An Experimental and Finite Element Study of the Porcine Carotid Artery Under Dynamic Loading

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Center for Injury Biomechanics

WAKE FOREST UNIVERSITY SCHOOL of MEDICINE THE BOWMAN GRAY CAMPUS

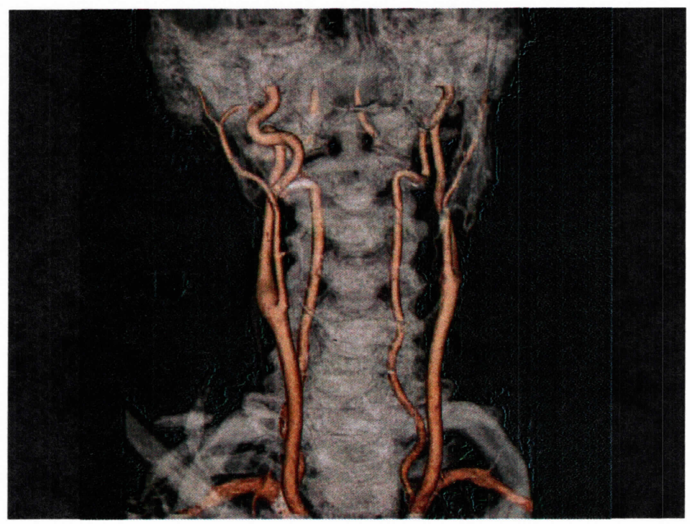
Virginia Tech COLLEGE of ENGINEERING

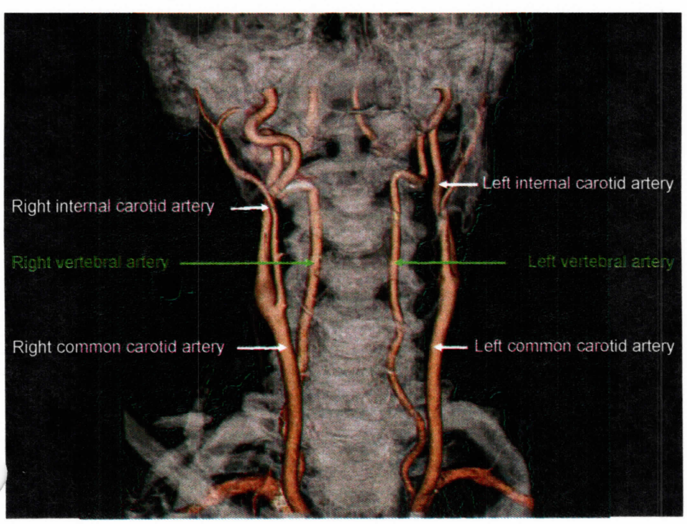
Study motivation and hypothesis

- 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)

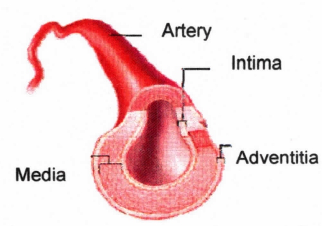
- Blunt injury to either carotid or vertebral arteries
- Uncommon injury, but potentially devastating consequences
  - 1% of trauma admissions
  - Mortality(40%), morbidity(40-80%)
- Injury causation
  - Car crash, stretching
- Injury mechanisms (regional level)
  - Blunt impact, hyperextension / rotation,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



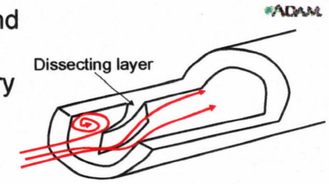


Pathophysiology and study goals

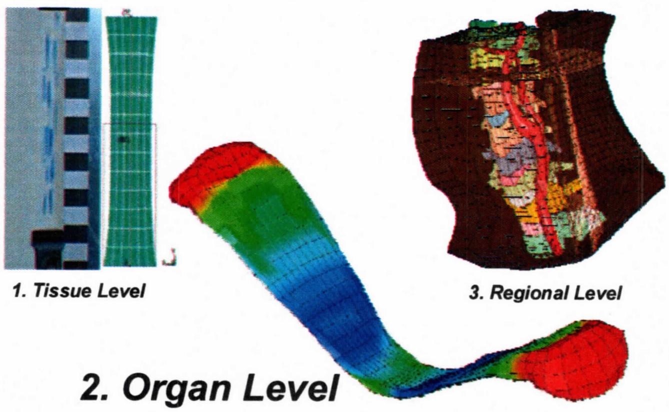
Intimal Damage
↓ Thrombosis
Dissection
↓ Embolism
Occlusion



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

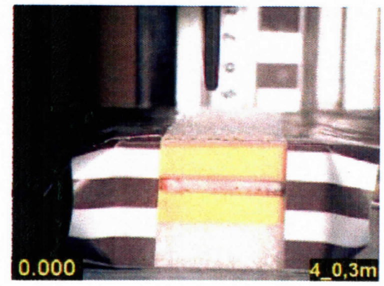


FE model development strategy



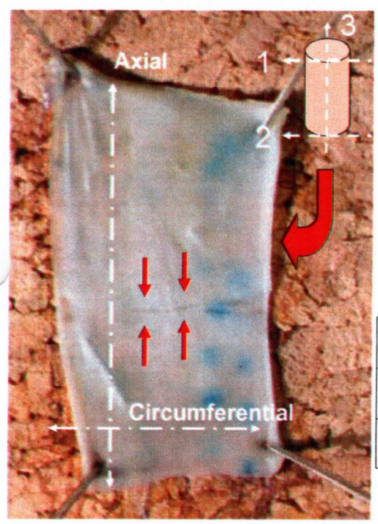
Experimental protocol for blunt impact test

- 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



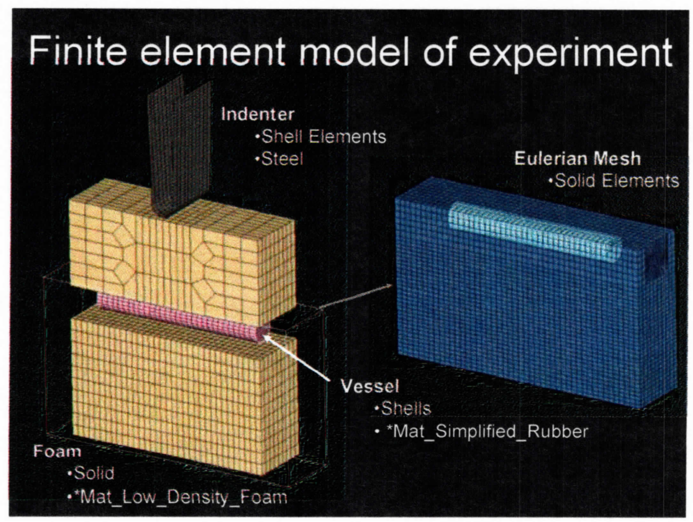
2.4 kg steel indenter, 5 mm beveled tip

Experiment results

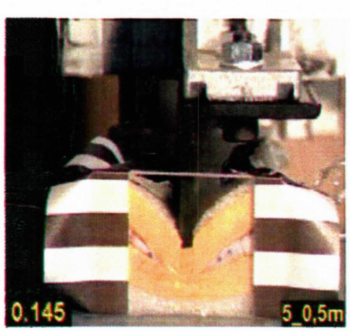


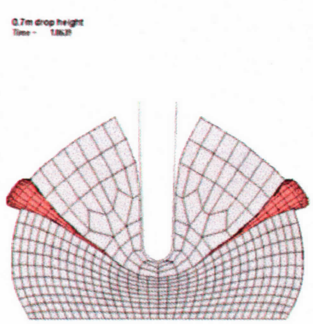
Drop Height (m)	Impact Velocity (m/s)	n tests	Injury frequency
0.3	2.4	2	0%
0.5	3.1	4	25%
0.7	3.7	4	100%

Used to develop FE model

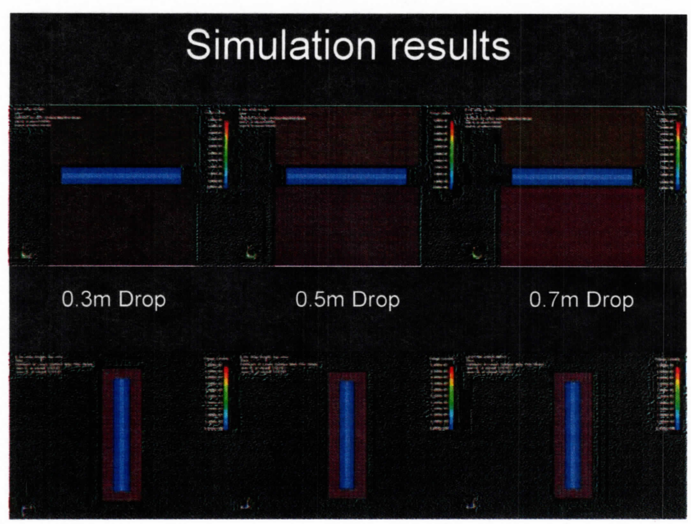


Boundary conditions and validation procedures

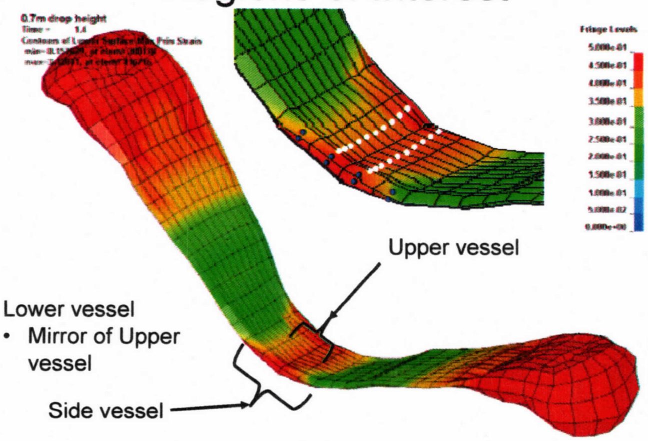




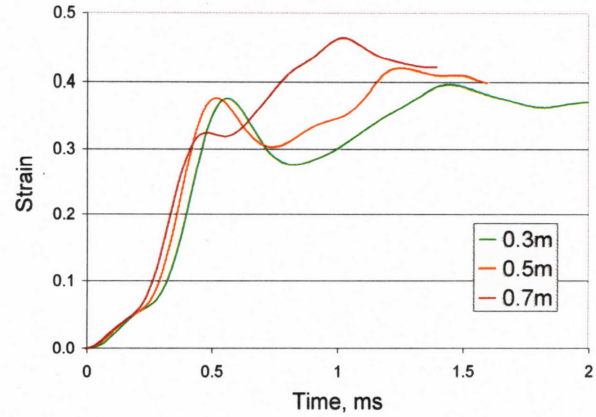
- Mesh constructed from video of impact test (*imageJ, NIH*)
- Validation procedures conducted by tracking indenter and foam motion on high speed video



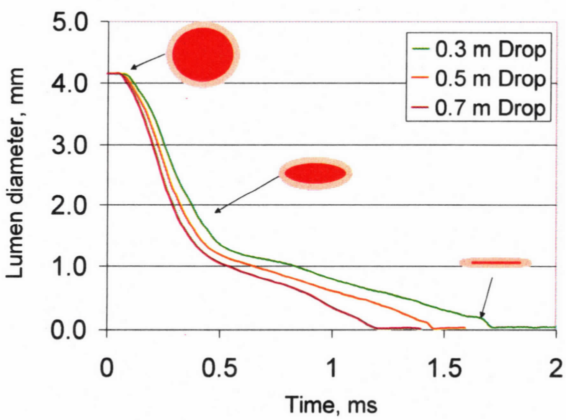
Regions of Interest



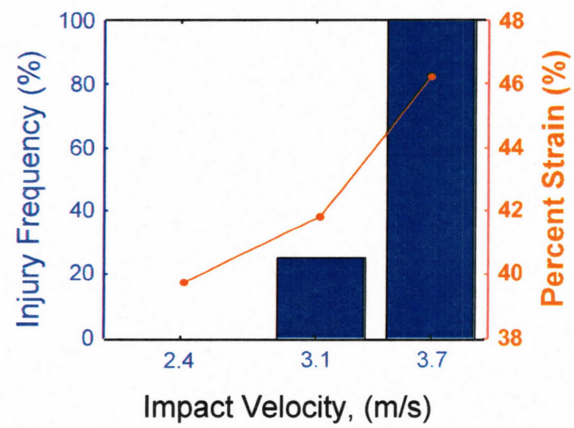
Upper vessel strain, 3 drop heights



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

Loading Rate	Tissue	Diameter (mm)	Pre-conditioning	Strain to sub-failure (true, %)
Quasi-static	Porcine descending aorta	8.5±1.5	5 cycles @ 1 mm/sec	ε = 49
Dynamic ~70strain*sec^{-1}	Porcine carotid artery	5.1±0.6	None	40 < ε < 46

Study limitations

- Experimental design precludes direct validation of arterial strain
- Model should include strain rate dependency:
  - FE model strain rate of >70 strain•sec^{-1}
  - Aorta test up to 80 strain•sec^{-1}
    - (Mohan and Melvin, 1982, J. Biomech.)
  - Arterial sub-failure tested at 30 strain•sec^{-1}
    - (Stemper et al., *J Biomech.*, in press)

Current and future research

Regional level model development and validation:

Contrast-enhanced CT | Regional carotid

Acknowledgments

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  - **Josh Tan**, Wake Forest University Baptist Medical Center
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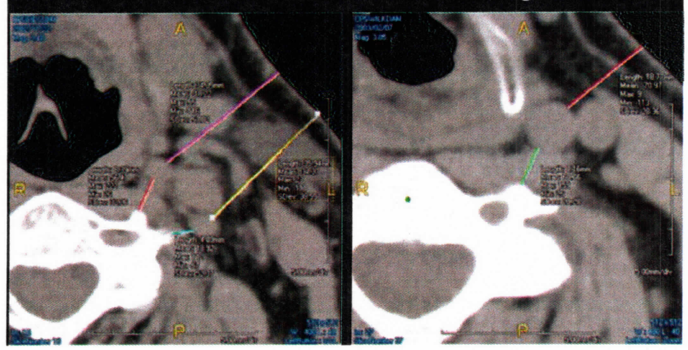
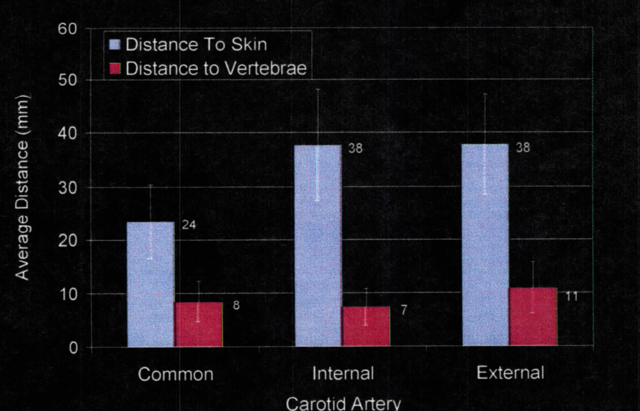
Ongoing Research

Current research

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

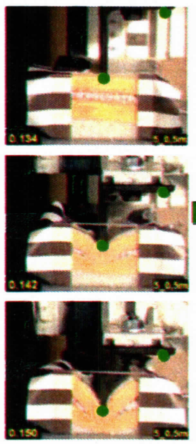


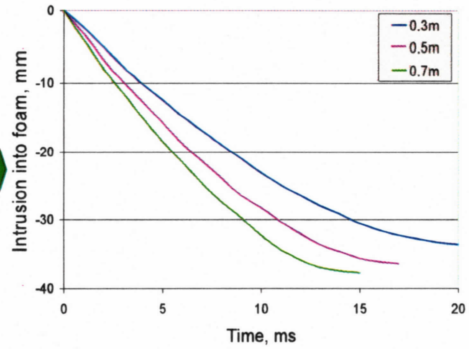
Carotid region morphology study



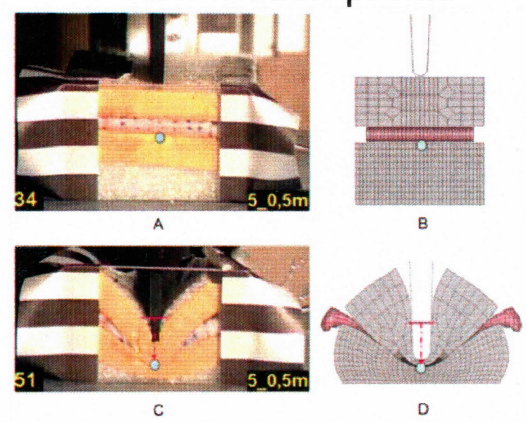
Model validation slides

Indenter Motion Profile Test Matrix





Foam motion profile



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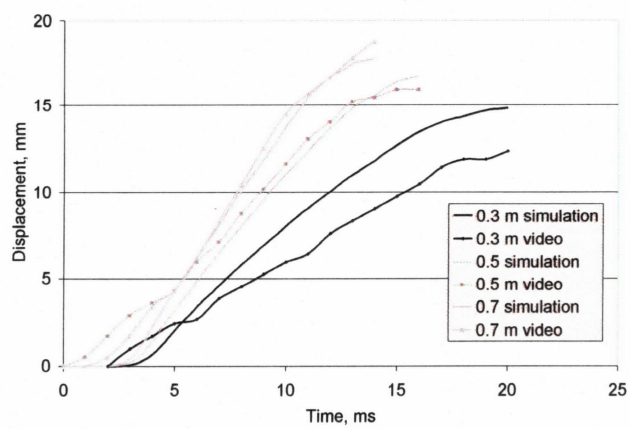
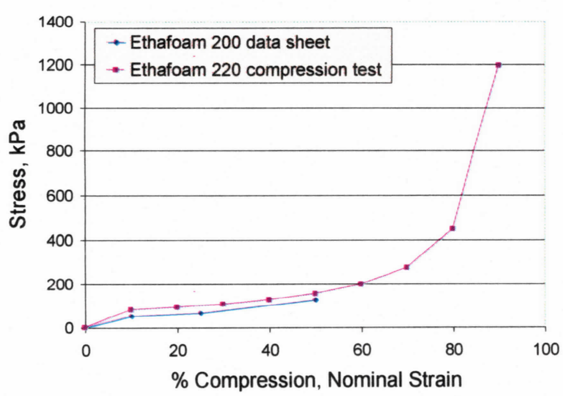


Foam Material Model Summary

- *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

ρ	$36x10^{-6}$	g/mm^3
E	0.236	MPa, $[N/mm^2]$
DAMP	0.5	

Material Model - Foam



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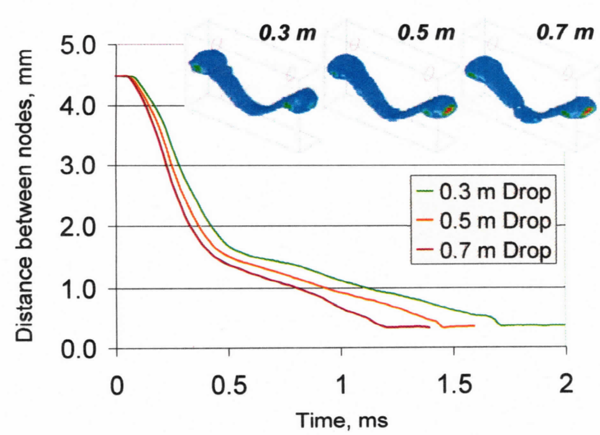
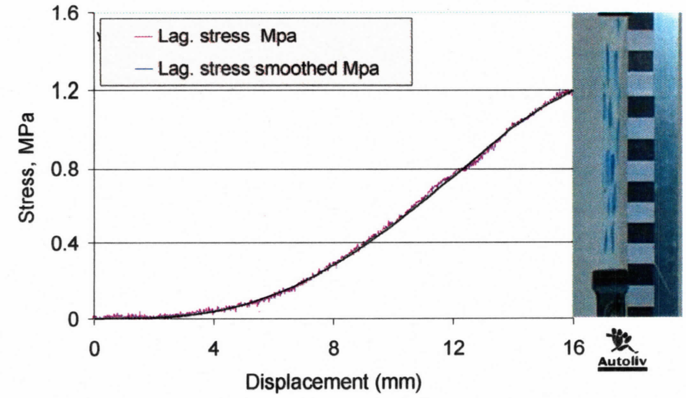


Material model summary

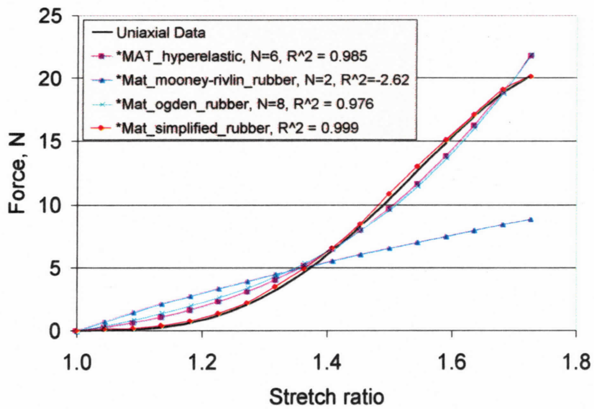
- *MAT_simplified_rubber
  - Direct curve fit model
- Shell elements
- Model is robust
  - Parameter study
  - Mesh density study
- Strain rate effects and damage can be incorporated
  - Enter curves at discrete strain rates
  - Damage function can be implemented

ρ	0.001	g/mm³
K	2610	MPa, [N/mm²]
G	5.2	MPa, [N/mm²]
SIGF	5.2	kPa, [N/mm²]
HG	Stiffness	

Material Model - Artery



Tissue level validation



Material Model and Mathematics

Finite element model of impact test