Comparison of MRI and CFD based wall shear stress and their relationship with wall thickening in human carotid arteries

Merih Cibis[1], Wouter V Potters[2], Mariana Selwaness[3], Frank J Gijsen[1], Andres M Arias Lorza[4], Aad van der Lugt[3], Aart J Nederveen[2], and Jolanda J Wentzel[1]
[1]*Biomedical Engineering, Erasmus MC, Rotterdam, Netherlands,* [2]*Radiology, AMC, Amsterdam, Netherlands,* [3]*Epidemiology, Erasmus MC, Rotterdam, Netherlands,* [4]*Radiology and Medical Informatics, Erasmus MC, Rotterdam, Netherlands*

Introduction: Atherosclerosis is a disease resulting from slow build-up of plaques in the vessel walls. The plaque formation initiates in the innermost layer of the arterial wall just behind the endothelial lining at bifurcations and inner curves of the vasculature co-localizing with low wall shear stress (WSS) [1]. Current studies provide strong evidence that the low level of wall shear stress triggers endothelial dysfunction causing increased permeability, accumulation of cholesterol and inflammatory processes. Assessment of WSS in-vivo is therefore essential for a better understanding of the mechanism underlying atherosclerotic plaque formation. WSS can however not be directly measured in-vivo. Instead, it is calculated by multiplying dynamic viscosity with the gradient of velocities perpendicular to the vessel wall which can be obtained either by computational fluid dynamics (CFD) simulations or in-vivo MRI flow measurements. Since calculation of WSS is based on the spatial derivatives of velocities, the accuracy of the estimated WSS relies on the accuracy and the spatial resolution of the velocity measurements. In this study, our aims were to compare MRI and CFD based wall shear stress (WSS_{MRI} and WSS_{CFD}) in the carotid arteries of an elderly population and to investigate the similarity of the associations between WSS_{MRI} vs wall thickness and WSS_{CFD} vs wall thickness (WT).

Methods: 16 elderly subjects (74±6y) with plaques in their left carotid arteries were selected from the Rotterdam study (cohort study in a suburb of Rotterdam). These subjects underwent MRI scans including time averaged 3D-flow (resolution: 0.70x0.7x1.0mm, TR/TE: 13ms/4.3m) and PDw-EPI (resolution: 0.51x0.51x1.2mm, TR/TE: 12000ms/24.3ms, venc: 60cm/s) using 1.5T GE Scanner (GE Signa Excite II; GE Healthcare, Milwaukee, WI, USA). The PDw-EPI images were used to segment the lumen and the wall manually. The lumen area, outer wall area and WT were calculated using the segmentations. An in-house developed MATLAB algorithm was used to calculate WSS_{MRI} [2]. First, the inward normal direction was found for each point on the lumen surface. The MRI velocities were interpolated at 2 points on the inward normal at a distance of 1.25 and 2.5 mm from the lumen surface. These velocities were fitted to a smoothing spline curve and wall shear rate (WSR) was calculated by taking the gradient of the fitted velocity curve at the lumen. Finally, WSS was calculated by multiplying WSR with the blood viscosity. To calculate WSS_{CFD}, steady state CFD simulations were performed using commercial finite element software FIDAP 8.7.4 (Ansys). MRI measured flows at common carotid artery (CCA) and internal carotid artery (ICA) were used as boundary conditions for CFD. External carotid artery (ECA) boundary condition was left as stress free. The blood density was assumed to be 1.06 g/cm^3 and viscosity was assumed to obey Carreau-Yasuda model. The results were analyzed for CCA and ICA separately and ECA was excluded. WSS_{MRI} and WSS_{CFD} were compared point by point by Bland-Altman analysis. WSS_{MRI} and WSS_{CFD} values were also sorted and divided into the tertiles representing low, medium and high WSS tertiles. WT of each tertile was calculated and compared to each other by one-way ANOVA, post-hoc test. $p<0.05$ was chosen as significant.

	CCA	ICA
Lumen area [mm^2]	38.3±9.5	27.0±7.4
Outer wall area [mm^2]	76.2±19.4	55.3±14.7
Mean WT [mm]	1.5±0.3	1.3±0.2
WSS_{MRI} [Pa]	0.5±0.3	0.5±0.3
WSS_{CFD} [Pa]	0.7	0.8±0.5

Table-1: The artery properties of participants

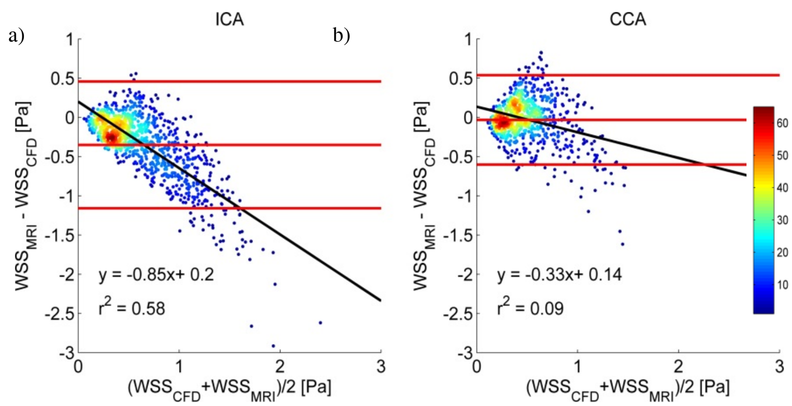

Figure-1: Bland-Altman plots of WSS_{MRI} and WSS_{CFD} in a) ICA and b) CCA Red lines indicate mean of the difference and the 95% confidence interval. The colors indicate the density of the data points scaled with the color bar on the right.

Results: The lumen areas, outer wall areas, mean WT, WSS_{MRI} and WSS_{CFD} for CCA and ICA are reported in Table-1. While mean WSS_{MRI} (0.5±0.3Pa) was lower than mean WSS_{CFD} (0.8±0.5Pa) in ICA, they were almost equal in CCA (WSS_{MRI}: 0.5±0.3 Pa and WSS_{CFD}: 0.5±0.7 Pa). The Bland-Altman plot comparing WSS_{MRI} and WSS_{CFD} is presented in Figure-1. Figure-1a shows that WSS_{MRI} was lower than WSS_{CFD} and the difference between WSS_{MRI} and WSS_{CFD} increased with larger WSS values in ICA. The differences between WSS_{MRI} and WSS_{CFD} were generally found to be smaller in CCA as shown in Figure-1b. The relationship between WSS and WT for both methods is shown in Figure-2. WT was significantly different in each tertile and the highest WT was found in the lowest WSS tertile with both WSS_{MRI} ($p<0.001$, Figure-2a) and WSS_{CFD} ($p=0.007$, Figure-2b) in ICA. WT was also inversely correlated in CCA with WSS_{MRI} ($p=0.005$, Figure-2c) but this correlation was not observed between WT and WSS_{CFD} in CCA ($p=0.692$, Figure-2d).

Discussion: Although several studies have previously compared CFD and MRI based WSS, to our knowledge, the associations of WSS_{MRI} and WSS_{CFD} with wall thickness have never been compared point to point [3]. In our study, mean WSS_{MRI} was lower than mean WSS_{CFD} in ICA, but they were equal in CCA. WSS_{MRI} and WSS_{CFD} patterns were similar in ICA and both showed an inverse relationship with WT. A similar inverse relation in CCA was only found with WSS_{MRI}, but not with WSS_{CFD}. This might be caused by the MRI velocities used as boundary conditions and/or the use of steady state CFD simulations. In conclusion, although CFD and MRI can be used equally to associate wall characteristics with hemodynamic parameters such as WSS in the ICA, caution has to be exercised for the associations made for CCA.

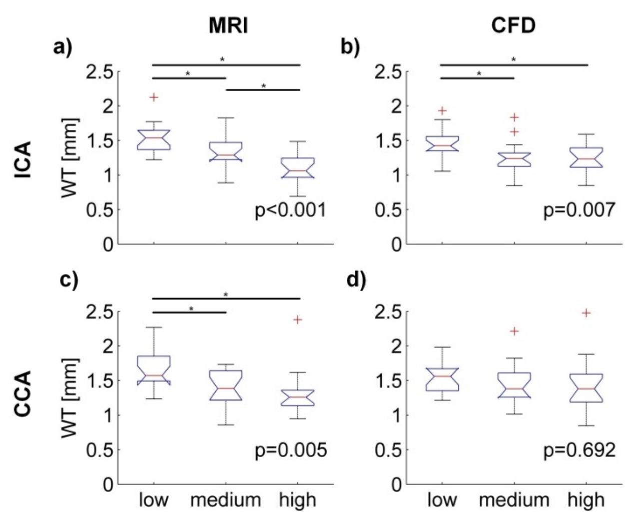

Figure-2: Low, medium and high WSS categories and the corresponding WT [mm]. Left column: categories based WSS_{MRI}, right column: categories based WSS_{CFD}. Top row: ICA, bottom row: CCA. *indicates statistical significance between the subgroups.

References: 1- Davignon, J, et al. *Circulation* 2004 Jun 15; 109: III27-32. **2-** Potters W, et al, *JMRI*. 2014 Jan 17:1-12. **3-** Peiffer V, et al. *Cardiovasc Res*. 2013 Jul; 99(2); 242-250.

Acknowledgments: Grant support by Dutch Technology Foundation STW [Carisma 11629]