Spatio-temporal sacrifices for wall shear stress and oscillatory shear stress calculations

Wouter V Potters[1], Merih Cibis[2], Frank JH Gijsen[2], Henk A Marquering[1,3], Ed vanBavel[3], Jolanda J Wentzel[2], and Aart J Nederveen[1]

[1]*Radiology, Academic Medical Center, Amsterdam, Netherlands,* [2]*Biomedical Engineering, Erasmus Medical Center, Rotterdam, Netherlands,* [3]*Biomedical Engineering & Physics, Academic Medical Center, Amsterdam, Netherlands*

Target audience: Researchers/ clinicians interested in non-invasive quantification of wall shear stress.

Purpose: There is ample evidence that shear stress of blood at the vessel wall is involved in the initiation and progression of atherosclerotic plaque formation. [**1,2**] In addition ithas been suggested that also oscillations in the direction of the shear stress promote atherogenic conditions. Oscillatory Shear Index (OSI) is one of the WSS-related parameters which quantifies the change in the direction of the WSS vectors over the cardiac cycle. 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. Although both WSS and OSI are associated with cardiovascular diseases [**3,4**], most of the MRI based studies limit themselves to the average or maximum WSS values over the cardiac cycle. The main reason limiting the previous studies might be the intrinsic challenge of obtaining velocities in both high spatial and temporal resolution which might be neccessary for accurate WSS and OSI estimation. In this study we aim to assess the effect of spatio-temporal resolution on the accuracy of WSS and OSI measurements using PC-MRI.

Methods: A carotid phantom model was 3D printed based on a healthy carotid bifurcation of a healthy volunteer. The silicon carotid phantom was connected to a flow set-up (figure 1) that supplies a pulsating flow (LifeTec, Eindhoven, NL). Flow pulse frequency was set to 1/second, which together with the outflow volume resuled in an average flow rate of 160 ml/min, with the flow waveform matched as much as possible to the physiological waveform from the volunteer. Consistency of the applied flow curve was checked outside the scanner room by means of a calibrated realtime flow probe (echo probe, LifeTec, Eindhoven, NL). All the PC-MRI scans were made on a single day on a 3T MR system (Ingenia R4, Philips Healthcare, Best, NL) with a solenoid rat coil. We acquired time-resolved 2D phase contrast scans proximal to the carotid bifurcation with 36 different spatio-temporal resolutions varying between 0.2 to 1 mm and 6 to 140 ms. Retrospective triggering was applied to the flow set-up signal and three directional velocity encoding (3x100 cm/s) was applied. TE/TR/FA were 4.7-6.6ms/8.9-24.1ms/10º. Scan time for the scans varied between 1 to 21 minutes. All velocity data was corrected for the phase offsets induced by eddy currents (average correction values were -2.2±3.5 cm/s). The scans were fully automatically segmented. Initial segmentation was provided by kmeans clustering and vessel-like structure detection, followed by an active contour segmentation using the method by Herment [**5**], which was extended with a smoothness constrain on the temporal evolution of the contour. Flow was quantified by integrating velocity over the segmented area. WSS calculations were performed using the method by Potters [**6**]; basically a spline was fitted to each point on the vessel wall and the shear rate was calculated. OSI was calculated with the method by He [**7**]. As we used water as a medium, the viscosity was kept constant at 1*10-3 Pa*s.

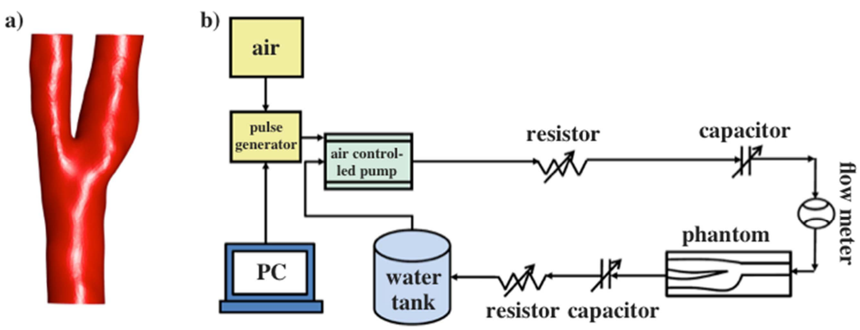

***Fig 1**: **a)** carotid bifurcation phantom model **b)** Phantom setup. The pulse generator and PC are located outside the MR room. The echo based flow meter was not MR compatible.*

Results: The high spatio-temporal resolution flow curves from the PC MR measurements match very well to the high resolution flow reference method (figure 2). The surface area of the fully automatic segmentation (area size 21.8 ± 1.7 mm^2) is less accurate at lower resolutions, see figure 2. Figure 3 shows the average WSS and the average OSI for all measurements. The average WSS (figure 4) was found to be 0.63±0.14 Pa (Poiseuille: 1.1 Pa) and the OSI was found to be 0.22±0.16 at the highest resolution measurement (0.2 mm /22 ms resolution).

Discussion: As was already shown extensively in existing research papers (**6, 8, 9**) the WSS magnitude is under estimated if the resolution is lower. We add to this information the fact that the average WSS is also influenced greatly by the temporal resolution. In addition the OSI measurements change due the change in spatio-temporal resolution. OSI is especially hampered by lack of temporal resolution while WSS magnitude is specifically hampered by spatial resolution. Although we aimed to optimize the automated segmentation as far as possible, the segmentation might still have an influence on the WSS. However this effect is the same when the measurements were performed in vivo; hence we incorporated these segmentation effects in the current analysis.

Conclusion: Both OSI and WSS magnitude are heavily influenced by spatio-temporal resolution. OSI tends to be more effected by temporal resolution, whereas WSS magnitude tends to be more effected by spatial resolution.

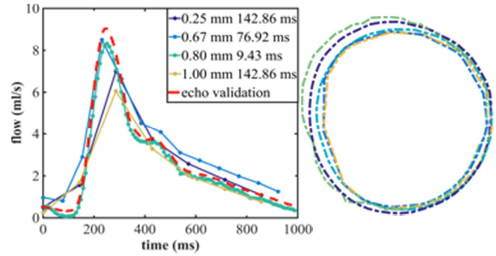

***Fig 2**: Segmentations (right) and time-resolved flow patterns (left) for 4 measurements. The red line on the left shows the flow validation measurement with echo.*

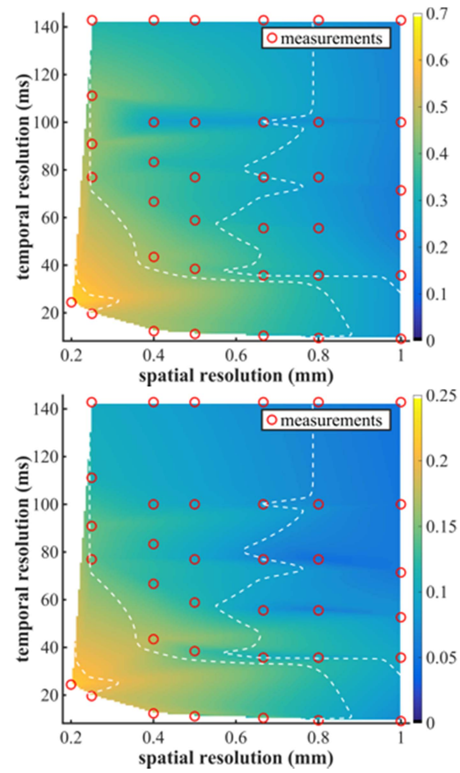

***Fig 3**: Mean WSS in Pa (top) and OSI (bottom) quantification for different spatiotemporal resolutions. The dashed isolines denote measurement duration (from left to right: 18, 8 and 2 minutes). Color scales depict WSS (Pa) and OSI respectively.*

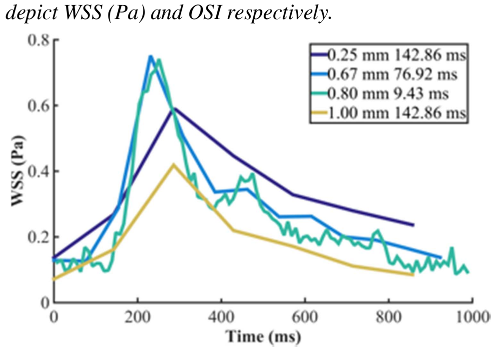

***Fig 4**: Time-resolved WSS patterns (average over the contour) for four spatio-temporal resolutions.*

References:
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9: Cheng et al. Ann Biomed Eng 2002.