MESH DEVELOPMENT FOR A FINITE ELEMENT MODEL OF THE CAROTID ARTERY

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ABSTRACT

A technique for developing a structured, hexahedral and quadrilateral mesh for use in finite element analyses of the carotid artery is presented. The model is reconstructed from 270 Computed Tomography (CT) images (slice thickness 0.625mm) of a 57 year old male subject and extends from the arch of the aorta to the base of the jaw. The structured mesh was generated using an unstructured, automatically generated tetrahedral mesh of the intimal surface of the carotid artery and its branches. A parametric meshing software package was used to create the structured mesh, facilitating mesh density studies. The change in volume and surface area introduced when converting the mesh from tetrahedral to hexahedral elements (+1.5% change in volume, -1.4% change in surface area) is small in comparison to estimated error introduced in the segmentation process. The technique introduced will benefit finite element and fluid dynamic studies of the carotid artery investigating mechanically induced pathology at both physiologic loading rates (i.e., atherosclerotic plaque formation) and high strain rates (i.e., blunt trauma).

Keywords: finite element, mesh, parametric, carotid, hyperelastic, biomechanics

INTRODUCTION

The internal branch of the left and right common carotid arteries along with the vertebral arteries together are responsible for delivering blood to the brain. Disruptions in this blood supply lead to stroke, the third leading killer in the United States. The incidence is rising, and it is estimated 700,000 Americans will become victims of stroke this year. In 2005, the estimated direct and indirect costs of stroke in the United States will reach $56.8 billion[1]. Disruptions of blood flow to the brain can come in the form of a blockage of blood flow (ischemic stroke) or complete structural breakdown of the arteries delivering blood (hemorrhagic stroke).

Of all strokes, 88% are ischemic [1] and of these, atherosclerosis is responsible for more than half. Sites of complex hemodynamics are associated with the formation of atherosclerotic plaques, since the disease is commonly observed at arterial bifurcations and regions of high vessel curvature. These observations have lead to many computational studies seeking to uncover the etiology of the disease by studying mechanical factors such as shear stress, and vessel strain. It is widely accepted that low or oscillatory shear stress contributes to atherogenesis [2]. The wall shear stress temporal gradient, which is of importance due to the pulsatile nature of blood flow, has been related to the expression of atherogenesis-related genes in endothelial cells[3]. Cyclic mechanical strain in the vessel has also been researched extensively. Cyclic strain in endothelial cells and vascular smooth muscle cells is related to elevated synthesis of a potent chemotactic agent for monocytes, leading to lesion development [4].

Not all ischemic strokes are due to atherosclerosis. Spontaneous dissections of the carotid or vertebral artery account for 2% of ischemic strokes but larger percentages of stroke in young or middle aged patients (up to 10 to 25%) [5]. Cervical artery dissection begins as a tear or defect of the intimal lining of the artery, and while uncommon can lead to luminal occlusion and ultimately cerebral ischemia [6]. Internal carotid artery dissection (ICAD) is 3 to 5 times as likely to occur as vertebral artery dissection, and more than 7000 cases of internal artery dissection per year occur in the United States alone [7-9]. A review of the available literature found that nearly 30% of all ICAD cases are attributed to some form of trauma[6]. Blunt or penetrating carotid artery injures are most commonly encountered in automobile accidents, resulting from interaction with interior structural components of the vehicle or hyperextension and rotation of the head and neck complex [10]. While the incidence of these injuries is low (present in roughly 1% of trauma admissions) the associated mortality and long term neurological morbidity are estimated at 40% and 40-80% respectively [10]. Intimal arterial injury remains the most common initial injury, leading to delayed development of symptoms and diagnosis [11, 12].

Regardless of the etiology of the blood flow disturbance, understanding the complex biomechanics and fluid dynamics of the carotid artery is critical to developing interventions. Finite element analysis (FEA) and computational fluid dynamics (CFD) are widely used in the investigation of arterial mechanics. These techniques lend themselves to investigating the mechanical response at both low (physiologic) and high (traumatic) rates of applied stress and strain. When undertaking a computational study of any system, it is important to know with certainty the material properties, geometry and boundary conditions of that system. Modeling continues to evolve, incorporating sophisticated material models [13], and geometries by using imaging modalities such as MRI and CT. Doppler ultrasound is currently in use to provide more accurate boundary conditions for coupled fluid/solid models [14]. But an important aspect of model development which can lead to spurious results if overlooked is the mesh of the geometry. The mesh refers to how a system is broken into discrete elements which are used in the finite element framework. By and large, the current research in this area is conducted using unstructured meshes composed of tetrahedral elements. This research focuses on the development of a structured, quadrilateral mesh of the carotid artery for use in future research on the biomechanics of the carotid artery.

METHODS

The carotid artery model was constructed from a Computed Tomography (CT) angiography of 57 year old male patient with a history of coronary artery disease with cerebrovascular accident. A bolus of ISOVUE 370 contrast agent was introduced to investigate perfusion through the carotid and cerebral arteries. The carotids were assessed as normal by a qualified radiologist and the image sequence was assumed to representative of an average adult male. Images were taken using a Lightspeed Pro 16 Scanner (GE medical systems, Minneapolis, MN). A total of 270 slices were obtained, from the base of the jaw to the insertion of the artery to the aortic arch. In the sketch of the head and neck complex in Figure 1, the levels of the superior-most and inferior-most scans are depicted by the grey lines. Slice thickness was 0.625 mm and with a resolution of 160 mm x 160 mm. The image size was 512x512 for a resolution of 3.2 pixels/mm or 0.3125 mm per pixel. The images had a grayscale depth of resolution of 16 bits per pixel. The scans were exported to a GE 4.1 Advantage Workstation (GE medical systems, Minneapolis, MN) in DICOM format. Segmentation and thresholding tools were used to extract a region of interest (ROI)

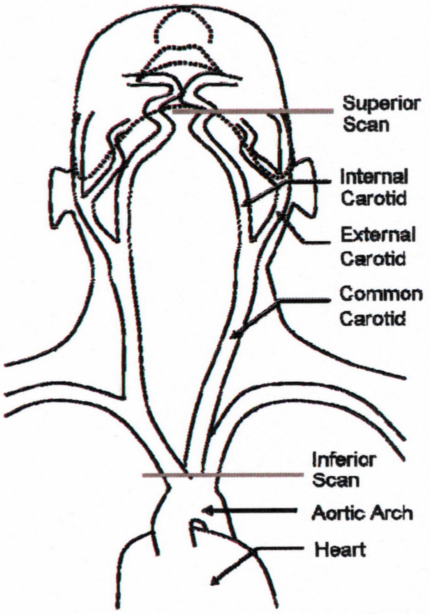

Figure 1. Sketch of head neck complex showing scanned region.

around the left carotid artery from the image stack. The ROI facilitated the subsequent, more detailed segmentation of the arterial lumen.

The lumen of the vessel was segmented using Mimics (Materialise, Leuven, Belgium). Multiple dilation and erosion steps were used to isolate the lumen of the artery. An automatic surface meshing algorithm was used to form a tetrahedral mesh along the intimal surface of the artery. This mesh was exported to TrueGrid (XYZ Scientific Technologies, Inc., Livermore, CA) for hexahedral mesh generation. Splines were drawn circumferentially and longitudinally along the surface of the tetrahedral mesh using existing nodes. Surfaces created from these splines split the carotid model into separate parts which can be meshed parametrically. Parametric meshing is accomplished by mapping each surface of the parts comprising the model to a simple geometric block. The hexahedral mesh is defined on the simplified block and projected back to the complex surfaces of the carotid model. Nodes at the boundaries of the parts composing the parametrically meshed model are then merged.

The structured mesh was imported to LS-PrePost finite element preprocessor (Livermore Software Technology Corp., Livermore, CA) and coated with shell elements. Since the mesh was created by segmenting around the intimal side of the artery, the vessel walls can be modeled with one or more outer layers of shell elements or solid elements.

The geometry data for our work came from scans of a patient at Wake Forest University Baptist Medical Center. All protocols pertaining to confidentiality of patient information, and de-identification of patient data, were strictly followed. The protocol for use of geometry from clinical medical images was reviewed by Wake Forest's Internal Review Board and approved prior to commencement of work.

RESULTS

The entire structured mesh of the carotid artery is shown in Figure 2A. Figure 2B and C show detailed images of the structured mesh and the automatically generated tetrahedral mesh in the region of the bifurcation. The total volume and surface area of the structured mesh matches closely with tetrahedral mesh, see Table 1. The parametric meshing capability of this approach allows for the mesh of the complex structure to be adjusted quickly. Figure 3 demonstrates this capability, showing a cross section of the common carotid artery with the baseline mesh and a mesh with twice the number of elements.

A. B. C.

Figure 2. Results of mesh generation. A. Complete structured mesh of carotid artery. B. Detail of bifurcation, hexagonal mesh. C. Detail of bifurcation, tetrahedral mesh

Table 1. Mesh volume and surface area measurements

	Volume, cm^3	Surface area, cm^2
Hex.	7.59	51.2
Tria.	7.71	51.9
% Diff.	+1.56	-1.35

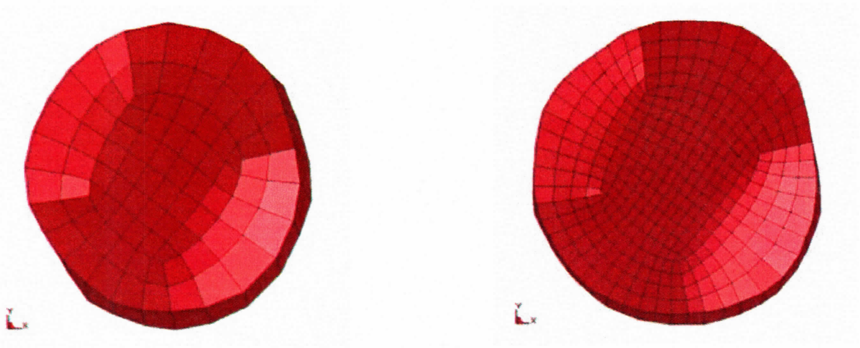
A. B.

Figure 3. Cross section of carotid model showing mesh density. A. Mesh baseline, B. Mesh with double the number of elements

DISCUSSION

A structured mesh of the common carotid artery and its two branches can be a valuable asset in conducting a fluid dynamic or solid mechanic analysis. Since the mesh is created parametrically, the task of refining the mesh density is greatly simplified. Changing the number of elements along any dimension of the model is accomplished simply by changing a parameter and recompiling the input file. Such functionality greatly facilitates analyzing the effect of mesh density on results. It is accepted that models employing structured meshes generally provide more accurate solutions and are more computationally efficient than models employing tetrahedral elements. There are other limitations of tetrahedral meshes when solid mechanics models are concerned; it is possible to encounter material models that are not formulated for use with tetrahedral elements and two-dimensional shells. Using a structured hexahedral mesh with quadrilateral shell elements removes this potential road block.

With any model reconstructed from medical images error is present, however we believe that no significant increase in geometrical error is introduced by meshing the model with hexahedral elements. Error is introduced in each of the three major steps of creating a model; data acquisition, image segmentation, and mesh generation (3-D model construction). Similar studies with roughly the same resolution images have estimated the error due to image segmentation at ±8% in both area and volume. This estimate is based on a ±1 pixel error in segmentation and a roughly circular arterial cross section [14, 15]. Therefore the segmentation error estimate is much larger than the difference in volume and surface area experienced when moving from a tetrahedral to hexahedral mesh (Table 1).

A complete survey of the literature on this subject is beyond the scope of this study. The following brief summary demonstrates that structured meshes are yet to be fully integrated into the most recent works in this area. Coupled fluid/solid models investigating the complex hemodynamics in the area of the carotid bifurcation have widened what is understood regarding plaque formation and rupture [14, 16, 17]. In all of these studies however, unstructured tetrahedral meshes are used in the analysis and several directly cite the complex geometry of the carotid as the reason for using unstructured meshes

[14, 15]. Other studies do employ structured meshes of the bifurcation, but sacrifice geometrical accuracy in the process [18]. A recent study investigated the role atherosclerosis plays in changing the material properties of the vessel wall using the finite element method [19]. While this study employs a structured mesh, the geometry of the model is cylindrical and does not include the bifurcation. No computational models investigating the role blunt trauma to the head neck complex plays in spontaneous carotid artery dissection were found, despite the high incidence of morbidity and neurological deficits associated with this injury. Future research will incorporate material property data into this carotid model. The model will also be placed into a larger model of the neck for use in predicting carotid artery injury in vehicle side impact simulations.

CONCLUSIONS

A method for producing a structured hexahedral and quadrilateral mesh for use in finite element analyses of the human carotid artery is presented. The error introduced in converting from a tetrahedral mesh to a hexahedral mesh is small in comparison to the estimated error introduced during segmentation. The mesh is generated parametrically, facilitating studies of mesh density.

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