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

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Blast – C2B2
Blunt Impact - Panther

Protect the U.S. Warfighter
Multiscale Model of Cavitation Injury
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
$X = 340 \text{ mm} = 34.0 \text{ cm}$

Mid-sagittal + 2 cm offset
$X = 360 \text{ mm} = 36.0 \text{ cm}$
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

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
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 ± 0.15 µm

Microscale Model of the White Matter Axon Fiber Bundle

Pressure

400 kPa compressive wave

Damage at final time of 69 ns
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?

- 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

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Volumetric Response</th>
<th>Deviatoric Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray Matter</td>
<td>Tillotson-Brundage</td>
<td>Swanson</td>
</tr>
<tr>
<td>Astrocyte</td>
<td>Tillotson-Brundage</td>
<td>Swanson</td>
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<tr>
<td>Basement Membrane</td>
<td>Tillotson-Brundage</td>
<td>von Mises</td>
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<tr>
<td>Tight Junction Strand</td>
<td>Mie-Gruneisen</td>
<td>Swanson</td>
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<tr>
<td>Endothelial Cells</td>
<td>Tillotson-Brundage</td>
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<tr>
<td>Blood</td>
<td>Tillotson-Brundage</td>
<td>-</td>
</tr>
<tr>
<td>CSF</td>
<td>Tillotson-Brundage</td>
<td>-</td>
</tr>
<tr>
<td>Bubble contents</td>
<td>Sesame Tabular EOS</td>
<td>-</td>
</tr>
</tbody>
</table>

- **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

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Effect of Standoff Distance

0.10 μm diameter bubble

1.6  2.0  2.5
Effect of Standoff Distance

Data taken at tight junction strand
Bubble diameter: 0.10 um
Effect of Bubble Diameter

- 0.10 µm
- 0.15 µm
- 0.20 µm

1.6 standoff distance
Effect of Bubble Diameter

Data taken at tight junction strand
Standoff distance: 1.6
Path Forward

**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

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Thank You

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