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Patient-Specific FEM Analysis of the Atherosclerotic Carotid Bifurcation

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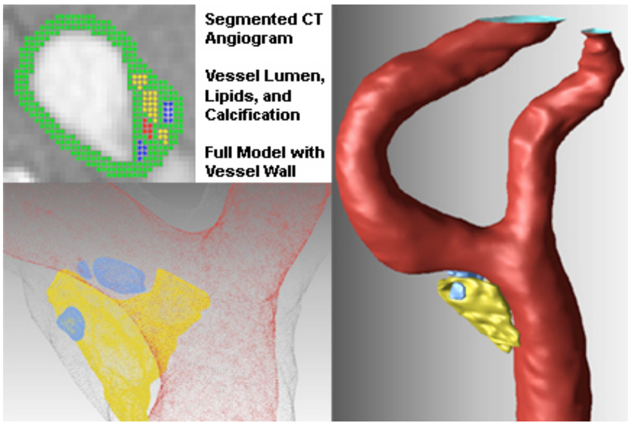
ABSTRACT

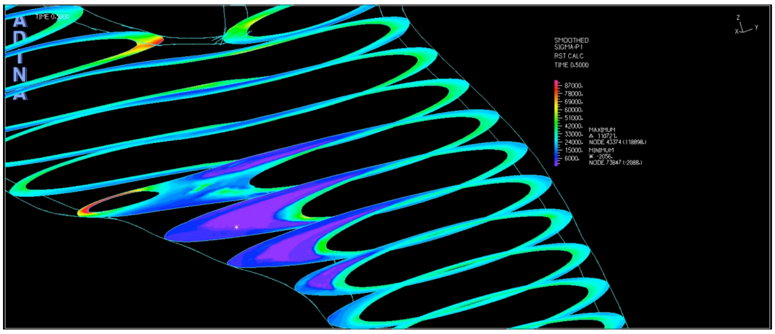
Introduction Atherosclerosis in the carotid bifurcation is a highly variable disease that, in its stable form, can cause a dangerous reduction of blood flow to the brain. Should the plaque rupture or ulcerate, the patient is likely to experience a thrombotic or embolic stroke. Stroke is the 3rd leading cause of death in the western world, and approximately 10-15% of these cases develop from carotid atherosclerosis.[1] In addition to the complex biochemistry involved in the initiation, progression, and acute insult of carotid disease, the mechanical environment of the carotid bifurcation may also play a pivotal role in these disease states.

The finite element method can be used to interrogate the local mechanical environment of the carotid bifurcation throughout the cardiac cycle. The complex time-dependent stress and strain fields can thus be estimated to derive an understanding of the vessel's mechanical response that may be used within the contexts of various failure criteria and conditioning of the materials present. In addition to the strictly solid-loading approach, fluid-structure interaction (FSI) simulations can be used to include the wall-pressure perturbations induced by flow in more stenotic vessels.[2] With a sufficiently fine fluid mesh, wall-shear-stress may also be measured, allowing characterization of the mechanical signals relevant to the intimal endothelium.[3] While much has been learned from idealized cases, patient-specific analyses are important due to the compounding effects of highly irregular geometry, nonlinear materials, and variable pressure loading. It is hoped that the further development of such analyses will lead to a useful predictive capacity that can be employed in a clinical setting.



Methods In this work, CT angiograms of the carotid vessels are segmented using in-house software such that the contours of vessel wall, calcification, lipids, and the vessel lumen may be obtained at intervals of 0.5mm from 20mm above and below the bifurcation. The smoothed contours are used in a lofting procedure in Solidworks (Solidworks Corporation, Concord, MA) to generate surfaces for each material component present in the vessel. This set of surfaces is further translated into a set of solid bodies which are then meshed, in a conforming unstructured fashion, using ADINA (ADINA R&D, Watertown, MA). 10-node tetrahedral elements are used throughout the solid model. A model of the vessel lumen is constructed in the same way, and meshed separately using 4-node linear tetrahedral elements. Non-linear Mooney-Rivlin material models[4] are used for each material component in the diseased vessel, and an implicit dynamic analysis is made in ADINA. ADINA's 3D-iterative solver, which is intended specifically for higher-bandwidth problems with many higher-order elements, is used to solve the solid system matrix. Newmark's method is employed to handle the time integration. Scaled carotid pressure waveforms are used as fluid boundary conditions at the inlet and outlets, with phase delays and magnitude offsets estimated from material properties, geometry, and steady-state flow simulations. Because of the scale of the problem, the fluid and solid equation systems are coupled iteratively, reducing memory requirements for the computation.

Results and Discussion Patient-specific finite element models of the diseased carotid bifurcation were constructed. The geometrical features of the vessel wall, and the arrangement of lipid and calcific inclusions agree well with radiologic data. Preliminary analysis shows a complex stress field within the diseased arterial wall, influenced primarily by geometrical factors and the disparate material properties of lipid pool and calcification. Focal stress concentrations surrounding the calcific inclusions result from the local stiffness and the surrounding materials' relative inability to support the stress from the pressure load. Further investigation of this stress-concentration phenomenon may allow the characterization of plaque stability in terms of the "knife effect" in which a small calcific inclusion can exert acute forces on surrounding tissues, exceeding their yield strength. Work is ongoing to implement more realistic and patient-specific fluid boundary conditions and various vessel-tethering schemes that will allow for more realistic solid boundary conditions.



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