ARC Farside Meeting Update
Task 3: Carotid Artery

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Center for Injury Biomechanics

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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)

Background and significance

- Cervical artery dissection begins as a tear of the intimal lining
  - Over time → luminal occlusion → cerebral ischemia
- Internal carotid artery dissection (ICAD) is 3 to 5 times more frequent than vertebral artery dissection *(Schievink et al. 1994, Haneline, et al. 2003)*
- 30% of all ICAD cases are attributed to some form of trauma *(Haneline and Lewkovich, 2005)*

Pathophysiology and study goals

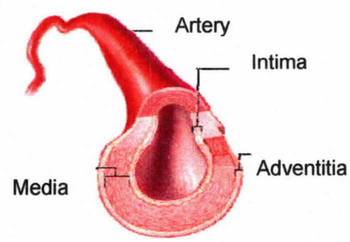
Intimal Damage

↓ Thrombosis

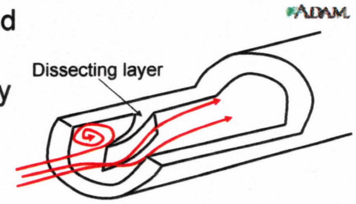
Dissection

↓ Embolism

Occlusion



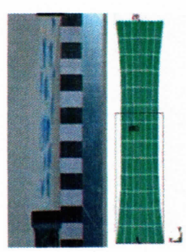
- **Study Goal:** Develop and validate an *organ level* model of the carotid artery for prediction of strain to intimal damage



Carotid artery modeling purpose and goals

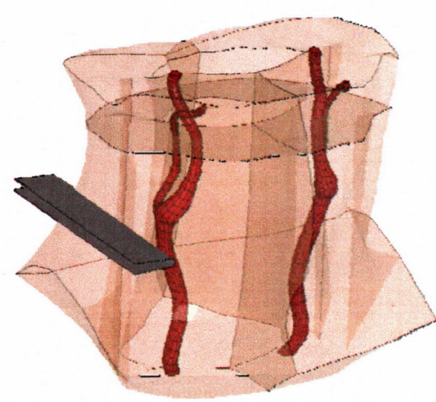
- Computational model of the carotid artery for the prediction of injury
- What's been done:
  - Develop a robust material model and mesh of the artery *(Gayzik et al. RMBS, 2005)*
  - Organ level validation of the material model *(Gayzik et al. AAAM 2006, Gayzik et al. ASB 2006)*
- Currently:
  - Regional level neck model

FE model development strategy

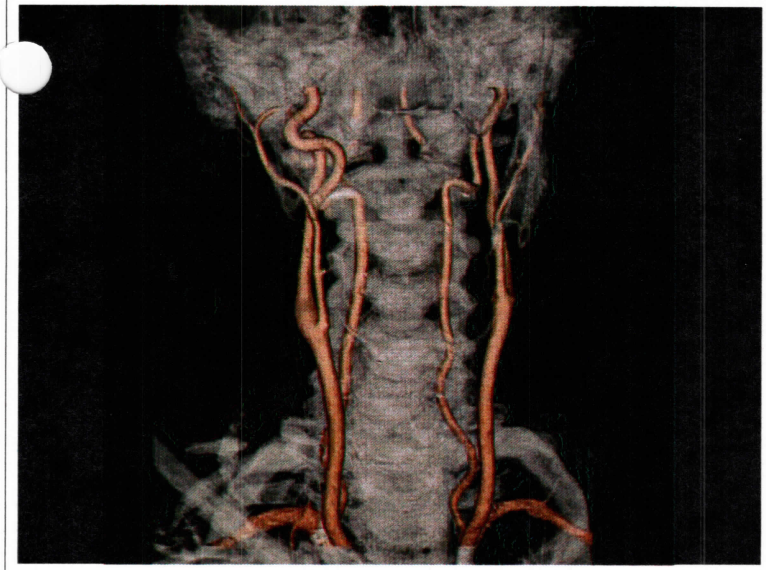


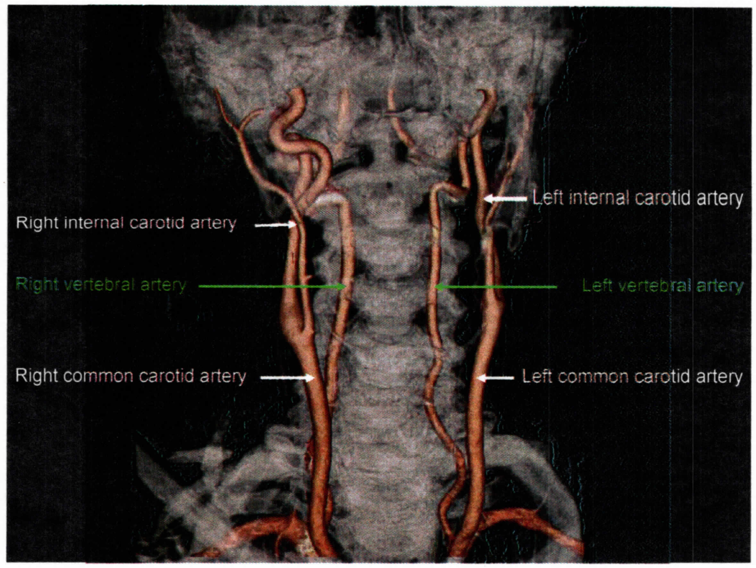
1. Tissue Level

2. Organ Level



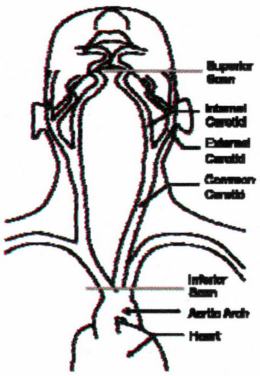
3. Update: Regional Level





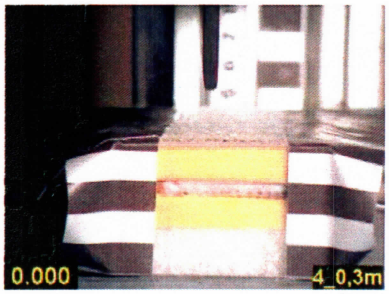
Review: Mesh development of carotid artery

- Model constructed (CT) angiography of 57 year old male
- A total of 270 scans with slice thickness = 0.625mm
- Image data is from left carotid artery



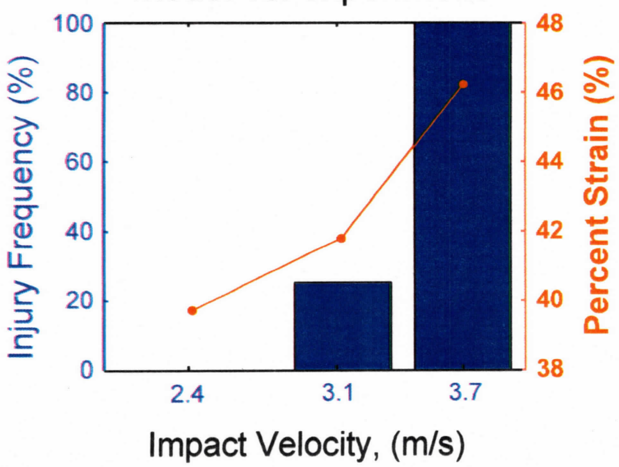
Review: Experimental protocol for organ-level impact test

- 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

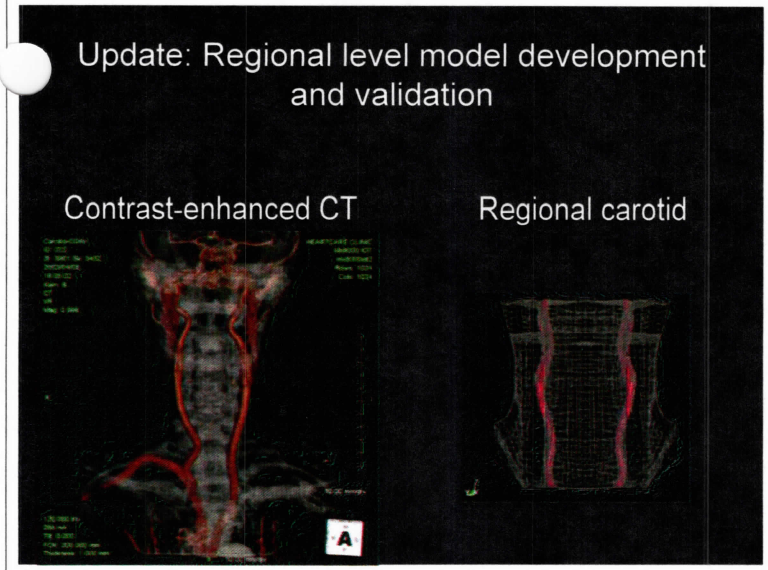
Review: Organ level testing finite element model vs. experiment

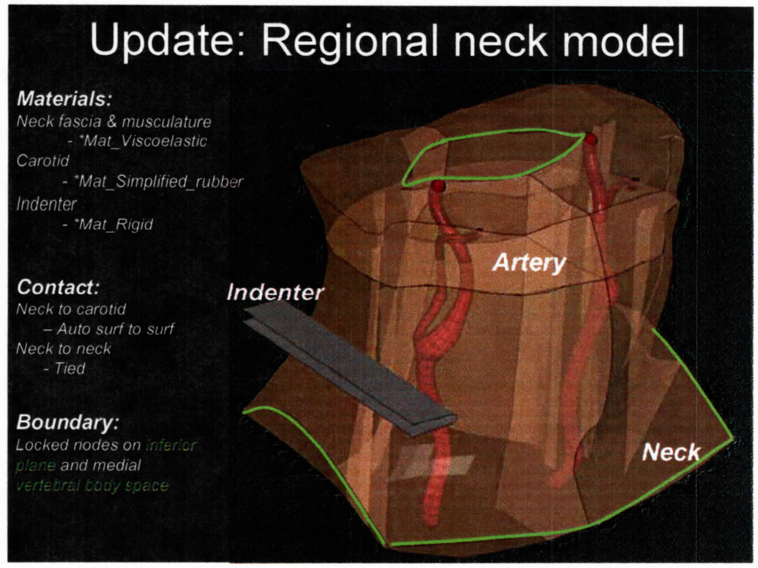


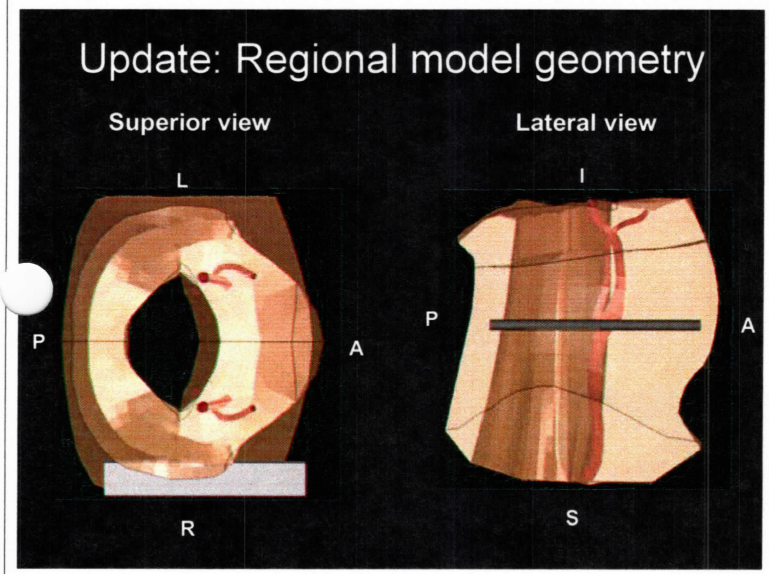
Review: Model results vs. literature

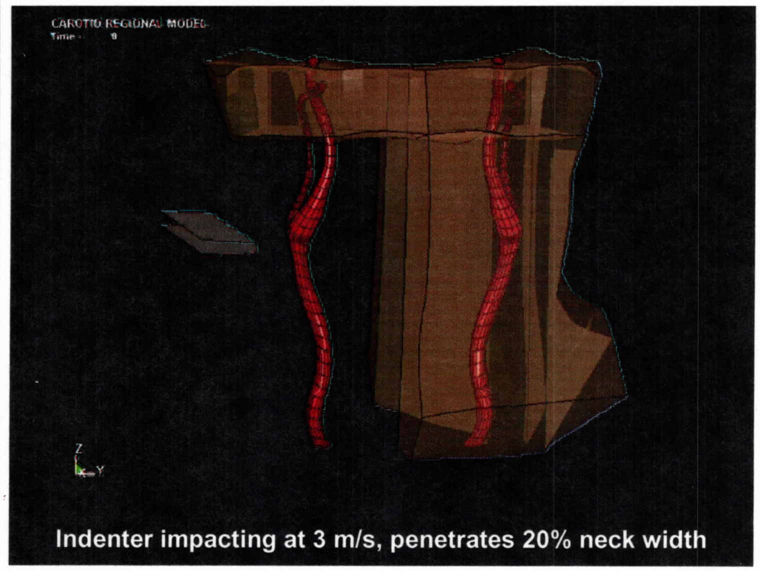
- Finite element model strain approaches published values in the literature

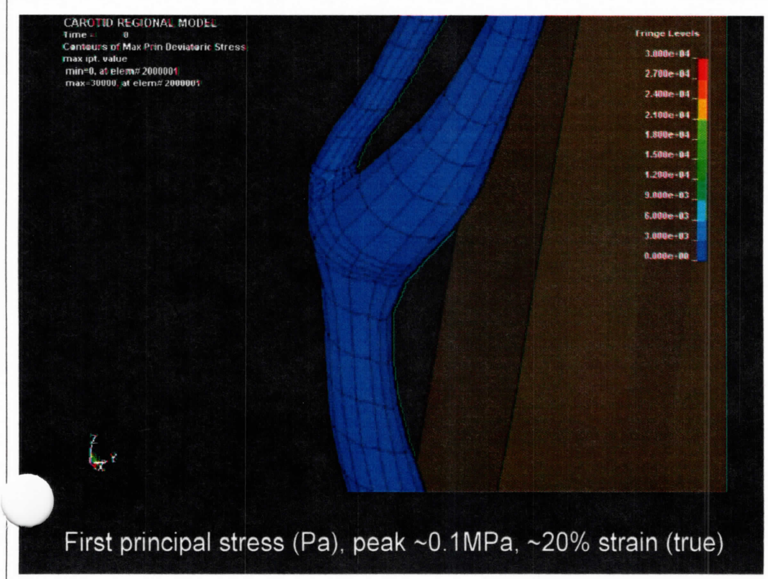
Loading Rate	Tissue	Diameter (mm)	Pre-conditioning	Strain to sub-failure (true, %)
Quasi-static	Porcine descending aorta	8.5±1.5	5 cycles @ 1 mm/sec	ε = 49
Dynamic ~70strain*sec^{-1}	Porcine carotid artery	5.1±0.6	None	40 < ε < 46











Proposed regional model simulation matrix

PMHS Test No.	Carotid Injury	Belt Position	ΔV
134	No	Low	Low
135	No	Low	High
140	Yes	High	Low
141	Yes	High	High

Use T1 and head accelerations or displacements and belt reaction forces for model validation

MCW Sled Test Configuration Chart

Test Number	Low Delta-V	High Delta-V	Outboard Belt (0)	Pelvis (1)	Thorax (2)	Shoulder (3)	Inboard Belt (4)	3-pt belt pre-tension	Inboard belt HIGH	Inboard belt LOW	90-Deg test	60-Deg test	D-ring forward	
1		X	X	X				X			X			
2	X		X	X								X		
3		X	X	X								X		
4	X			X	X		X			X	X			
5	X			X		X	X			X	X			PMHS 134
6		X		X	X		X			X	X			
7		X		X		X	X			X	X			PMHS 135
8	X			X			X		X		X			PMHS 140
9		X		X			X		X		X			PMHS 141
10	X		X	X							X		X	
11		X	X	X							X		X	
12	X			X	X		X	X		X		X		
13		X		X	X		X	X		X		X		
14	X			X			X		X			X		
15		X		X			X		X			X		
16		X	X	X		X		X			X			
17		X	X	X	X			X			X			
18		X		X			X	X		X	X			
19		X		X			X	X		X		X		

Have data from MCW for these 4 tests.

Update: Regional neck model with embedded carotid artery

- Current modeling issues and tasks
  - Fluid-filled carotid
    - Issues with fluid-solid interface
  - Include boundary conditions on bony structures
    - Vertebral motion from full body model will be used as boundary condition
  - Apply belt loading
    - Current indenter is modified version of sausage testing

Acknowledgments

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  - Far Side Group
  - Josh Tan, Wake Forest University Baptist Medical Center
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  - Department of Veterans Affairs Medical Research

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Supplemental Slides

Model Information

Model Information at State 1:

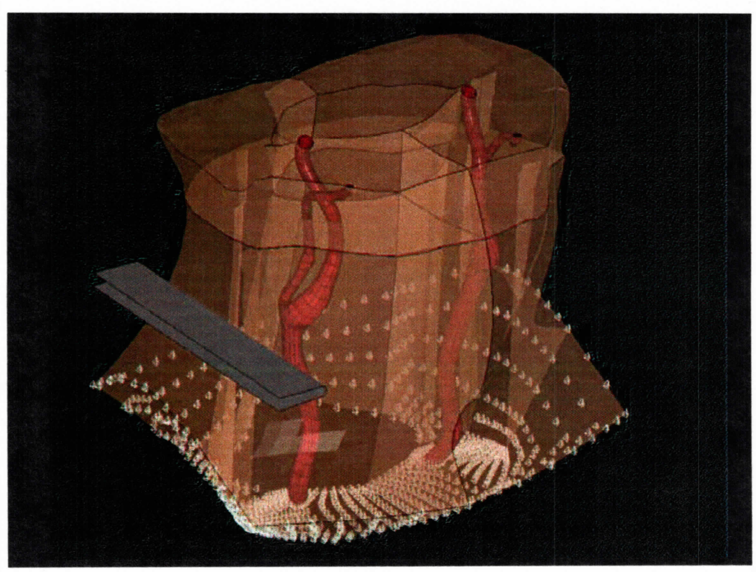
42912 Nodes
3794 Shells, 3 Shell Materials
33756 Solids, 4 Solid Materials
1170 Rigid Elements
36380 Deformable Elements

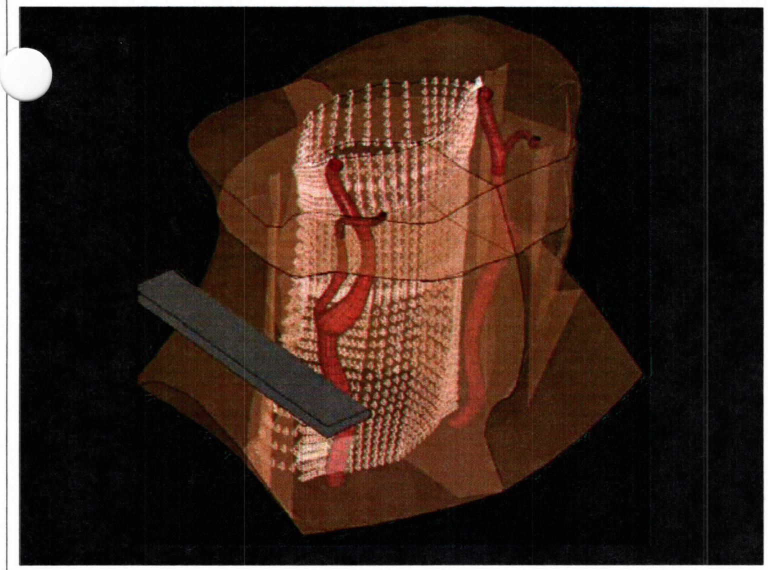
Total no. of Elements = 37550
Total no. of Materials (Parts) = 7

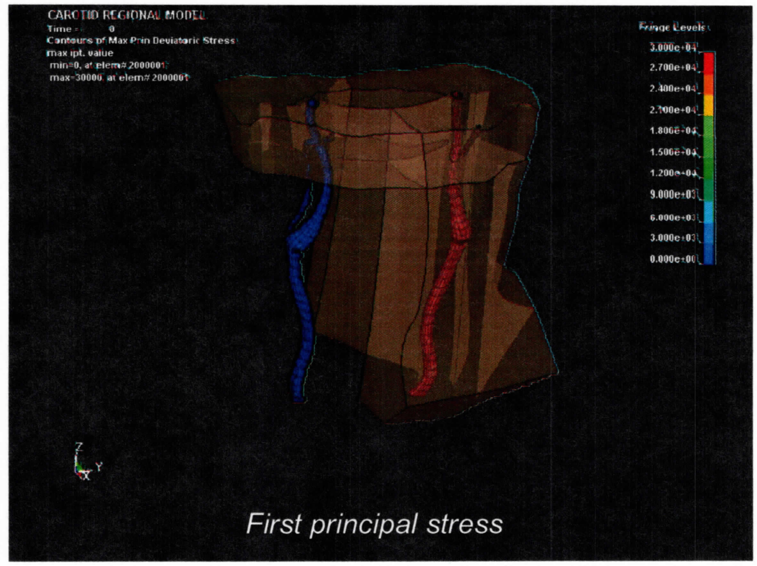
Model Extends:
-2.6951e-001 < x <-1.2689e-001
-8.4101e-002 < y < 8.0010e-002
4.4856e-001 < z < 5.9860e-001

Projection details:
view distance = 2.2155e-001
z near plane = 2.2155e-004
z far plane = 7.7132e-001
field of view = 45.0

Ok   Update






CAROTID REGIONAL MODEL
Time = 0
Contours of Max Prin Deviatoric Stress
max ipt. value
min=0, at elem# 2000001
max=30000, at elem# 2000001
Fringe Levels
3.000e+04
2.700e+04
2.400e+04
2.100e+04
1.800e+04
1.500e+04
1.200e+04
9.000e+03
6.000e+03
3.000e+03
0.000e+00
Z
Y
X
First principal stress

Characterization of the Carotid Artery and Adjacent Anatomy Using Non-Contrast CT for Biomechanical Model Development

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Introduction

While the overall incidence of blunt carotid artery injury (CAI) is low, patients diagnosed with this injury demonstrate a mortality rate estimated to be as high as 40%. [1] The majority of blunt CAI cases result from motor vehicle crash. [2] Injury mechanisms include component contact with the neck, such as belt loading, and hyperextension and rotation of the head and neck. CAI may result in intimal sub-failure or complications following the formation and release of atherosclerotic plaque in the artery. [2] The location of the insult and the type of loading are likely to play a role the severity of the injury due to structural changes in the artery and proximity of the artery to surrounding bony structures (cervical vertebrae). Mitigation of this injury can be accomplished by increased awareness of CAI in the clinic and improved countermeasure design. Computational modeling can be used in the design of improved countermeasures.

Purpose

Past computational modeling efforts studying CAI have laid the foundation for the development of a detailed regional level finite element model of the neck including surrounding bony structures. [3] For the regional model, it is imperative to characterize the location of the carotid artery in the neck through measurements of the average distance from the carotid to nearby structures. Specifically, this study determines the average distance from the external wall of the carotid artery and its branches to both the skin and cervical vertebral structures. Data from this study will be of use in model development, and for the development of future biomechanical experiments studying CAI. Characterizing the anatomy adjacent to the carotid may also aid the determination of injury causation scenarios following real-world CAI from motor vehicle crash and other forms of trauma.

Methods

Non-contrast CT scans were obtained for seven individuals with a slice thickness of 2.5 mm. Scans were imported into TeraRecon software (San Mateo, CA). Patients had no diagnosed arterial injury or abnormal neurological symptoms. The anatomy common to all sets of scans was determined to be the cervical vertebrae between levels two and six (C2-C6).

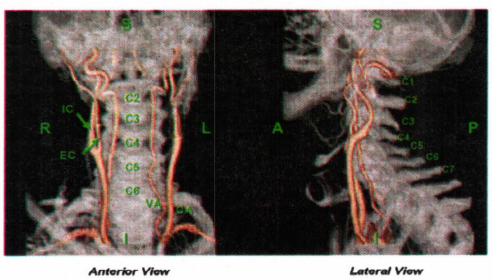

Figure 1. Anterior (Left) and lateral (Right) views of a Computed Tomography (CT) reconstruction of the neck with carotid (CA) and vertebral (VA) arteries highlighted. The internal (IC) and external (EC) branches of the carotid are visible. The vertebral artery passes through vertebral foramen and was not included in the characterization study. Cervical vertebrae are labeled. Due to limitations of the retrospective CT data, the carotid's position relative to C1 and C7 were not recorded in this study.

Using TeraRecon's measurement tool the shortest distance from the external wall of the carotid to the skin was measured for the common, internal, and external carotid arteries. The shortes. distance from the external wall of the carotid to the nearest vertebral structure was also measured for each of these arteries. Scans were measured at the level of the transverse process and at the level of the vertebral body. This was repeated for two measurements per vertebrae from C2 through C6.

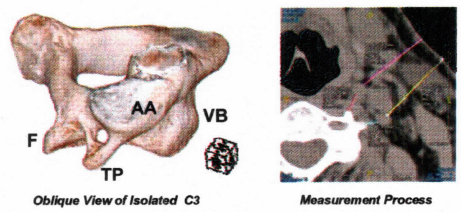

Figure 2. Oblique view of isolated C3 vertebral body (Left) and screen shot of data collection technique (Right). Vertebral aspects used to collect distances are identified. Inferior articular facet (F), transverse process (TP), anterior arch (AA) and vertebral body (VB). Measurements from the various aspects were collected using TeraRecon software.

The results are summarized in Figures 3 through 5. Figure 3 displays the average distance from the common, internal, and external carotid arteries to the nearest structure, with error bars representing one standard deviation. The average distance to a particular aspect on the vertebrae are found in Figure 4. The distance from the carotid to the nearest structure is also sorted by level in Figure 5.

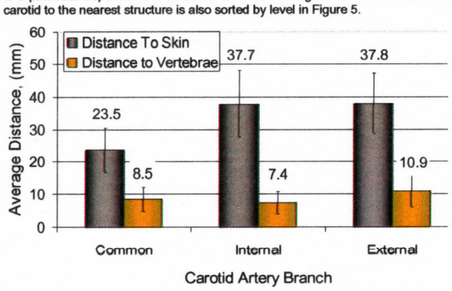

Figure 3. Average distance from common carotid artery and its branches to nearest structure and skin. See Figure 1 for related anatomy. Nearest structure refers to any aspect of the cervical vertebrae that was closest to the wall of the artery. Error bars represent one standard deviation.

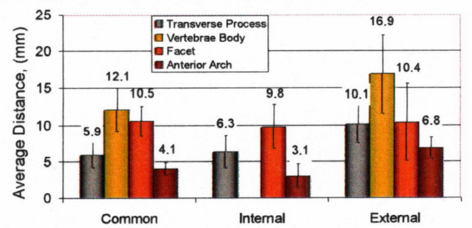

Figure 4. Average distance from common carotid artery or arterial branch to nearest bone structure. Results sorted by bone structure, see Figure 2.

Discussion

Characterizing the location of the carotid artery is of importance to both the clinical and impact biomechanics communities. When developing FE models for blunt impact studies, the preferred paradigm is to add complexity by working from the tissue, to organ, to regional level. This strategy provides a structured transition from models that are relatively easy to validate to models that are difficult to validate. Thus for a regional carotid artery and neck model, it is insufficient for only the morphology of the artery be accurate, the placement of the artery relative to surrounding structures must also be valid.

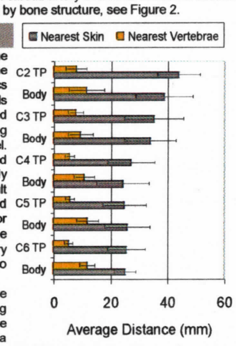

Figure 5. Average distance from artery to nearest structure or skin, arranged by cervical vertebrae level.

This data is of use outside the modeling domain as well. Characterizing the region of the carotid is useful for the design of experiments intended to elicit a particular injury causation scenario thought to occur in MVC. Anecdotal data exists supporting the notion that proximity of the artery to bony processes could induce elevated local strain in the carotid depending on the motion of the head and neck and the location of the insult. The imaging data presented in this study is retrospective and the method presented was devised accordingly. During imaging, the precise positioning of the patient's head and neck was not controlled, a common limitation of retrospective imaging studies. ***Acknowledgement***: This study was supported in part by the Wake Forest University Graduate School of Arts and Sciences Summer Research Opportunities Program (SROP).

References

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3. F. S. Gayzik, O. Bostom, P. Ortenwall, S. Duma, and J. D. Stitzel, "An experimental and computational study of blunt carotid artery injury," *Annu Proc Assoc Adv Automot Med*, vol. 50, pp. 13-32, 2006.

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