MRI-based Biomechanical Imaging: Role of Hemodynamic Forces on the Early Plaque Remodeling

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Figure 1. Time lines of experimental procedure in two pigs. The number under the line indicates the weeks after the first injury.

Purpose

Early atherosclerotic plaque developed with endothelial dysfunction and characterized by proliferation of endothelial cell and vascular smooth muscle cells, resulting in intima thickening. Despite the systemic nature of atherosclerosis, local hemodynamic forces, such as fluid shear stress, were thought to play an important role in the progression of the early plaque, but such assessment procedures are often invasive [1-2]. The goal of the study is to develop a non-invasive MRI-based biomechanical imaging technique to address biomechanical pathways of atherosclerosis progression and regression in vivo with a 3D fluid-structure interaction (FSI) model [3].

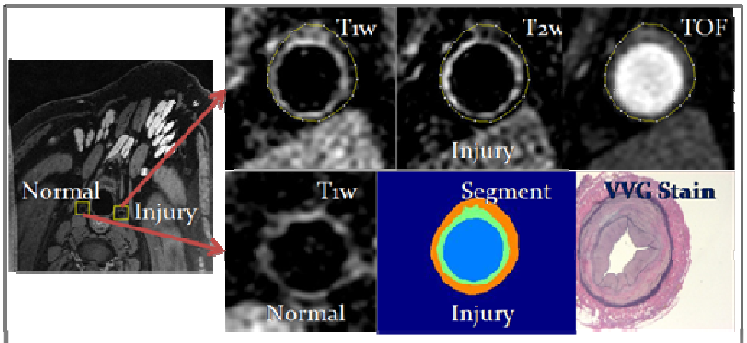

Figure 2. Contrast-enhanced MR images of injured and normal carotid walls after the injection of Gadofluorine M. Segmented images from injured artery shows a similar pattern of neointima formation with the histopathology (VVG stain).

Methods

Three Yucatan pigs were fed cholesterol-enriched diets (HC) and then underwent a balloon-overstretch injury to the left carotid arteries. The first pigs underwent the first MRI scans at 10 weeks after the injury, followed by another MRI scan 4 weeks later. The carotid lesions in two other pigs were re-injured by balloon angioplasty and 4 MRI scans were performed while the pigs were maintained on HC or normal chow (NC) (Figure 1). The MRI scans were performed with an injection of a plaque-targeted contrast agent, Gadofluorine M at a dose of 0.05 – 0.075 mmol/kg, one hour prior to the scans at each time point. The pigs were euthanized after the last MRI scan and the left and right (normal) carotid arteries were dissected for histopathology and mechanical testing to obtain subject-specific material properties.

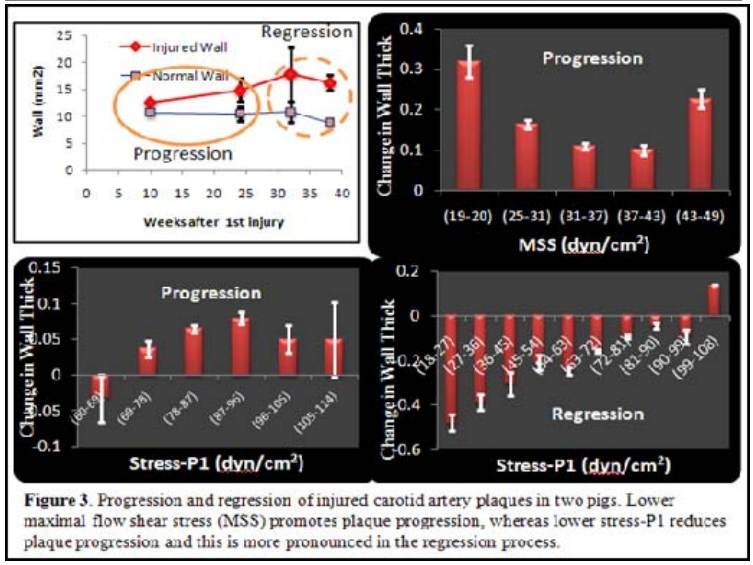

Figure 3. Progression and regression of injured carotid artery plaques in two pigs. Lower maximal flow shear stress (MSS) promotes plaque progression, whereas lower stress-P1 reduces plaque progression and this is more pronounced in the regression process.

The MRI (3-T Siemens Trio MRI System) protocol consisted of 20-slice T1w and T2w imaging using dark-blood turbo-spin-echo sequence, as well as a 20-slice 3D time-of-flight (TOF) imaging. The slice thickness was 2 mm and the true image resolution was 0.33mm x 0.33 mm. The left carotid vessel wall and plaque images were segmented based on contrast enhancement patterns. Using the material properties obtained from mechanical testing, the 3D FSI computational model was then applied to data from the first two pigs to calculate various structure stress and strain distributions, including maximal fluid shear stress, at different time points. These stress and strain data at each time point were grouped into different categories with lower numbered category being lower stress or strain values. These categories were then plotted against the changes in wall thickness from one time point to the next one.

Results (1) Gadofluorine enhancement of plaque, which has been associated with extracellular matrix, was increased by 60-100% compared with non-enhanced plaque areas (Figure 2). The plaque structure resembles early plaque with thickened intimal. The use of three-contrast images helped to define the plaque components and boundaries. Positive remodeling was shown throughout the study period with enlarged vessel lumen and wall (Figure 3). (2) With subject-specific plaque material parameters and improved plaque image quality, structure stress/strain in the left carotid plaques was successfully calculated. Maximal Flow shear stress (MSS) and maximal principle structure stress/stain (stress-P1 and strain-P1) were shown to correlate interestingly with the change in the plaque dimension during plaque progression and regression

Conclusion MRI-based biomechanical imaging may allow non-invasive dynamic assessment of local hemodynamic forces on the development of early atherosclerotic plaques in vivo.

Reference

1. Stone PH, et al. Curr Opin Cardiol. 2003;18:458-470.
2. Cheng C, et al. Circulation. 2006; 113:2744-2753.
3. Tang D, et al. Ann Biomed Eng. 2004; 32:947-960.