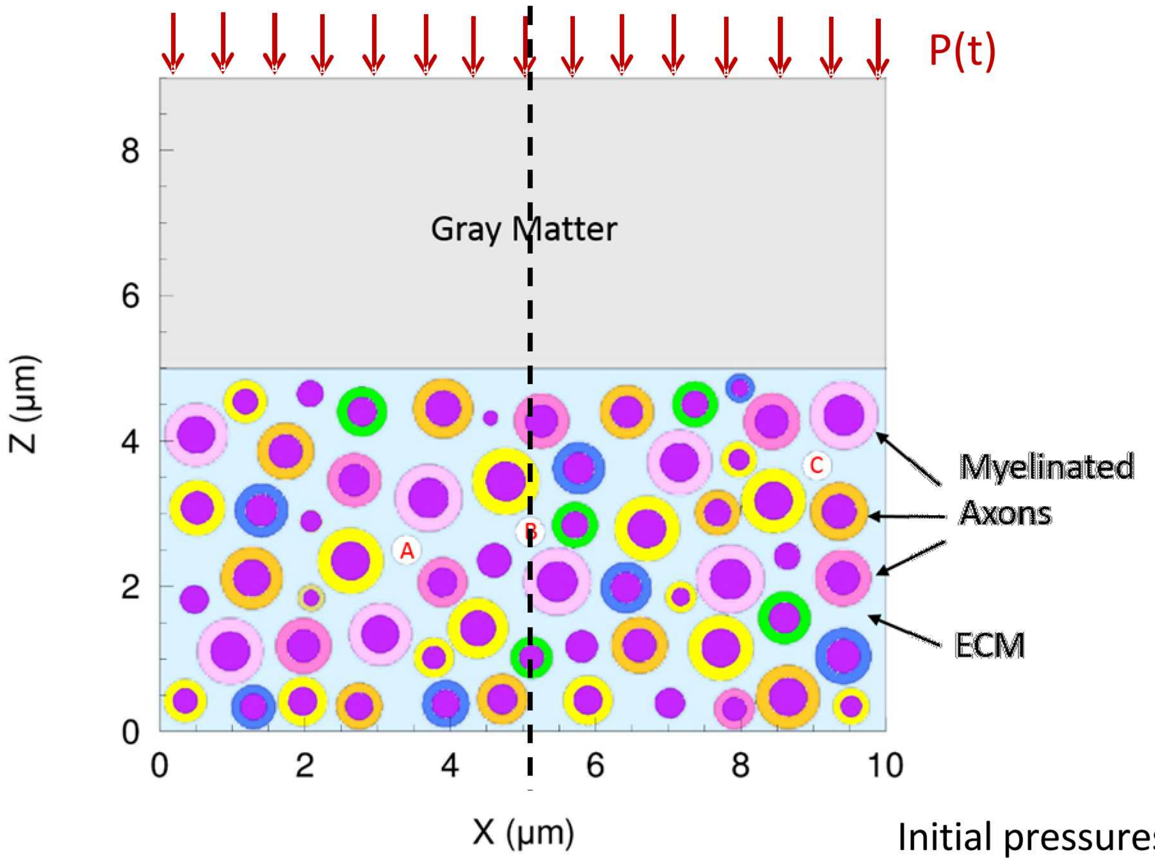
Results of Study:

- Cavitation bubble collapse dependent on:
  - Strength of intracranial stress wave (related to blast strength)
  - Bubble diameter

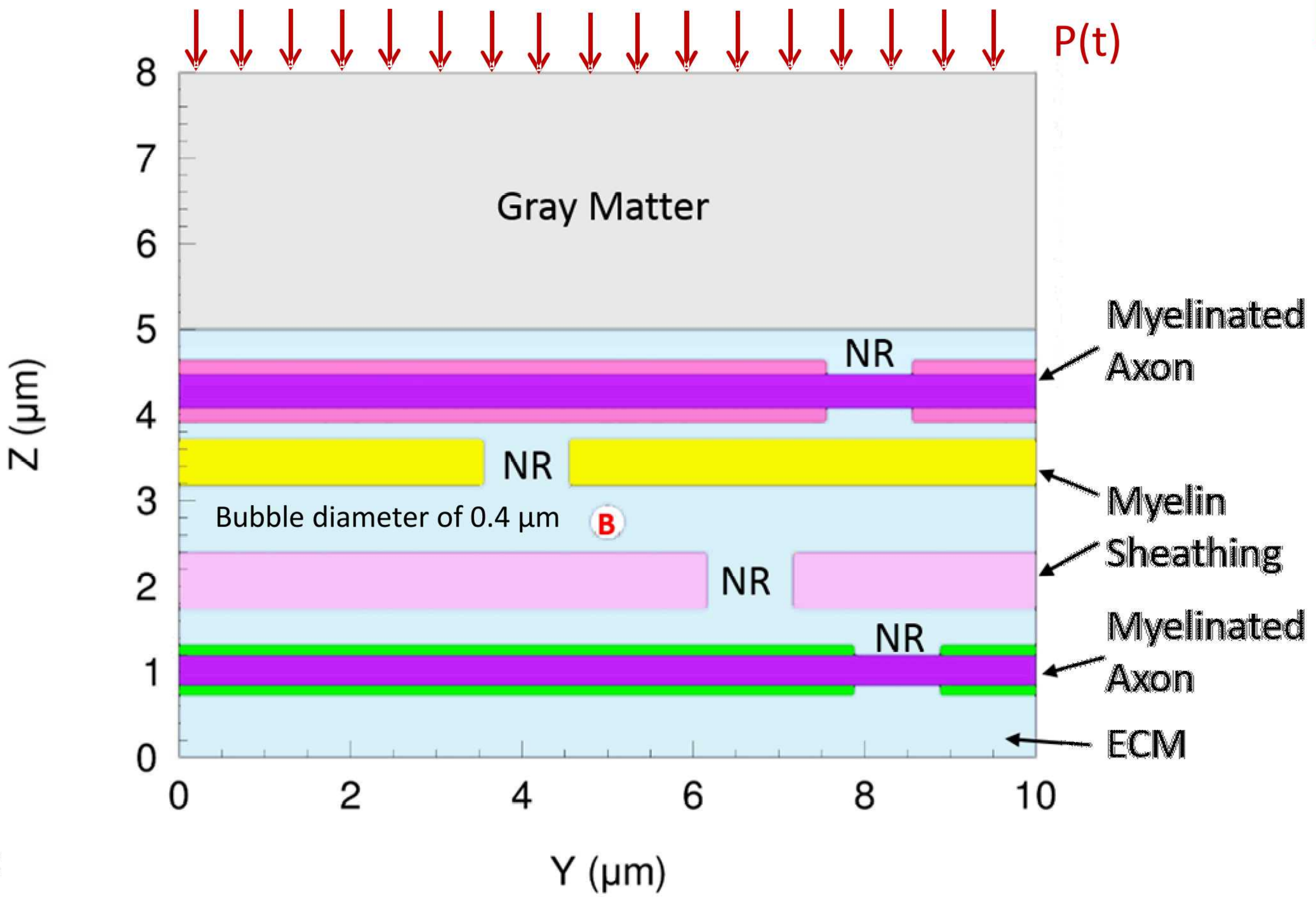
- Effects of cavitation bubble collapse:
  - Generation of high pressure region around bubble site
  - Microjetting of fluid surrounding bubble in downstream direction
  - Significant levels of shear stress downstream from bubble
  - → Shearing of tissue downstream

Microscale Model of the White Matter Axon Fiber Bundle

Axial View



Longitudinal View



Initial pressures:
Bubbles: 5 kPa
100 kPa for all other materials

RVE: 10 μm x 10 μm x 9 μm, 0.04 μm cell size
53% volume fraction of randomly distributed axons
axon+myelin sheath diameter = 0.72 $\pm$ 0.15 μm

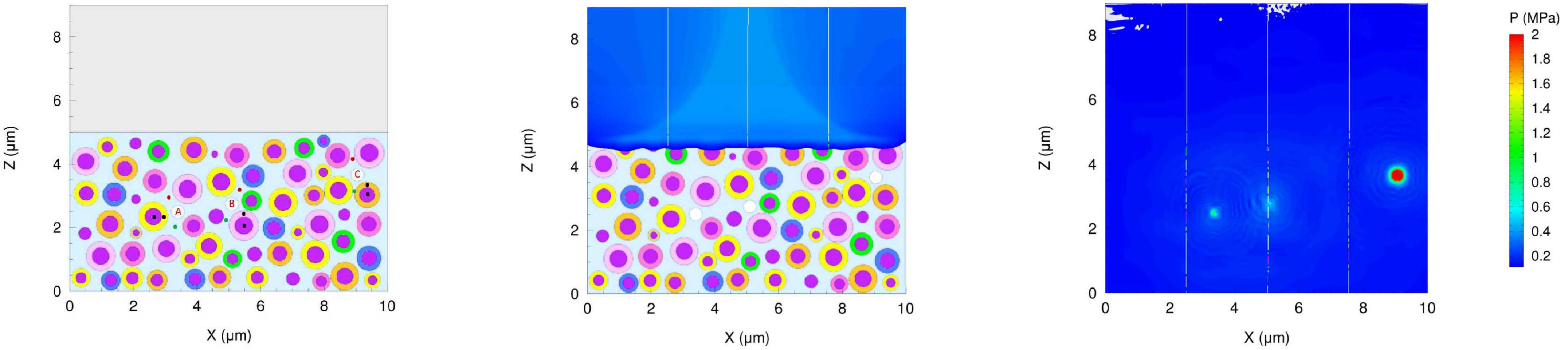
Haniff, S., Taylor, P.A.: In silico investigation of blast-induced intracranial fluid cavitation as it potentially leads to traumatic brain injury. Shock Waves **27**(6) (2017).

Microscale Model of the White Matter Axon Fiber Bundle

400 kPa compressive wave

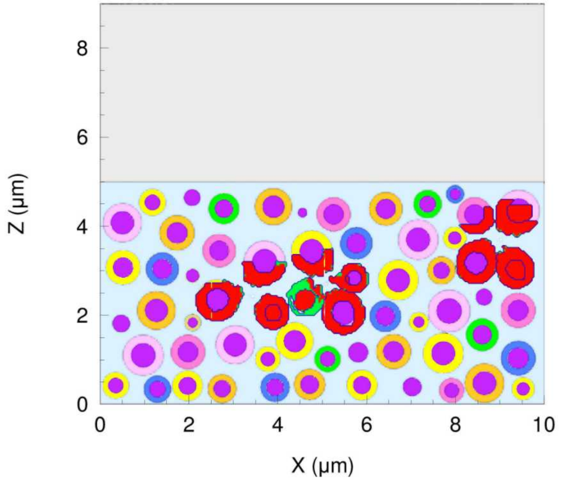
Pressure

0 ns | **3 ns** | **18 ns**

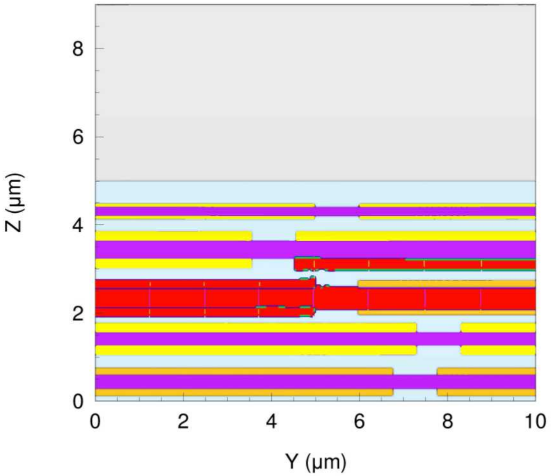


Damage at final time of 69 ns

Axial View



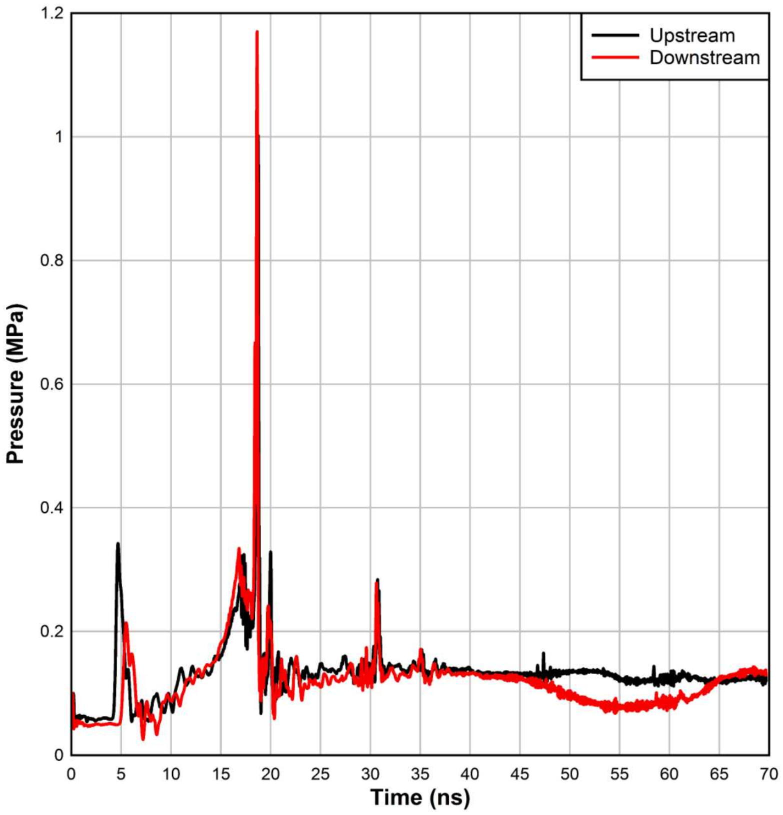
Longitudinal View



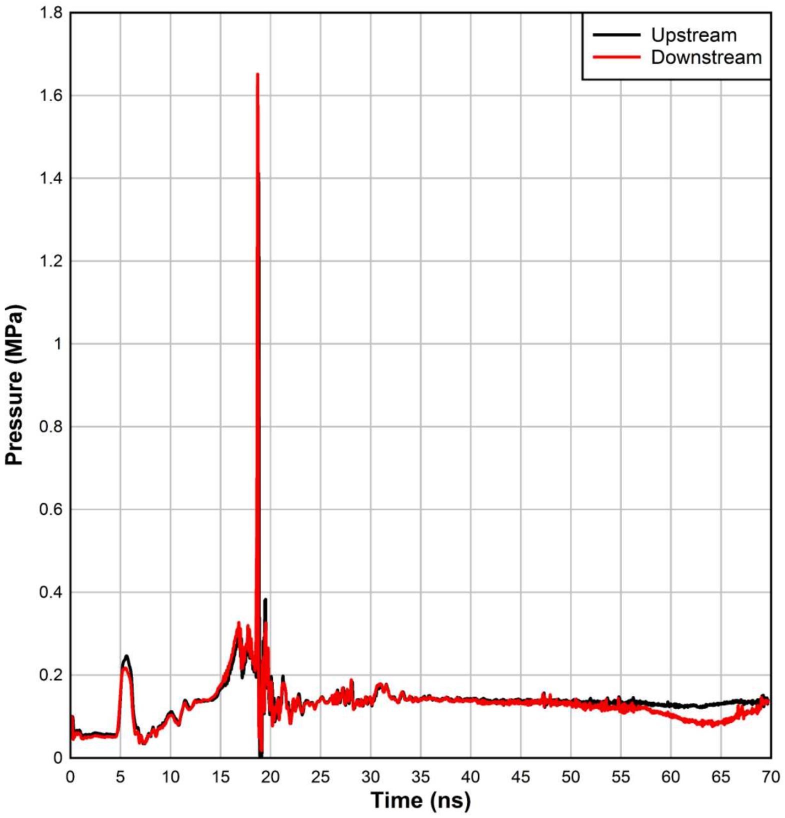
Microscale Model of the White Matter Axon Fiber Bundle

- Upstream and downstream pressures of 0.4 µm diameter bubbles during passage of a 400 kPa compressive wave

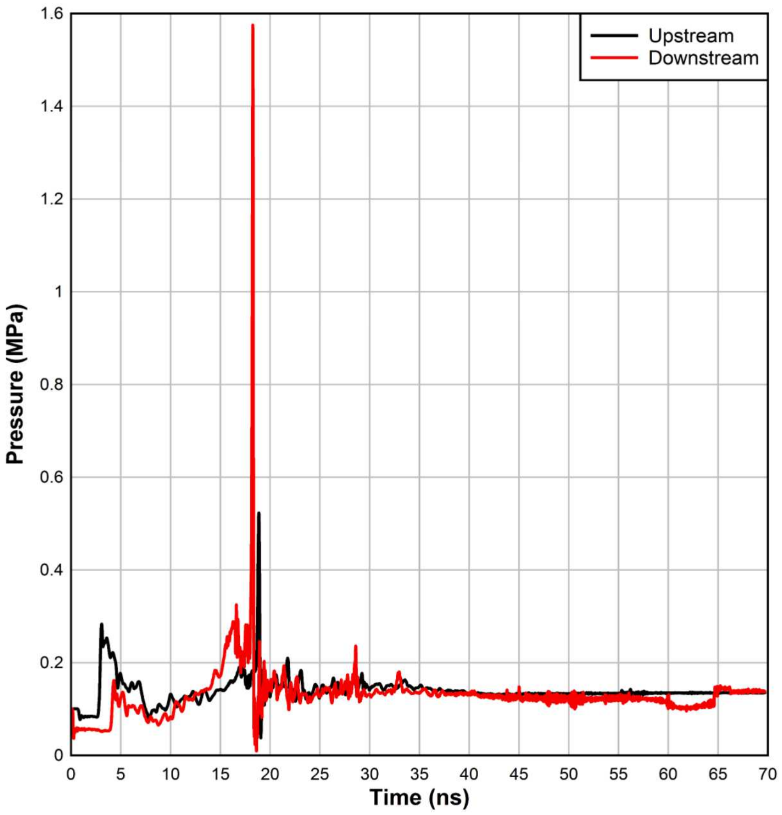
Bubble A



Bubble B

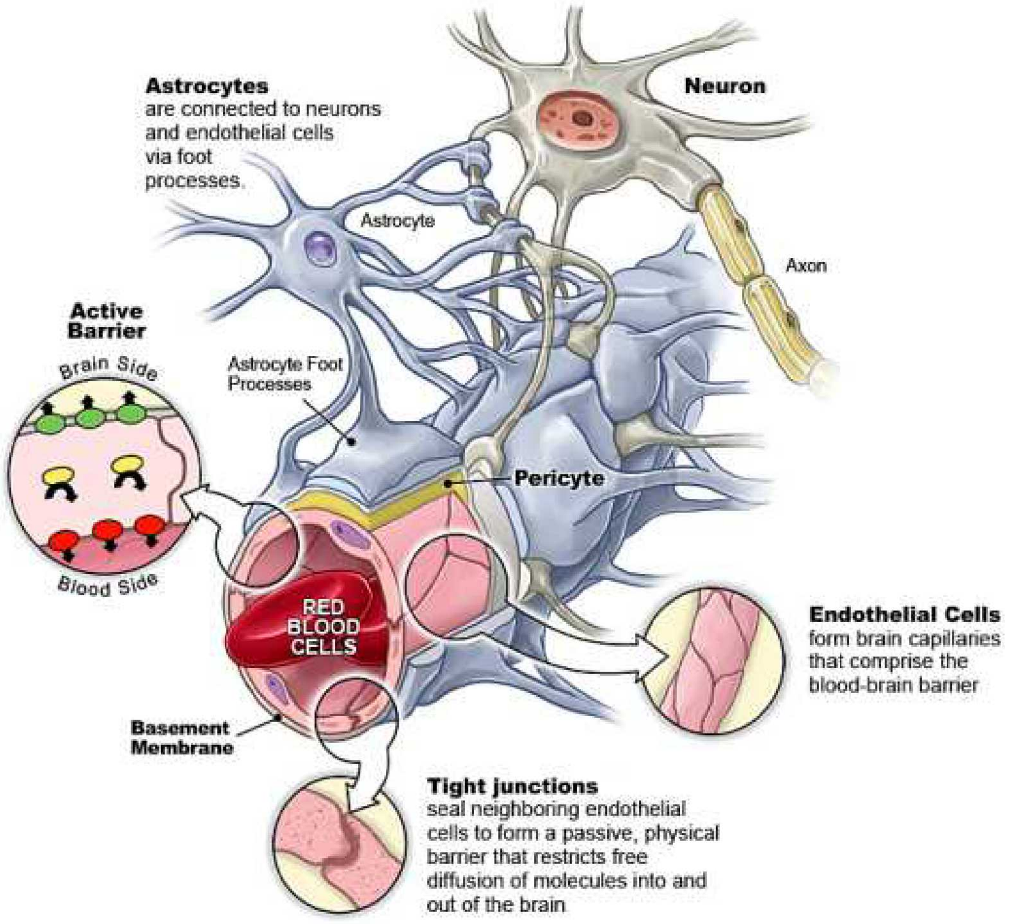


Bubble C



Difference between the peaks in the upstream and downstream pressure histories indicate a unidirectional collapse of the bubbles leading to microjetting (directed downstream)

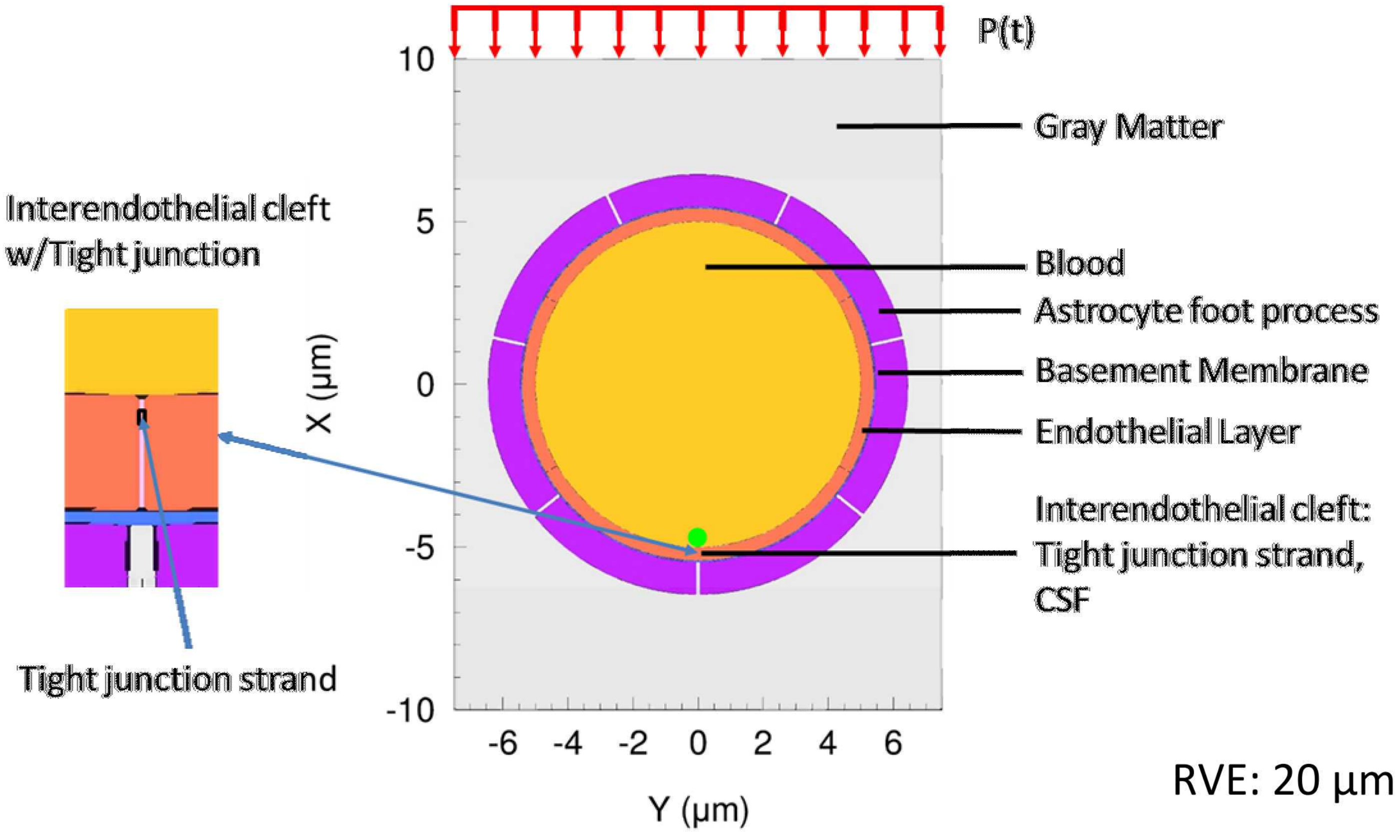
What is the blood brain barrier?



http://kollathdesign.com/portfolio/university-of-minnesota-college-of-pharmacy-duluth-blood-brain-barrier/

- Semi-permeable passageway between the circulating blood and the cerebrospinal fluid in the Central Nervous System (CNS) formed by endothelial cells connected by tight junctions
- Protects the CNS tissues, especially neurons, against harmful substances
- Allows the passage of water, some gases, and lipid-soluble molecules as well as molecules such as glucose and amino acids
- Astrocytes surrounding the endothelial cells provide support

Microscale Model of the Blood Brain Barrier



RVE: 20 µm x 15 µm x 5 µm

Parameters:
Compressive wave amplitude – 0, 400, 700 kPa
Bubble diameter – 0.025, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35 µm
Standoff distance (bubble center to wall/bubble radius) – 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 3.5, 4.0

If bubble collapse causes a member of the BBB to fail, the barrier breaks down, which could lead to neuroinflammation (meningitis) or neurodegeneration

Material Model

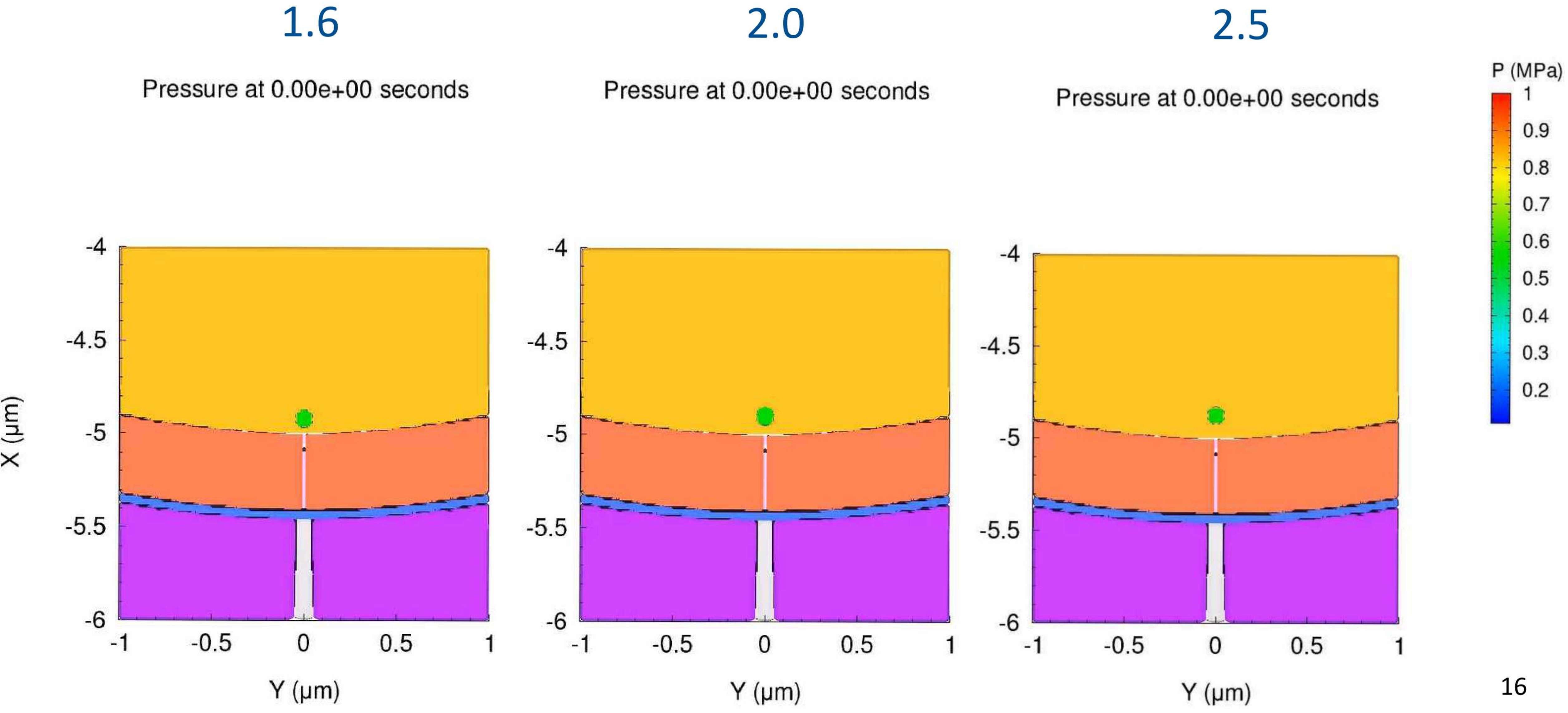
Material	Volumetric Response	Deviatoric Response
Gray Matter	Tillotson-Brundage	Swanson
Astrocyte	Tillotson-Brundage	Swanson
Basement Membrane	Tillotson-Brundage	von Mises
Tight Junction Strand	Mie-Gruneisen	Swanson
Endothelial Cells	Tillotson-Brundage	Swanson
Blood	Tillotson-Brundage	-
CSF	Tillotson-Brundage	-
Bubble contents	Sesame Tabular EOS	-

- EOS (volumetric response)
  - Equations relating pressure, volume, and temperature
  - The Tillotson-Brundage EOS accurately captures the respective bulk properties under compression and their susceptibility to fluid cavitation when subjected to isotropic tension (i.e. tensile pressure)
- Constitutive model (deviatoric response)
  - Use Swanson hyperelastic model for gray matter, astrocytes, endothelial cells, and tight junction strand [3]
  - Use von Mises for basement membrane

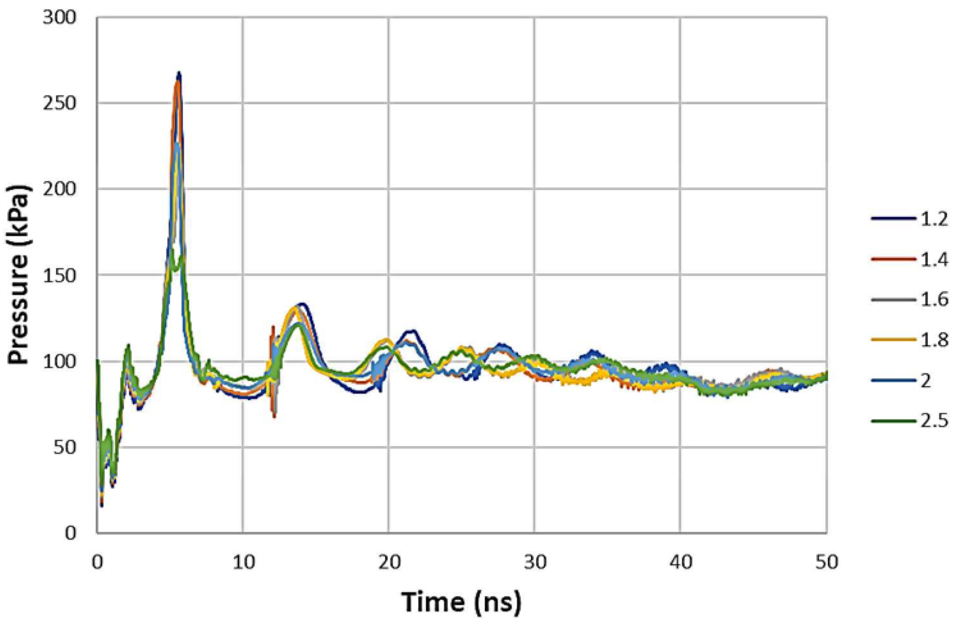
[3] Swanson, S. R., 1985, "A constitutive model for high elongation elastic materials," Trans. Am. Soc. Mech. Eng., **107**, pp. 110–114.

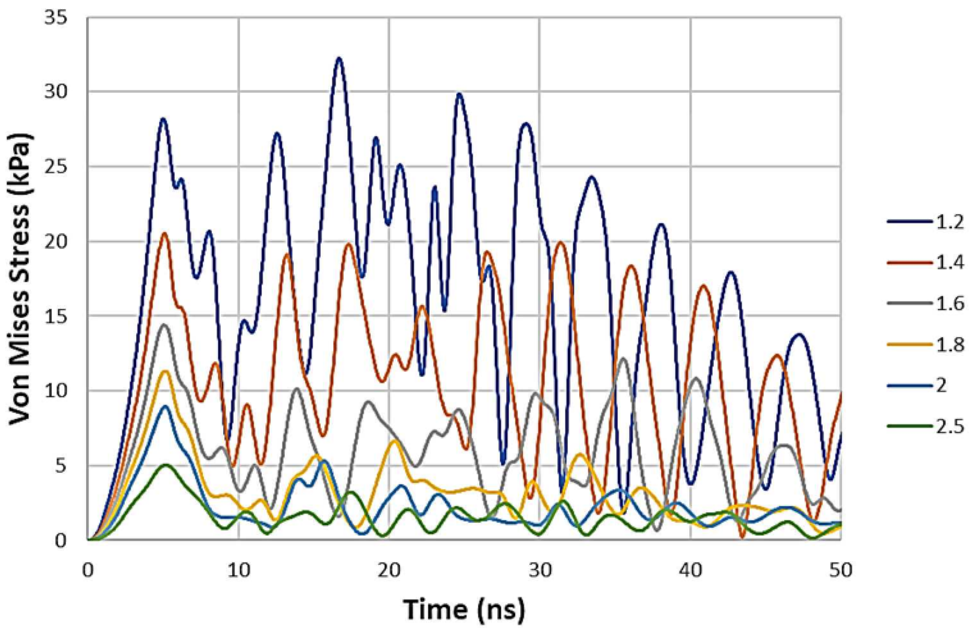
Effect of Standoff Distance

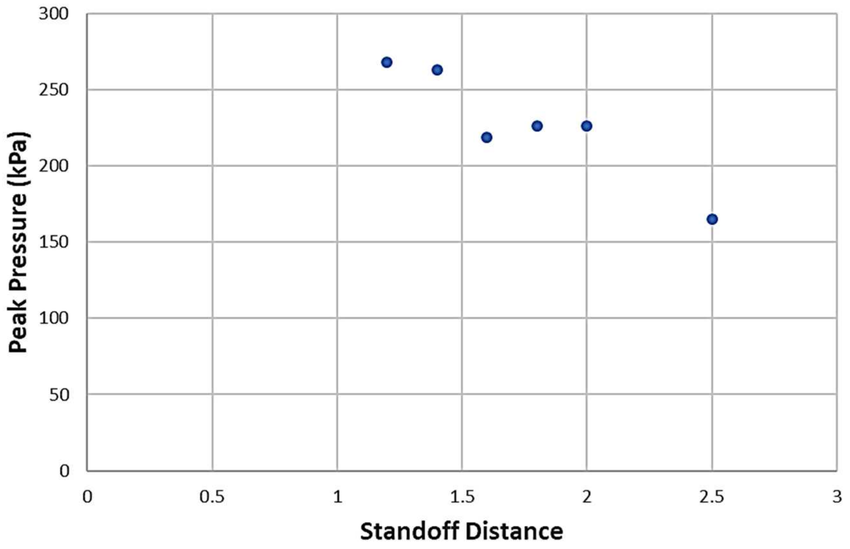
0.10 μm diameter bubble



Effect of Standoff Distance





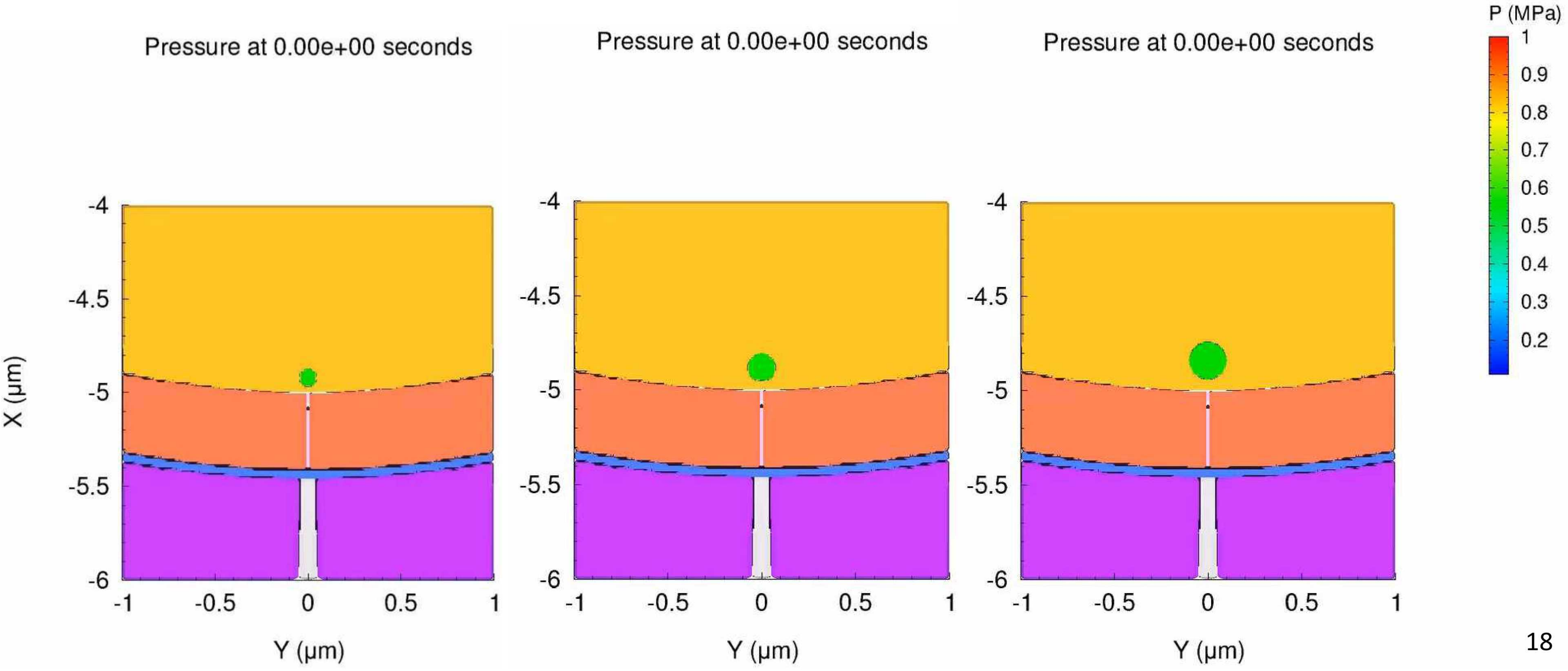


Data taken at tight junction strand
Bubble diameter: 0.10 um

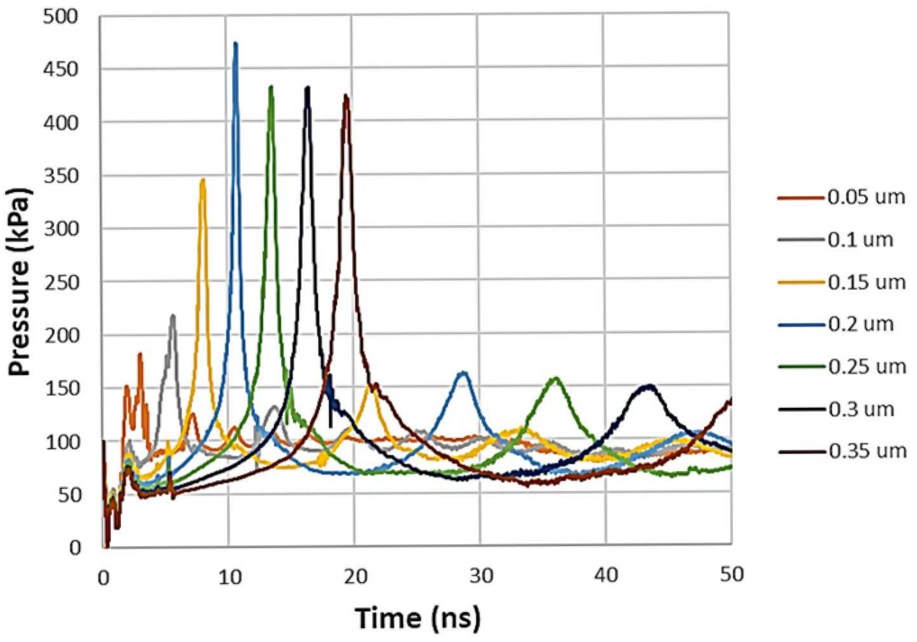
Effect of Bubble Diameter

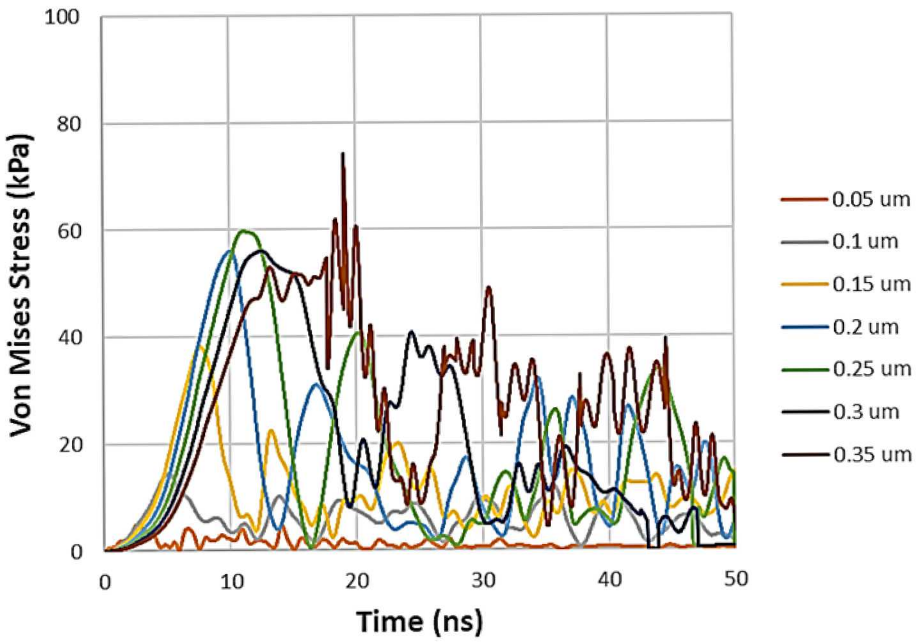
1.6 standoff distance

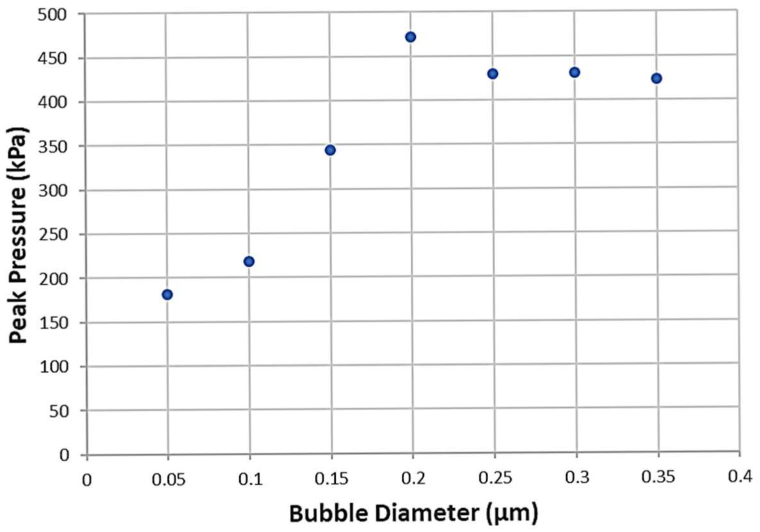
0.10 µm | 0.15 µm | 0.20 µm



Effect of Bubble Diameter







Data taken at tight junction strand

Standoff distance: 1.6

Path Forward

Task 1 Micromechanical Models	Task 2 Cavitation Experiment	Task 3 Injury Risk

Task 1 – Micromechanical Models

- Investigate blast-induced brain damage as a result of fluid cavitation at the microscale level
- Determine whether certain structures in the brain such as white matter axonal fiber bundles or the blood brain barrier are at risk from cavitation

Task 2 – Cavitation Experiment

- Design of an experiment
- Use **novel** x-ray imaging

"X-ray movie of fast event"

Visualize damage from cavitation

- *In Vitro* (animal surrogate)
- Contemporaneous, not just *ex post facto* histology
- See through opaque skin/skull without mechanical modification (e.g., probes, cranial windows).

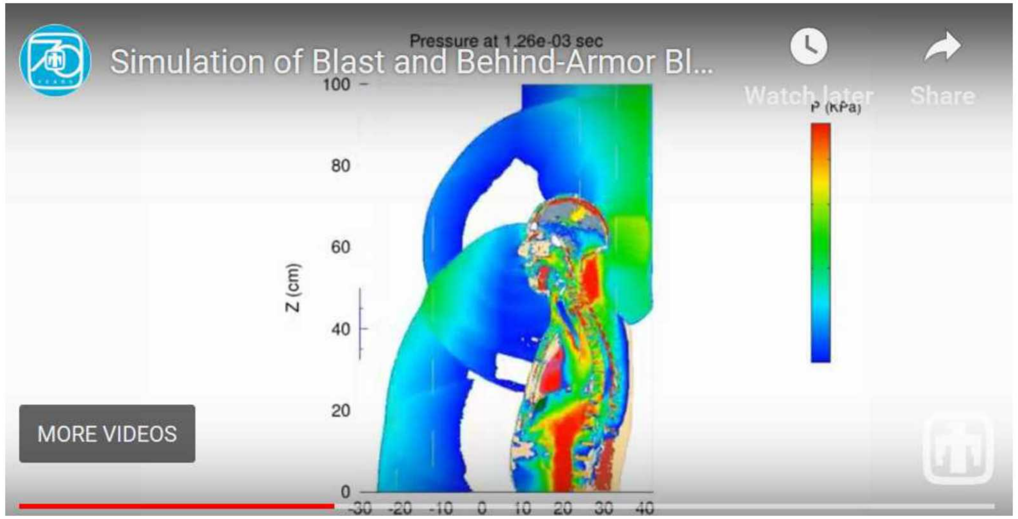
Task 3 – Injury Risk

- Quantify percent of brain, by volume, that is exposed to high vapor fraction, as a function of blast overpressure.
- Vapor fraction is portion of a given volume that has predicted to undergo a phase change from liquid to vapor.
- High vapor fraction is suggestive for the potential for cavitation, since is it caused by tensile pressures on hydrated tissues.

Summary

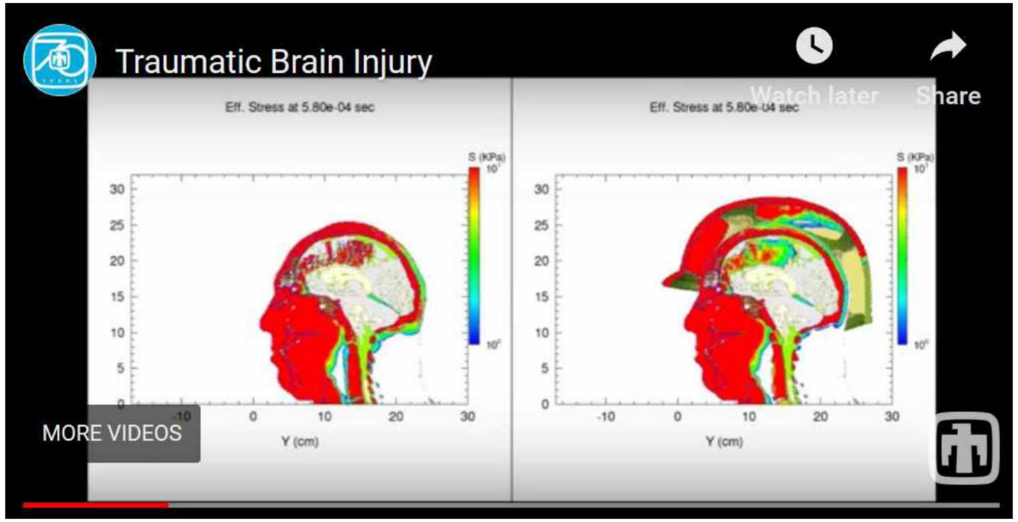
What we have learned …

- Macroscale **blast simulations** predict regions of intra-cranial **fluid cavitation**.
- Formation of **vaporized cerebrospinal fluid** is predicted in posterior regions of the brain.
- The process of **bubble formation**, **collapse**, and **jetting** is theorized as a possible injury mechanism.
- As standoff distance increases, peak pressure decreases.
- **Increase in bubble diameter** up to critical diameter of 0.2um **increases peak pressure**. Thereafter peak pressure plateaus with increasing bubble diameter.
- **Increases in bubble diameter** cause delays in **peak pressure arrival time.**



Head/neck/torso high-fidelity human models

- high-fidelity: 6M elements, 1-mm resolution
- finite volume and finite element
- blast, blunt, and ballistics



Please see www.sandia.gov/biomechanics for

- simulation videos
- UUR publications, SAND Reports

Acknowledgements

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- Office of Naval Research (ONR)

Thank You

Sandia Injury Biomechanics Laboratory (SIBL)
www.sandia.gov/biomechanics