Wall shear stress vectors derived from 3D phase contrast MRI at increasing resolutions in an intracranial aneurysm phantom

Pim van Ooij[1,2], Wouter V. Potters[1], Charles B. Majoie[1], Ed vanBavel[2], and Aart J. Nederveen[1]

[1]*Radiology, Academic Medical Center, Amsterdam, Netherlands,* [2]*Biomedical Engineering & Physics, Academic Medical Center, Amsterdam, Netherlands*

Introduction: Wall shear stress (WSS) is the friction force that blood flow exerts on the vessel wall. It is thought to affect the function of endothelial cells and the development of atherosclerosis and aneurysms [1]. WSS can be estimated with blood flow velocity information in vessels. A promising technique to measure blood flow velocity is three-dimensional phase contrast MRI (PC-MRI) [2]. Due to limited spatial resolution and SNR, estimating WSS from PC-MRI is challenging. In this study, a recently in-house developed WSS algorithm is tested on PC-MRI data obtained in an intracranial aneurysm phantom, measured with steady flow at different resolutions. The results are compared with WSS calculations from a computational fluid dynamics (CFD) simulation.

Materials & methods: A glass reproduction of an aneurysm located in the anterior communicating artery was manually created based on a 3D Rotational Angiography (3D-RA) dataset. Informed consent was given by the patient. The phantom with an inner size of 6x4x9 mm^3 (length, width, height, no up-scaling), as shown in figure 1, was connected with a pump supplying a constant flow of water. PC-MRI measurements were performed on a 3T MR system (Philips Healthcare, Best, The Netherlands) in a solenoid rat coil with a diameter of 7 cm at isotropic resolutions starting at 0.2 mm up to 0.9 mm with steps of 0.1 mm. Imaging parameters were TE/TR = 5.4/11.7 ms (0.2 mm resolution), flip angle: 15°, velocity encoding: 30x60x30 cm/s in the x, y and z direction (see figure 1) respectively. The lumen of the phantom was semi-automatically segmented in every slice of the fast field echo images using a level set evolution algorithm [3]. The CFD geometry was obtained with 3D-RA and consisted of 742.316 tetrahedral cells with an average node spacing of 0.14 mm. CFD was performed in FLUENT. The x, y and z components of the inflow as measured with PC-MRI (0.2 mm) were applied as the inflow boundary conditions and Murray's law [4] was applied for outflow conditions. WSS can be calculated by: $\vec{\tau} = 2\eta\dot{\varepsilon}\cdot\vec{n}$ with $\vec{\tau}$ the WSS vector, η the dynamic viscosity, $\dot{\varepsilon}$ the rate of deformation tensor and $\vec{n}$ the normal vector at the wall. At each point at the wall, a rotation was performed such that $\vec{n} = (0,0,1)$ in the rotated frame. The PC-MRI dataset was rotated likewise. By assuming that no flow occurs through the vessel wall, it holds that $\vec{n}\cdot\vec{v}$=0. The inner product of the rate of deformation tensor and the normal vector is then reduced to: $\dot{\varepsilon}\cdot\vec{n} = (\frac{\partial v_x}{\partial z}, \frac{\partial v_y}{\partial z}, 0)$. The shear rates $\frac{\partial v_x}{\partial z}$ and $\frac{\partial v_y}{\partial z}$ are the gradients at the wall of 1D smoothing splines fitted through the x-, and y-velocity values in the direction of the normal.

Results: In figure 2 it is shown that the maximum, mean and standard deviation of WSS increased with resolution, approaching and surpassing the values found for CFD. In figure 3a, b and c the direction and magnitude of the velocity vectors in a characteristic sagittal slice measured at 0.9, 0.5 and 0.2 mm, respectively, are displayed. Complexity of the flow increased with increasing resolution. The main vortex could be seen in every figure. In these figures, maximum velocity increased with resolution. In figure 4a, b and c, directions of WSS vectors and regions of high and low WSS are similar. However, in these figures, maximum WSS and WSS complexity increased with resolution. Note in figures 3 and 4 that a more detailed segmentation of the phantom was obtained at higher resolutions.

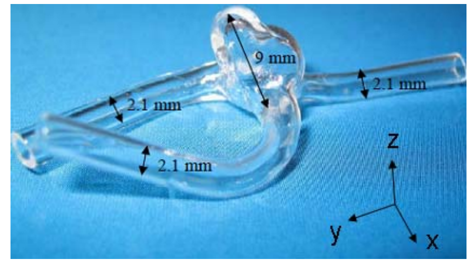

Fig 1. Aneurysm phantom

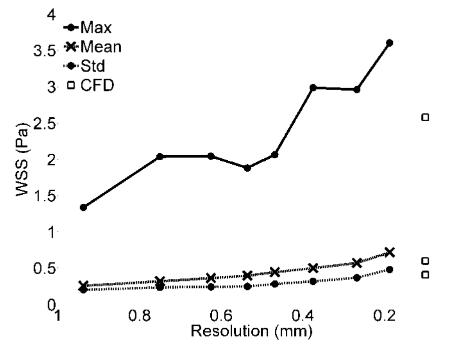

Fig 2. Mean, maximum and standard deviation of the PC-MRI wall shear stress at all resolutions compared to CFD (□)

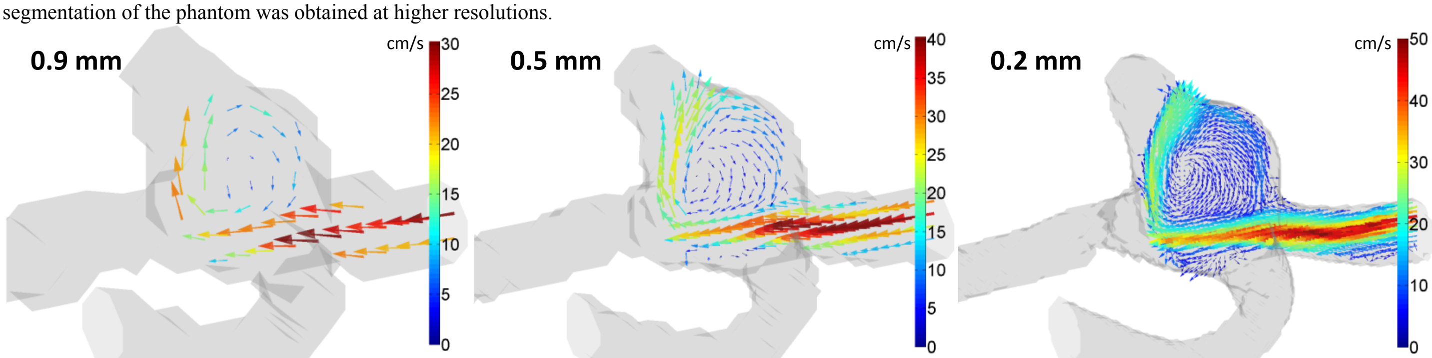

Fig 3a. Velocity in a characteristic slice at 0.9 mm *b. Velocity in a characteristic slice at 0.5 mm* *c. Velocity in a characteristic slice at 0.2 mm*

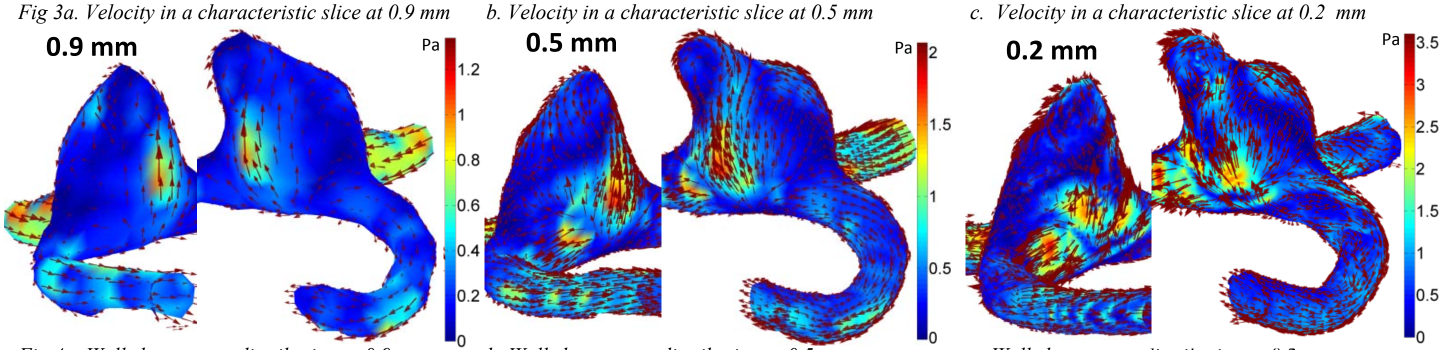

Fig 4a. Wall shear stress distribution at 0.9 mm *b. Wall shear stress distribution at 0.5 mm* *c. Wall shear stress distribution at 0.2 mm*

Discussion/Conclusion: At higher resolutions, more detailed flow information and wall delineation is obtained than at lower resolutions. Both are important factors for minimizing wall shear stress underestimations. However, these high resolutions are often difficult to attain in clinical PC-MRI protocols. To obtain qualitative indications of wall shear stress distributions, acquisitions at intermediate resolutions may be sufficient.

References:
[1] Stalder et al. MRM; 60(5):1218-1231 (2008)
[2] Wigstrom et al. MRM; 36(5):800-3 (1996)
[3] Li et al. Proc IEEE CVPR'05, San Diego, USA 2005;1:430-436
[4] Murray. Proc Natl Aca Sci USA;12(3):207-14 (1926)