

Automated Calculation of Wall Shear Stress in the Middle Cerebral Arteries of Healthy Volunteers using PC-VIPR and Spline Interpolation

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Introduction:

Atherosclerosis is the leading cause of death in industrialized countries, and convincing evidence has emerged indicating that abnormally low wall shear stress values are prevalent at atherosclerosis prone sites.¹ Non-laminar flow, which leads to decreased shear stress, has been shown to change endothelial gene expression and homeostasis as well as increase boundary zone proliferation, leading to increased atherosclerotic plaque formation.² Abnormal wall shear stress has also been implicated in the formation and progression of saccular cerebral aneurysms.³ Therefore, wall shear stress analysis may have prognostic value in determining which areas are vulnerable to aneurysm and atherosclerotic plaque formation. This information has many clinically significant uses, including assessment of treatment for atherosclerosis, dyslipidemia and other vascular diseases. However, obtaining fast and accurate non-invasive in-vivo measurements of arterial wall shear stress has been challenging, especially inside the cranial vault. PC-VIPR, a MRA technique that uses a radial undersampled readout, is capable of fast, whole-brain high-resolution imaging with hemodynamic measurements, and the velocity data from a PC-VIPR acquisition can be processed using spline interpolation to generate reasonable estimates of 3D wall shear stress in the entire brain with scan times of around 5 minutes and automated wall shear stress calculations.

Methods:

10 healthy volunteers (6 female, 4 male) were scanned using a GE Health Discovery 750 3.0T MR Scanner (GE Healthcare, Waukesha, WI) with an 8 channel head coil (Excite HD, GE Healthcare, Waukesha, WI) using PC-VIPR⁴, a radial undersampled PC-MRA technique that greatly accelerates acquisition time and allows high resolution whole brain MR angiography with acceptable signal to noise ratio and scan times of 5 minutes or less. A PC-VIPR angiograph of the axial whole brain is shown in Figure 1b. Vessel segmentation was performed manually with in-house software (MATLAB version 8.0, The MathWorks Inc., Cambridge, MA, USA). First, the field of view was narrowed to a 50mm cube surrounding the M1 segment of the right middle cerebral artery. Next, points were selected around the circumference of the artery on complex difference images reformatted as axial to the vessel. From these points, a cubic spline was created. This step was repeated on axial slices ranging from the confluence with the internal carotid to the end of the M1 segment. From these axial splines, splines in the medial to lateral (ML) direction—along the length of the M1 segment—were created. The intersection of the M1 and axial splines created surface points along which an inward unit normal vector was computed; longitudinal wall shear stress was then calculated as the viscosity of fluid multiplied by the slope of the velocity along this unit normal vector (Figure 1a). Viscosity was assumed to be 4.0 cP for all subjects. This process was repeated for each time frame over the cardiac cycle. The process is automated such that placing splines defining the vessel of interest is the only input needed to generate a WSS map for a given blood vessel. The average WSS over the cardiac cycle was plotted for each of the volunteers. Similarly, whole brain WSS maps (Figure 1c) can be generated using automated spline interpolation. Total scan time was 5 minutes. Total WSS processing time was about 30 minutes per case.

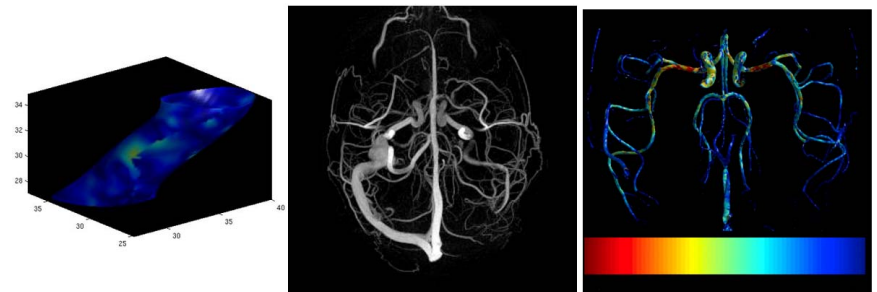


Figure 1: a) WSS Plot of the M1 segment of the right MCA. b) PC-VIPR MIP of the axial whole brain. c) WSS map of the axial whole brain.

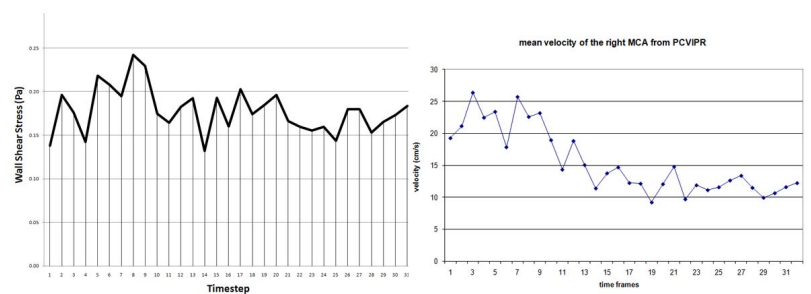


Figure 2: a) Average wall shear stress (Pa) from all segments for each timestep. b) Mean Velocity (cm/s) for all segments from each timestep.

Results:

The average wall shear stress in each timestep for all segments in all subjects is shown in Figure 2a. The wall shear stress averaged across all timesteps for all subjects was $0.20 \text{ Pa} \pm 0.016 \text{ Pa}$, which is consistent with values found in the literature for WSS measured with PC-MRA.⁵ The average velocity in each timestep is presented in Figure 2b. As wall shear stress is proportional to the derivative of velocity with respect to distance from the wall, one can see that the calculated wall shear stress closely matches the plot of average velocity. Wall shear stress measured in the MCA was higher in systole than in diastole but the difference was not as pronounced as one might see in the aorta.

Discussion:

This technique can calculate WSS in medium and large-sized arteries with MR scan times of less than 5 minutes without requiring the use of contrast material, which allows WSS maps to be generated quickly and non-invasively. As in-vivo WSS measurements have prognostic value for determining areas predisposed to aneurysm and atherosclerotic plaque formation, a fast, automated method would have high clinical utility. An automated spline interpolation program can produce WSS maps that provide a reasonable estimation of in vivo wall shear stress that is consistent with values found in the literature. While it is well-known that MR underestimates wall shear stress when compared to computerized fluid dynamics calculations⁶ because visualizing the boundary zone with the lower spatial resolution found in MR is challenging, these values can be used as surrogate parameters of the actual WSS and relative wall shear stress maps of the whole brain can have prognostic value in determining which areas are predisposed to atherosclerotic plaques.

Conclusion: This study showed that reasonable estimates of wall shear stress in large and medium sized arteries can be created from PC-VIPR MRA scans of 5 minutes or less duration and that the wall shear stress values obtained were consistent with previous published MR studies and with velocity measurements from PC-MRA. We are currently performing PC-VIPR scans and generating WSS maps on patients with arterial stenoses and aneurysms and will use the normal values obtained from volunteers as a baseline for comparison.

References: Malek et al, JAMA, 1999;282:2035-2042 2) Cunningham and Gotlieb, Laboratory Investigation, 2005, 85:9-23 3) Hoi et al, jns.2004.101.4.0676 4) Johnson et al, MRM 2008, 60:6, 1329-1336 5)Oyre et al, JACC, 1998, 32:1:128-134 6) Wood et al. JMRI. 2001;13:699-713.