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MRI-Based 3D Flow and Stress Analysis of Vulnerable Plaques

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Atherosclerotic plaques may rupture without warning and cause subsequential acute syndromes such as myocardial infarction and cerebral stroke. Accurate methods are needed to identify vulnerable plaques that are prone to rupture and quantify conditions under which plaque rupture may occur. Such information would be important for predicting possible rupture and aid in the optimal medical and surgical treatments to prevent it from happening. MRI technologies have been developed to quantify non-invasively plaque size, shape, and plaque constituents (fibrous, lipid, and calcification/inflammation). However, in addition to plaque morphology and constituents, mechanical forces clearly play an important role in the rupture process. Mechanical analysis based on MR images has been proposed but is limited mainly to two-dimensional (2D) structure-only or three-dimensional (3D) flow-only models due to complexity of the problem. MRI-based 3D models with fluid-structure interactions is lacking in the current literature.

In this paper, 3D multi-component computational models with fluid-structure interactions (FSI) based on MR images of human carotid plaques are introduced to perform flow and plaque stress/strain analysis, and to quantify critical stress/strain conditions under which plaque rupture is likely to occur. A 3D MRI data set consisting of 64 2D slices with high resolution (0.1mm x 0.1mm x 0.5mm) was read by VTK, a powerful visualization tool capable of handling various medical images. Various plaque components were identified for each slice using data ranges validated by histogram. Slices were examined to repair damages from surgery and to identify critical major objects in the plaque for numerical simulation. Two large lipid-rich necrotic pools were identified for this sample. 3D geometry of the plaque was re-constructed and computational mesh was generated using these treated slices. Both the artery wall and the lipid-rich core were assumed to be hyperelastic, isotropic, incompressible and homogeneous. The Mooney-Rivlin model was selected to describe the nonlinear material properties where parameters were chosen to match experimental measurements from our *in vitro* studies and data available in the current literature. The flow is assumed to be laminar, Newtonian, viscous and incompressible. The fluid and structure models were fully coupled and solved by a commercial finite-element package ADINA that has been tested by hundreds of real-life applications and our model has been validated by our in vitro experimental measurements. Controlling factors such as pressure, axial stretch, lipid pool size, plaque cap thickness, stenosis severity were varied to quantify the effect of those factors on flow and stress/strain distributions. Our results indicate that this model provides much more accurate predictions than the 2D-structure models and may serve as the base for many further investigations. Critical stress/strain conditions (max stress/strain and max compression) are much more sensitive indicators than stenosis severity and plaque morphology currently used clinically. Multi-year effort is needed to develop the method and automate the entire procedure, and large-scale patient studies are needed to obtain statistically significant database for possible plaque assessment and clinical applications.

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