Wall Shear Stress Measurement Error in the Common Carotid Artery: A Dual Modality Study

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Introduction: Wall shear stress (WSS) is reported to regulate transcriptional events in vascular remodeling. In addition, WSS regional patterns have been co-located with atherosclerotic lesions. [1,2] With these factors in mind, we reported the quantification of arterial WSS using phase-contrast MRI (PC-MRI) in the proximal systemic and pulmonary arteries of pathologic populations. [3,4] These *in-vivo* measurements have agreed well with computational fluid dynamic (CFD) models. [2,5] However, the proximal arteries in adults are large, typically greater than 10 mm in diameter (excluding cases of stenoses), and not representative of regions known to manifest at-risk lesions, such as in the carotid artery (which in adults averages 6.5 mm in diameter - before the bifurcation). [1] This is important because the use of clinically available 1.5 T PC-MRI sequences to quantify WSS in small arteries (<10 mm in diameter) is confounded by spatial resolution, partial volume errors, in-flow enhancement, and localization of the artery wall. Previous studies in small arteries have used a combination of PC-MRI and CFD to partially mitigate these factors when attempting to quantify WSS. [6] In the absence of alternative measurement techniques, CFD is an excellent tool; however, it is limited in capability to model wall compliance and is sensitive to boundary conditions. An alternative experimental technique, recently developed in our group, uses ultrasound-based particle image velocimetry (Echo-PIV) to determine velocity fields. [7] This technique, which uses microbubble contrast agents as particle tracers, is currently in clinical trials for interrogating carotid flow fields. It is a real-time modality which can resolve multi-component velocity vectors with excellent temporal (~ 2 ms) and spatial resolution (axial by lateral: 0.2 x 0.5 mm). As a result of this trial, the opportunity exists to compare PC-MRI and Echo-PIV for small artery WSS measurements. Therefore, the intent of this study is to clinically examine the *in-vivo* flow fields of the common carotid artery (CCA) in a number of patients using Echo-PIV and PC-MRI, specifically focusing on the use of these two modalities to directly calculate WSS in arteries spanning less than 10 mm in diameter.

Materials and methods: Analysis of the right CCA (rCCA) was performed on cine PC-MRI and Echo-PIV images of patients lying in the supine position. A 1.5 T fast low-angle shot (FLASH) gradient echo sequence (Philips Medical Systems) 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 bifurcation (voxel size, 1x1x6 mm). The PC-MRI data was temporally segmented using Segment [8] and exported to a Matlab program developed for this study (Mathworks, Inc). Echo-PIV imaging was performed at the rCCA using high frame-rate B-mode imaging (Sonix RP, Ultrasonix Medical) after intravenous administration of a microbubble contrast agent (Sonovue). The RF data was postprocessed offline to cross-correlate particle position and the artery was segmented using Matlab. Velocity mapping, flow quantification, bulk motion correction, and temporal and spatial axial WSS calculations were then computed for both modalities (viscosity was assumed constant at 3.2 cP).

Results and Discussion: The reconstructed carotid morphology obtained from 5 PC-MRI intensity slices of a 41 year old male example patient is shown in Figure 1a. Figure 1b and 1c show the corresponding Echo-PIV and PC-MRI velocity fields for this patient. As can be seen, the Echo-PIV 2D velocity field is obtained in a slice parallel to the near wall and far wall, along the longitudinal axis of the CCA, while the PC-MRI slices were obtained transverse to the longitudinal axis. These slice positions were necessary due to the acquisition limitations of both modalities. The peak velocity and calculated flow rates for each technique are shown in Figure 2. As is common in comparisons of ultrasound and MRI velocity data, the Echo-PIV method measured peak velocities slightly higher than MRI. This deviation is most likely due to temporal and spatial velocity averaging during the pre-processing of cardiac PC-MRI data. The differences between measured flow rates may be due to cardiac cycle averaging by PC-MRI, as well as the assumption of a circular cross-section for the Echo-PIV flow calculation. Efforts were made to minimize the time between MRI and Echo-PIV measurements; however, variations between the velocity, flow, and ultimately WSS could also be due changes in cardiac function. Perhaps the most notable measurement deviation was between the Echo-PIV and PC-MRI calculated WSS (Figure 2, bottom row). In the 5 patients examined thus far, all Echo-PIV WSS measurements were greater in peak magnitude than the PC-MRI measurements. While error due to co-registration may exist, there is little quantitative and some qualitative agreement between these waveforms. This may be due to the confounding PC-MRI errors previously discussed in the Introduction. Previous studies have shown that 1.5 T PC-MRI can resolve a satisfactory number of voxels across vessel diameters larger than 10 mm to quantify unsteady spatial velocity profiles. [9] However, below this threshold, the WSS calculation is known to become unstable and flow profile fitting routines are often employed (such as parabaloid fitting). Thus, a near-wall fitting routine for the PC-MRI data will be employed to determine if a convergence between these two WSS measurement techniques occurs.

Conclusion: A disconnect exists in the measured WSS of the CCA using Echo-PIV and 1.5 T PC-MRI. Additional patients are being enrolled to further understand this difference. A potential optimization scheme for the calculation of WSS in small arteries using PC-MRI velocity data is discussed.

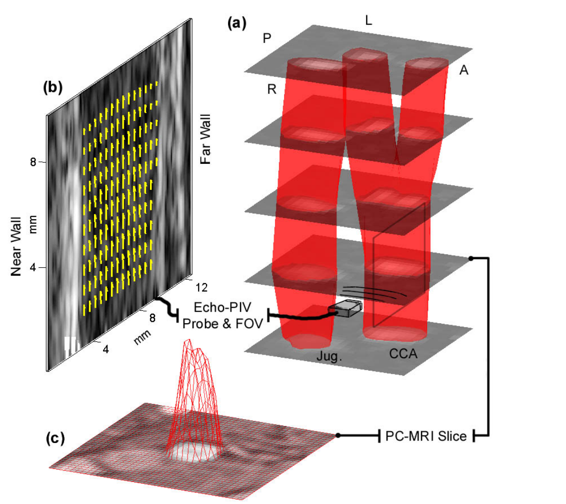

Figure 1. Example patient arterial morphology (a) at the CCA and bifurcation. A diagram identifies the orientation of the patient (b) Echo-PIV and (c) PC-MRI measured velocity fields at systole.

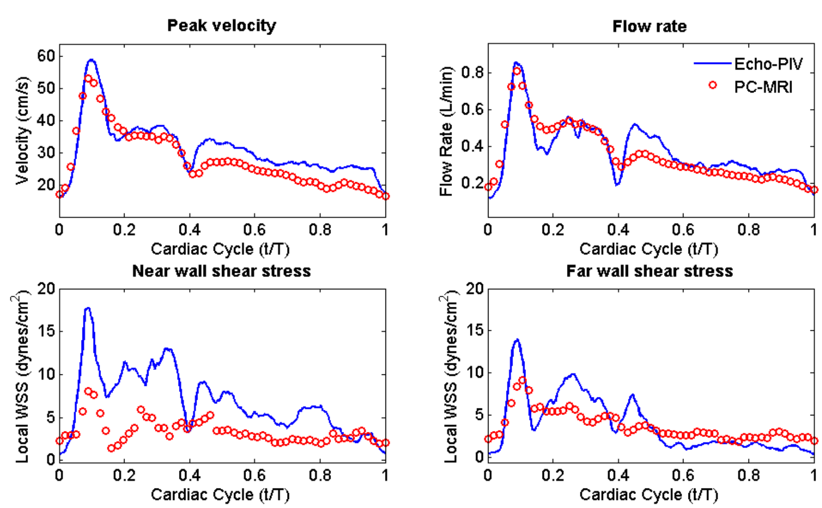

Figure 2. (top-row) Bulk hemodynamic flow parameters for the example patient. The larger peak velocities for Echo-PIV may be due to MRI spatial averaging. (bottom-row) In general, the WSS calculated by PC-MRI was lower than the WSS calculated by Echo-PIV.

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