Comparison between magnitude and direction of 4D phase contrast MRI based and computational fluid dynamics based wall shear stress calculations in healthy carotid bifurcations

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Target audience: Researchers and clinicians interested in non-invasive quantification of vessel wall parameters.

Purpose: Remodeling of the vessel wall is associated with wall shear stress (WSS) magnitude. It has been suggested that local low or high WSS may respectively promote or prevent atherosclerotic lesions in the carotid vessel wall.(1) The current gold standard for WSS quantification is computational fluid dynamics (CFD), which requires extensive computational power and non-clinical expertise. In the past years, methods that derive WSS directly from MRI 4D PC-MRI measurements have been developed (2,3). These allow patient-specific WSS quantifications while using less computational power. Recently, we presented such a method to map 3D WSS on the entire vessel wall (4,5). The purpose of this study was to compare both the magnitude and direction of MRI-based WSS with CFD-based WSS in the carotid bifurcation.

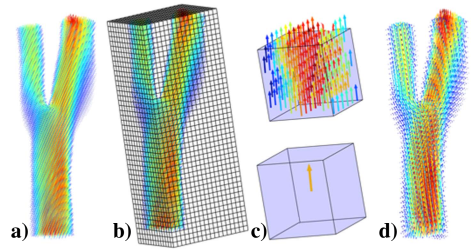

Figure 1: a) CFD velocity data b) MRI grid on CFD data. c) averaging of CFD velocity to MRI resolution d) CFD velocity data at MRI resolution

Methods: A pipeline for simultaneous MRI- and CFD-based WSS calculations was developed and applied to carotid artery data of healthy volunteers. After providing informed consent, 6 volunteers were scanned with a 3T MRI scanner (Philips Healthcare, the Netherlands) using a dedicated 8-channel carotid coil. 4D phase contrast MRI data were acquired using a spatial resolution of 0.63 mm, temporal resolution ~140 ms, TE/TR/flip angle 3.1 ms/ 6.7 ms/ 15º. Scan duration was ~25 minutes. We manually segmented the carotid bifurcation in the 4D PC-MRI images and converted this segmentation to a volumetric mesh for CFD calculations. Time-resolved CFD simulations were performed (Ansys Fidap). The inflow was set to a generalized flow waveform, which was matched (patient-specific) to measured (PC-MRI) inlet flow rates. These simulations resulted in the CFD-based WSS values. To avoid temporal smoothing due to the low temporal resolution in MRI, only diastolic WSS was compared. As it is known that spatial resolution affects the accuracy of the WSS (2,6), we assessed the contribution of this resolution effect by calculating WSS in down-sampled CFD data (figure 1). For the MRI-based WSS, we directly calculated shear rates for the entire vessel wall by fitting a smoothing spline to the measured velocities along the inward normal of each point on the vessel wall.(4,5) The CFD and MRI based calculations took ~15 hours and ~15 minutes respectively. The CFD and MRI-based WSS were compared by means of overlap of low, medium and high WSS tertiles. The angles between CFD- and MRI-based WSS vectors were calculated on the entire lumen surface.

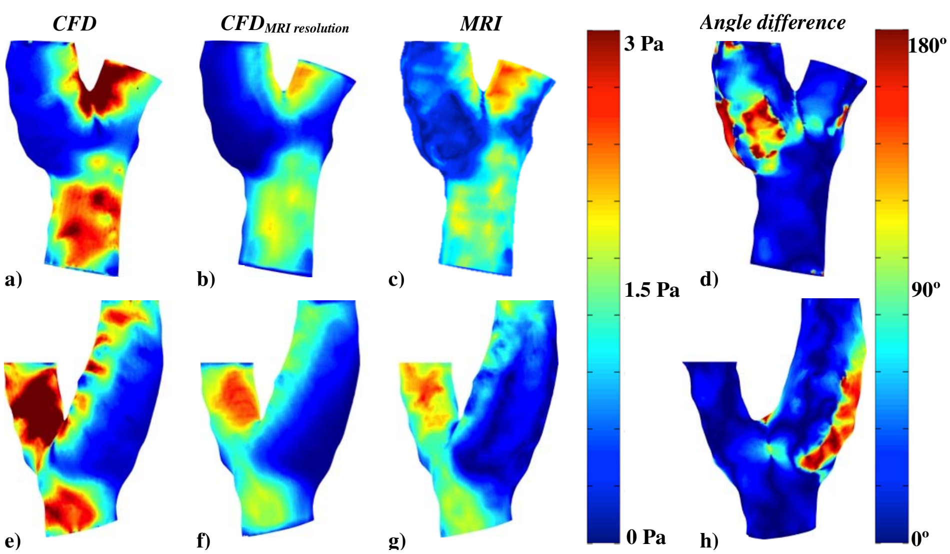

Figure 2: Calculated WSS maps in 2 healthy carotid arteries of 2 healthy volunteers. a,e) CFD-based WSS. b,f) Resolution down-sampled CFD WSS c,g) MRI-based WSS. d,h) Angular differences in WSS direction.

Results: Nine out of 12 carotids were of sufficient quality (no movement or acceleration artifacts) to include in our analysis. The WSS magnitudes were a factor 1.5-2 higher in CFD-based WSS. This difference in WSS magnitude disappeared when CFD results were down-sampled (figure 2b,f). The locations of low, medium and high MRI and CFD-based WSS magnitude matched well (figure 2a,c,e,g). Overlap of WSS magnitude tertiles of CFD and MRI was 69% (± 7%, averaged over 9 carotid arteries and low and high tertile, table 1). In the WSS directions we noticed large angular differences (figure 2d,h) at locations of low and complex WSS patterns in all carotid arteries. In the straight segments of the internal, external and common carotid arteries these angular differences were lower.

Discussion: The absolute MRI-based WSS calculations in this study is comparable to current literature using 4D PC-MRI (7). The systematic larger CFD-based WSS magnitudes (factor 1.5-2) are explained by the difference in resolution, in accordance with current literature (2,6). Despite the underestimation, WSS magnitude tertiles showed considerable overlap of the low and high WSS tertiles, which that are often associated with physiological changes of the vessel wall. Current research mostly focused on the comparison of WSS magnitude rather than direction of WSS between MRI and CFD. However in previous studies, it has been shown that parameters related to WSS vector angle, e.g. oscillatory shear index, are clinically relevant to identify atheroprone regions on the vessel wall. We found large angular differences at sites of low and complex flow, often associated with these atheroprone regions. There can be multiple explanations for this angular discrepancy. First the low WSS regions have a relative low velocity to noise ratio that degrades the segmentation and decreases the accuracy of the MRI WSS calculation. Second, with the current temporal resolution (~140 ms), we can only derive time-averaged rather than instantaneous WSS values using MRI data. This temporal averaging of velocity vectors in regions of complex velocity patterns may cause errors in the direction of the WSS vectors. CFD on the other hand uses rigid vessel walls and generalized inflow profiles, both of which may cause a mismatch with the measured data. Future research is needed to investigate the discrepancy in the direction of the WSS vectors obtained with CFD and MRI.

Table 1: overlap of CFD and MRI WSS tertiles.

[%]	Low WSS tertile	High WSS tertile
1L	65.3	69.5
2L	64.1	57.9
2R	66.5	70.9
3L	67.9	54.2
3R	74.7	84.7
4L	78.0	67.2
4R	65.3	78.7
5L	67.4	65.8
5R	68.9	72.0
Mean	*68.7*	*69.0*

Conclusion: Although WSS was underestimated with 4D PC-MRI, both the patient-specific CFD and the 4D PC-MRI based calculations resulted in similar low and high WSS patterns. The direction of the WSS vectors was similar in regions steady forward flow, but large discrepancies were observed in the regions of low and complex velocity patterns.

References:

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