

3-Component Phase-Contrast MRI WSS Vectors in the Carotid Bifurcation are Concurrent with Local Atherosclerotic Plaque Risk Hypotheses

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Introduction: Abnormal patterns of arterial hemodynamic wall shear stress (WSS) are postulated to be co-located with atherosclerotic lesions. [1] In agreement with this hypothesis, patient-specific computational fluid dynamic (CFD) simulations of the carotid bifurcation have shown that areas of low WSS occur at, or just proximal to the bifurcation – which are also known focal regions of plaque formation (typically near the ICA and ICA bulb). [2,3] As suggested by the CFD studies, *in-vivo* experimental validation is challenging, as the two dominant flow-imaging modalities (Doppler ultrasound and phase contrast MRI) are spatially and temporally limited in resolution (especially given that the carotid diameter averages 6.5 mm in adults – before the bifurcation). With this in mind, we previously presented the clinical trial results of an alternative multi-component, high resolution flow-imaging technique using ultrasound-based particle image velocimetry (Echo-PIV) and compared the results with phase-contrast MRI (PC-MRI) velocity measurements. In the pilot study, good inter-modality agreement was found with WSS measured in the common carotid artery (CCA). [4] The relatively straight and long CCA makes it an ideal candidate for a simplified 1D axial WSS calculation (and is widely reported in literature); however, this method is not appropriate at the level of the bifurcation (BIF), which requires the use of transverse velocity components. Given that the quantification of WSS at the bifurcation is highly clinically relevant, we measured the *in-vivo* 3-direction WSS traction vectors at the level of the BIF of 15 test subjects using PC-MRI, focusing on temporally and spatially localized measurements. In addition to quantifying the local and temporal WSS vectors, the overall aim of this work is to determine if PC-MRI measured WSS values correlate with ‘at-risk’ regions. Ultimately, it is hoped that this method will aid in profiling localized vascular morphology and function for the purpose of identifying patients at-risk for atherosclerotic lesions.

Methods: 15 test subjects lying in the supine position were scanned using PC-MRI (Philips Medical Systems). A 1.5 T fast low-angle shot gradient echo sequence was used to obtain retrospectively-gated tissue intensity and phase velocity maps encoded in the 3 principle directions at 5 levels orthogonal to the longitudinal axis of right carotid at the level of the BIF (through plane VENC = 100 cm/s, in-plane VENC = 20 cm/s; voxel size = 0.58x0.58x6 mm). The carotid wall was temporally segmented using the magnitude images at the level of the CCA and the BIF (Fig. 1a-b), providing a total of 30 cross-sections. [5] A B-spline interpolation model was used to calculate continuous velocity derivatives on the vessel contour, thus allowing for the calculation of the deformation tensor and WSS vector (assuming a dynamic viscosity of 4.5 cP). [6] The WSS vector magnitude and the axial and circumferential components were used to characterize the WSS patterns in the CCA and BIF at 8 locations - the anterior, right-anterior, right, right-posterior, posterior, left-posterior, left, and left anterior positions (abbreviated as A, RA, R, RP, P, LP, L, and LA, respectively). A paired two-tailed t-test was used to determine statistical significance of values measured between the CCA and BIF.

Results and Discussion: The morphology of the BIF and ICA region may be viewed as a bifurcation flare, a feature known to promote flow separation and ‘disturbed flow’. [2] A possible indication of disturbed flow is the contribution of velocity components perpendicular to the longitudinal axis of bulk flow. For example, the flow shown in Fig. 1(c) demonstrates the presence of transverse velocity (and thus circumferential WSS) components in the BIF. In support of this observation, the temporally and spatially averaged circumferential WSS components in the BIF were 42±22% of the axial WSS and they were 19±9% of the axial WSS in the CCA. At flow systole these circumferential BIF WSS components measured 25±9% of the axial value and 13±4% in the CCA. Figure 1(d) shows that this pattern is also locally apparent, with the systolic transverse WSS components significantly different in the posterior and right-posterior BIF regions. This significance pattern also manifests in plots of the overall WSS magnitude (at systole, and, time-averaged over the cardiac cycle, Fig. 1e-f). The patient-specific systolic WSS vector plot in Fig. 1(g) illustrates an example case and the areas of low WSS. In addition, it highlights the larger contribution of the circumferential components in these regions. Finally, Fig. 1(e-f) highlights the most notable findings in this study - that is, the presence of significantly low WSS at the posterior-lateral bifurcation region (as compared to the CCA). This location correlates to the ICA and ICA bulb, regions previously identified by CFD to exhibit low WSS (and known regions of focal plaque formation).

Conclusion: We demonstrated the use of 1.5 T PC-MRI to calculate temporally and spatially resolved 3D WSS traction vectors at the level of the carotid bifurcation. As predicted by WSS/atherosclerotic-risk hypotheses, the local WSS magnitudes were significantly low in atheroprone regions, correlating to the ICA and ICA bulb near the bifurcation. These locations correlate well with *in-silico* simulations and provide further support for the utility of MRI in the study of these risk hypotheses.

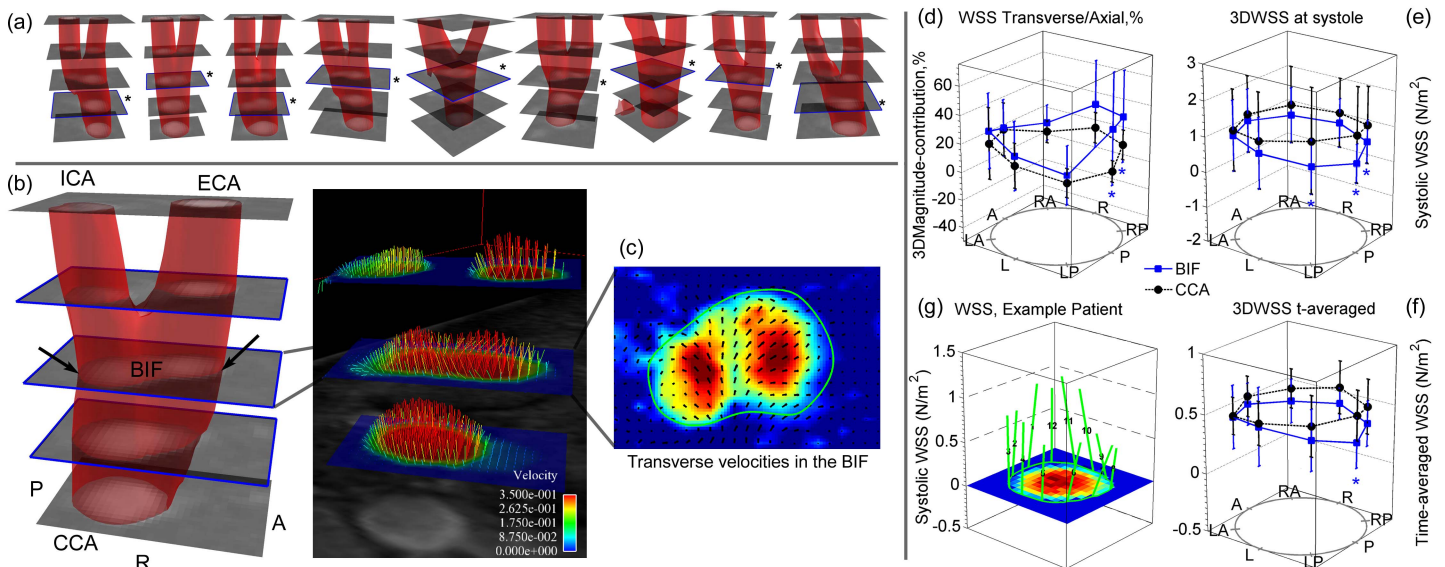


Fig.1. (a-b) MR angiograms of 10 out of the 15 right carotid arteries analyzed, showing BIF slice position (*). The proximal slice plane was used for CCA analysis (b) Anatomic plot (arrows shows ‘at-risk’ regions) and the measured 3D velocity vectors. (c) Example plot of a BIF slice illustrates the presence of transverse velocities. (d-f) WSS in the BIF as compared to the CCA. Statistically significant values ($p < 0.05$) are indicated (*). The percentage contribution of the transverse velocities are significant in the posterior region (‘d’, near the ICA). In ‘e’ and ‘f’ significantly different systolic WSS and temporally averaged WSS are located at the posterior and posterior-lateral positions (also near the ICA). (g) Example systolic WSS vectors demonstrate the WSS significance patterns found in graphs ‘d-f’.

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