4D Spiral Phase-Contrast MRI of Wall Shear Stress in the Mouse Aorta

R. L. Janiczek[1], C. H. Meyer[1,2], S. T. Acton[1,3], B. R. Blackman[1], and F. H. Epstein[1,2]

[1]Biomedical Engineering, University of Virginia, Charlottesville, VA, United States, [2]Radiology, University of Virginia, Charlottesville, VA, United States, [3]Electrical Engineering, University of Virginia, Charlottesville, VA, United States

Introduction

Atherosclerosis, the precursor to acute events such as myocardial infarction and stroke, is a focal inflammatory disease of the vessel wall believed to be influenced by local hemodynamic forces such as wall shear stress (WSS)[1]. Transgenic and knockout mouse models of atherosclerosis facilitate the investigation of the underlying molecular mechanisms of the disease. However, no existing technique is capable of measuring the hemodynamic environment throughout the mouse aorta. Recent methods for measuring WSS in mice have relied on computational fluid dynamics to model flows within the mouse aortic arch[2,3].

Peak blood velocity in the mouse aortic arch is comparable to humans; however the vessel geometry is orders of magnitude smaller resulting in severe flow and displacement artifacts when traditional rectilinear *k*-space trajectories are used for data sampling[4]. Spiral imaging enables two-dimensional phase contrast throughout the aortic arch. However, the curved geometry makes multi-slice acquisition to increase spatial coverage time-prohibitive. This work develops a 4D spiral phase contrast (PC) MRI sequence encoded for all vector components of velocity to directly measure WSS.

Methods

Imaging was performed on a 7.0T Clinscan MR system (Bruker, Ettlingen, Germany) using a 30 mm diameter cylindrical birdcage radiofrequency (RF) coil and an MR-compatible physiological monitoring and gating system for mice (SA Instruments, Inc., Stony Brook, NY). Mice were anesthetized using isofluorane and body temperature was maintained at 37º C using circulating water.

A three-dimensional ECG-gated stack-of-spirals sequence was implemented with four-point balanced velocity encoding. Relevant scan parameters were a 6.5 ms TR, 0.85 ms TE, 14 cardiac phases, 120 cm/s VENC, 160 spiral imaging interleaves, 32.64 mm x 32.64 mm x 5.44 mm FOV, and isotropic 170 μm pixel size. The slice was prescribed in the transverse plane to keep within gradient duty cycle limitations. The spiral readout duration was reduced to 900 μs because blood movement during the spiral readout can result in oblique flow artifacts due to movement of spins between encoding the low and high spatial frequencies[5]. A sub-millisecond readout was needed to reduce the in-plane movement during the readout period. To achieve the desired spatial resolution within reasonable scan times, *k*-space was undersampled using linear variable density spirals.

k-space trajectory errors due to eddy currents, gradient hardware imperfections, and discretization at 10μs intervals of the gradient waveform motivated the need to measure the *k*-space trajectory prior to gridding. Every *k*-space interleaf for every velocity encoding was measured[6] in a phantom and used in image reconstruction. Using the measured *k*-space trajectories improved signal homogeneity, increased edge definition, and reduced spiral streaking artifacts.

Images were automatically segmented using an active surface initialized at the aortic root. Velocities were fit using a cubic smoothing spline following nulling of velocities outside of the aorta. The longitudinal, $\tau_{wl} = \mu(\partial u_r/\partial l + \partial u_l/\partial r)$, and circumferential, $\tau_{wc} = \mu(\partial u_r/\partial c + \partial u_c/\partial r)$, components of WSS were calculated assuming a Newtonian fluid where u_r, u_l, are u_c are the locally radial, longitudinal, and circumferential components of velocity. The viscosity, μ, was assumed to be 4 cP.

Results:

The 3D stack of spirals trajectory, using the parameters given above, was immune to severe signal loss throughout the mouse aorta. The incorporation of measured *k*-space trajectories in image reconstruction significantly reduced blurring and edge artifacts. Fig. 1 shows a 3D map of WSS magnitude in the mouse aortic arch during peak systole using the proposed method. The spatial distribution of WSS shows higher values near the outer radius and lower values near the inner radius of the aortic arch. This agrees with the regional initiation and progression of atherosclerosis where plaques initially form in regions with lower and/or oscillatory WSS. Recently, comparable spatial distributions, but larger peak shear stresses, were seen in CFD models[2,3]. Measurement of WSS across the cardiac cycle enables analysis of WSS waveform variability using the oscillatory shear index and the harmonic index.

Conclusions:

A 4D spiral PC-MRI sequence was developed and used for measuring WSS throughout the mouse aortic arch. Short spiral readouts, variable density spirals, and *k*-space trajectory measurement correction enabled measurement of the entire hemodynamic environment in the mouse aortic arch. Using these methods, future work in genetically engineered mice may elucidate the roles of specific genes in the relationship between WSS and the development of atherosclerosis.
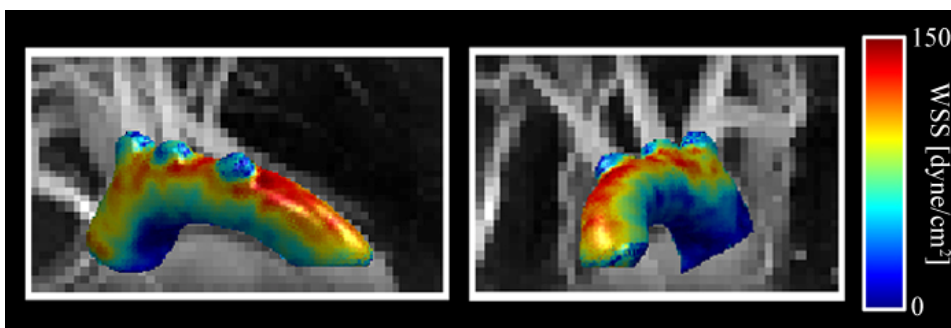
[1]Dai et al. PNAS, 2004; 101(41):14871-6.
[2]Suo et al. ATVB, 2007;27:346-351.
[3]Huo et al. ABME, 2008; 36(5): 685-699.
[4]Janiczek et al. ISMRM, 2008.
[5]Gatehouse et al. MRM, 1999;41(5):1023-31.
[6]Zhang et al. MRM, 1998;39(6):999-1004.

Figure 1. Wall shear stress magnitude in the mouse aortic arch during peak systole. WSS is lower along the inner radius of the aortic arch in agreement with spatial localization of plaque formation.