Study motivation and hypothesis

- Experiment: Blunt impact to porcine carotid arteries → intimal-side damage
- Simulation: Use finite element method to determine dynamic strains within the vessels during this experiment
  - How do computed strain values compare to what is known about carotid artery injury?

Blunt cerebrovascular injury (BCVI)

- Blunt injury to either carotid or vertebral arteries
- Uncommon injury, but potentially devastating consequences
  - 1% of trauma admissions
  - Mortality (40%), morbidity (40-80%)
- Injury causation
  - Car crash, stretching
- Injury mechanisms (regional level)
  - Blunt impact, hyperextension / rotation, skull / vertebral body fracture
- Injury mechanisms (tissue level)
  - tension, pinching (intima-intima contact)

Pathophysiology and study goals

Intimal Damage
  - Thrombosis
  - Embolism
  - Occlusion

- Study Goal: Develop and validate an organ level model of the carotid artery for prediction of strain to intimal damage
**FE model development strategy**

1. Tissue Level
2. Organ Level
3. Regional Level

**Experimental protocol for blunt impact test**

- Porcine carotid arteries
  - Impacted from 3 heights
  - Indenter motion stopped by foam (no sudden stop)
  - Saline filled, (zero gauge pressure)
  - Free end conditions
- Data from experiment
  - Video of drop
  - Percent injury based on drop height

2.4 kg steel indenter, 5 mm beveled tip

**Experiment results**

<table>
<thead>
<tr>
<th>Drop Height (m)</th>
<th>Impact Velocity (m/s)</th>
<th>n tests</th>
<th>Injury Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>2.4</td>
<td>2</td>
<td>0%</td>
</tr>
<tr>
<td>0.5</td>
<td>3.1</td>
<td>4</td>
<td>25%</td>
</tr>
<tr>
<td>0.7</td>
<td>3.7</td>
<td>4</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Used to develop FE model*

**Finite element model of experiment**

- Indenter
  - Shell Elements
  - Steel
- Eulerian Mesh
  - Solid Elements
- Vessel
  - Shells
  - `Mat_Simplified_Rubber`
- Foam
  - Solid
  - `Mat_Low_Density_Foam`

**Simulation results**

- Mesh constructed from video of impact test (image, NIH)
- Validation procedures conducted by tracking indenter and foam motion on high speed video
Regions of Interest

- Lower vessel
  - Mirror of Upper vessel
- Side vessel

Upper vessel strain, 3 drop heights

Evidence of intima-intima contact

Finite Element Model vs. Experiment

Discussion: Model results vs. literature

- Finite element model strain approaches published values in the literature

<table>
<thead>
<tr>
<th>Loading Rate</th>
<th>Tissue</th>
<th>Diameter (mm)</th>
<th>Pre-conditioning</th>
<th>Strain to sub-failure (true, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-static</td>
<td>Porcine descending aorta</td>
<td>8.5±1.5</td>
<td>5 cycles @ 1 mm/sec</td>
<td>ε = 49</td>
</tr>
<tr>
<td>Dynamic ~70strain/sec¹</td>
<td>Porcine carotid artery</td>
<td>5.1±0.6</td>
<td>None</td>
<td>40 &lt; ε &lt; 46</td>
</tr>
</tbody>
</table>

Study limitations

- Experimental design precludes direct validation of arterial strain
- Model should include strain rate dependency:
  - FE model strain rate of >70 strain/sec¹
  - Aorta test up to 80 strain/sec¹
    - (Mohan and Melvin, 1982, J. Biomech.)
  - Arterial sub-failure tested at 30 strain/sec¹
    - (Stemper et al., J Biomech., in press)
Current and future research

Regional level model development and validation:

- Contrast-enhanced CT
- Regional carotid

Ongoing Research

Current research

- Further organ level validation: Quantifying soft tissue thickness in cervical region

Carotid region morphology study

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance to Skin</th>
<th>Distance to Vertebral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>Internal</td>
<td>36</td>
<td>7</td>
</tr>
<tr>
<td>External</td>
<td>38</td>
<td>11</td>
</tr>
</tbody>
</table>

Model validation slides

Acknowledgments

- Collaborators:
  - Dr. Brian Stemer and Dr. Frank Pintar, Medical College of Wisconsin
  - Josh Tan, Wake Forest University Baptist Medical Center
- Funding:
  - Australian Research Council Linkage Grant
  - Department of Veterans Affairs Medical Research

The funding for this research has been provided in part by an Australian Research Council linkage grant and by private parties, who have selected Dr. Kenneth Diggers and PHA/RMNTSA National Crash Analysis Center at the George Washington University to be an independent auditor of end funder for research in motor vehicle safety, and to be one of the peer reviewers for the research projects and reports.
**Indenter Motion Profile**

Test Matrix

- 0.3m
- 0.5m
- 0.7m

**Foam motion profile**

- 0.3 m simulation
- 0.3 m video
- 0.5 simulation
- 0.5 m video
- 0.7 simulation
- 0.7 m video

**Foam Material Model Summary**

- `MAT_low_density_foam`
  - Direct curve fit model
- Solid elements
- Use load curve to define nominal stress-strain curve
- DAMP — Viscous coefficient to model damping

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>(36 \times 10^{-6}) g/mm(^3)</td>
</tr>
<tr>
<td>( E )</td>
<td>0.236 MPa, [N/mm(^2)]</td>
</tr>
<tr>
<td>DAMP</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Material Model - Foam**

- Ethafoam 200 data sheet
- Ethafoam 220 compression test

**Evidence of intima-intima contact**

- 0.3 m Drop
- 0.5 m Drop
- 0.7 m Drop

- Distance between nodes, mm

\[ \text{Distance between nodes, mm} \]

\[ \text{0.3 m Drop} \]

\[ \text{0.5 m Drop} \]

\[ \text{0.7 m Drop} \]

\[ \text{Distance, mm} \]

\[ \text{Time, ms} \]
Material model summary

- MAT_simplified_rubber
  - Direct curve fit model
- Shell elements
- Model is robust
  - Parameter study
  - Mesh density study
- Strain rate effects and damage can be incorporated
  - Enter curves at discrete strain rates
  - Damage function can be implemented

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>0.001 g/mm(^3)</td>
</tr>
<tr>
<td>( K )</td>
<td>2610 MPa, [N/mm(^2)]</td>
</tr>
<tr>
<td>( G )</td>
<td>5.2 MPa, [N/mm(^2)]</td>
</tr>
<tr>
<td>SIGF</td>
<td>5.2 kPa, [N/mm(^2)]</td>
</tr>
<tr>
<td>HG</td>
<td>Stiffness</td>
</tr>
</tbody>
</table>

Material Model - Artery

Tissue level validation

Material Model and Mathematics

Finite element model of impact test