In Vivo MRI Quantification of Circumferential Wall Shear Stress Distribution at Atherosclerotic-Prone Sites in Mouse Abdominal Aorta

A. Karim[1], H. Tang[2], M. C. Desiderio[3], L. Peterson[4], and H. Liu[2]

[1]Applied Computer Science & Mathematics, Merck Research Laboratories, Rahway, NJ, United States, [2]Imaging, Merck Research Laboratories, Rahway, NJ, United States, [3]Biomedical Engineering, Stevens Institute of Technology, Hoboken, NJ, United States, [4]Pharmacology, Merck Research Laboratories, Rahway, NJ, United States

Introduction

Fluid velocity field, as provided by phase-contrast MRI [1], is an important physiological parameter from which many different quantifiable markers may be obtained, such as maximum, minimum, and average (over a vessel cross-section) velocities. By incorporating pixel size we can obtain rough estimates of volume flow. These velocity based endpoints have been used extensively to track hemodynamic function and distinguish function across disease states and strains. However careful analysis and judicious use of these quantities is necessary as lack of tempo resolution, especially in rodents, may result in significant errors. Shear stress has long been thought to be linked to the process of plaque progression and deemed as one of the viable causes of damage to the endothelial layer of the wall [2, 3]. Studies have shown the correlation between low fluid shear stresses and the localization of atherosclerotic plaques in arteries [4, 5]. Thus the most interesting feature that we can extract is shear stress which could be used for the study of atherosclerotic plaque and localization in experimental animal models. In this study, phase contrast MRI was implemented at 11.7T to obtain velocity field map with sufficient spatial resolution, and computational methods were developed to quantify the circumferential wall shear stress (WSS) distribution at the atherosclerotic-prone sites in the abdominal aorta of an atherosclerosis mouse model (Ldlr null).

Methods

Phase-contrast MRI Experiments were approved by the Institutional Animal Care and Use Committee. The Ldlr null mice used in the study was on a high cholesterol Western diet for 9 months. MRI was performed on a Bruker Biospin 11.7T spectrometer (Bruker NMR, Inc., Billerica, MA) with an 89 mm vertical bore and a shielded gradient system up to 150 G/cm. Mice were anesthetized with 1.5% isoflurane/O_2 gas mixture within a birdcage coil of 25-mm ID during imaging. ECG gated phase contrast cine images were acquired within a cardiac cycle (n=12) with TR=150ms (heat beat rate is about 350 beat/min), and Venc=25cm/sec, to characterize the blood flow, specifically the blood velocity field, at atherosclerotic-prone sites in the abdominal aorta (located above the renal artery level) of Ldlr null (TG) and wild type (WT) mice. Contrast enhanced high resolution images were acquired to identify atherosclerotic plaque in the abdominal aorta area.

Quantification of Shear Stress Distribution The fluid velocity field is used in quantifying shear stress distribution along a vessel wall. By finding the vessel wall, as well as the distance to the center of the lumen, we can interpolate points along the vessel radius *R*. Using a quadratic interpolating function, we can then obtain the rate of change of the velocity at the wall. Scaling with viscosity, values of shear stress at each point of the boundary were obtained. The shear stress can then be represented as the circumferential distribution of values along the vessel wall as a function of the azimuthal variable.

This method assumes that the vessel is circular. The normal at a given point on the surface defined by the contour of one slice of a vessel is the radial line going through that point. It follows that for any deviations from our assumption, the error is measured as deviation of the true normal line to the radial line in the case of a circular vessel. The future goal is to use the equation $\sigma = \mu \nabla u_{axial} \cdot n_{in\_plane}$ for calculating the shear stress σ, where μ is the viscosity, u is the velocity, and the assumptions made are that flow in the in-plane directions is negligible compared to flow in the axial directions. The normal (n) in the equation is the unit normal to the wall at the point of interest, in the plane of a given slice. Moreover, accuracy of calculating shear stress may be low because of low spatial resolution, measured as number of pixels across diameter of vessel, hence sufficient spatial resolution of velocity map and spatial interpolation are needed. Current work is in progress to alleviate the assumption of a circular vessel and also to obtain better accuracy by making more use of interpolation methods.

Results

Figure 1a shows the cross sectional imaging plane of the abdominal aorta (indicated by red arrow) of a TG mouse. The velocity field map calculated from the phase-contrast MRI is shown in Figure 1b. The uniformly distributed plaque (bright ring) and wall thickening in abdominal aorta could be clearly seen in the contrast enhanced high resolution image (Figure 1c). WSS distribution along the vessel wall (arrows indicate both direction and magnitude) and blood velocity contour isolines is shown in Figure 1d. Quantifying the value of shear stress at each point in the wall yields more information regarding the shear rate at each position, as well as areas that consistently have high shear compared to others. The plots shown in Figure 2 indicate shear stress values along the vessel wall for two cardiac time points (beginning of systole and peak systole) at a given angle along the vessel wall in the TG and WT mice. The circumferential WSS at beginning of systole is flat and low. Figure 3 shows the average of the circumferential WSS values over a cardiac cycle. Maximum WSS occurs at the peak systole. There is significant decrease of WSS in the abdominal aorta of the TG compared to that of the WT mouse.

Conclusion

MRI provides a non-invasive means of obtaining quantitative information on blood flow and allows for powerful calculations and a multitude of visual representations. The extracted features thus far provide a preliminary investigation into the capabilities of an automated process for MRI analysis. We have shown that the shear stress can be calculated at each position along the vessel wall. Further computations and refinement of techniques may yield more information to better classify hemodynamic function. This may help in investigating the mechanical properties of the atherosclerotic lesions, plaque vulnerability, and the mechanism of plaque rupture.

References

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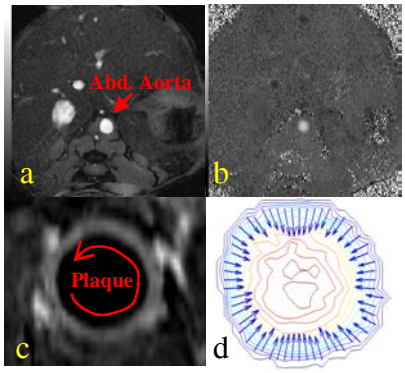

Figure 1. Velocity field map and wall shear stress distribution. (a) MR image of abdominal aorta; (b) velocity map; (c) high resolution plaque image; (d) shear stress distribution and velocity contour.

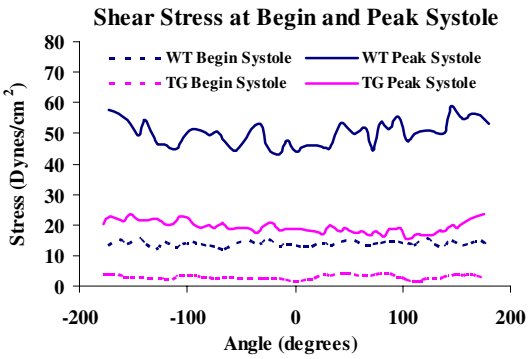

Figure 2. Wall shear stress as a function of azimuthal variable at the begin and peak systole along the aorta vessel wall of a WT and TG mouse.

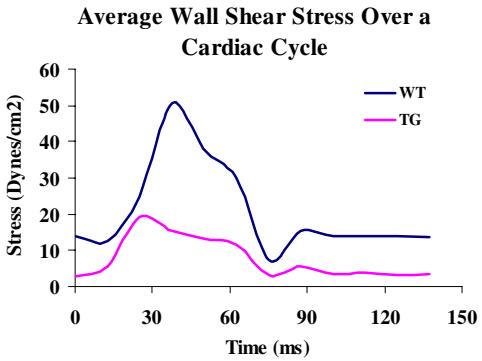

Figure 3. Average wall shear stress over one cardiac cycle in the abdominal aorta of a WT and TG mouse.