Wall shear stress quantification and reproducibility using variable VENC 4D phase contrast MRI in the aorta

Wouter V Potters[1], Anders Nilsson[2], Sandra van den Berg[1], Ed vanBavel[3], Karin Markenroth Bloch[4], Freddy Ståhlberg[2,5], and Aart J Nederveen[1]

[1]Radiology, Academic Medical Center, Amsterdam, Netherlands, [2]Medical Radiation Physics, Lund University, Lund, Sweden, [3]Biomedical Engineering & Physics, Academic Medical Center, Amsterdam, Netherlands, [4]Philips Healthcare, Lund, Sweden, [5]Diagnostic Radiology, Lund University, Lund, Sweden

Target audience: Researchers and clinicians involved in 4D velocity-encoded imaging who are interested in wall shear stress quantification.

Purpose: Wall shear stress (WSS) is the force exerted by the flowing blood on the endothelial cells. WSS has been correlated with endothelial function and wall thickness. Quantification of WSS from 4D phase contrast MRI (4DPC) can be performed in the aorta (1,2), but is challenging in the diastolic part of the heart cycle due to a low velocity to noise ratio (VNR). This low VNR can be ascribed to the relatively high VENC used to measure velocities in the aortic arch. Recently, Nilsson et al. presented a method to vary the VENC throughout the heart cycle (3). They showed that this significantly improved the VNR. We hypothesize that this improved VNR will also improve the quantification of diastolic WSS. The secondary aim of this study was to analyze the reproducibility in systole.

Methods: After approval of the local ethical committee and written informed consent, the aorta of 7 volunteers (age 27.5±2.2, 5 males) were scanned using both a 4DPC and a 4DvPC sequence. Data was acquired on a 3T MRI scanner (Philips Ingenia, Best, the Netherlands). Scan parameters were similar to (3): TE/TR/FA: 4 ms/ 8 ms/ 8º, spatial resolution 2x2x2 mm, temporal resolution ~83 ms, VENC for 4DPC was ~170 cm/s, VENC for 4DvPC varied between 50 and 200 cm/s. In order to keep the TE, TR and resolution equal, the bandwidth for 4DvPC (344 Hz/pixel) was slightly higher than the 4DPC bandwidth (248 Hz/pixel). Flow quantification was performed using GTFlow 2.1.4 (Gyrotools, Zurich, Switzerland) in the ascending and descending aorta. WSS was calculated using the method described previously(4,5). In short: for each point on the vessel wall we fitted a smoothing spline to three velocity vectors, equispaced along a 1 cm inward normal. The vessel wall was forced to zero velocity. Segmentation was performed manually for the average of the 3 peak-systolic heart phases. Manual segmentations of 4DPC and 4DvPC were divided into three parts: ascending aortic arch, descending aortic arch and descending aorta. Side branches, proximal ascending aorta and the distal descending aorta were cut off at equal positions for both scans. WSS results from 4DPC and 4DvPC were compared with a paired t-test for the entire aorta and the 3 separate parts (figure 2). Noise levels were determined in static back muscle tissue, using the method described in (3). The systolic WSS reproducibility was assessed by means of the reproducibility index (RI), which is defined as 1.96 times the standard deviation of the differences between WSS of successive 4DvPC and 4DPC scans, divided by the mean WSS.

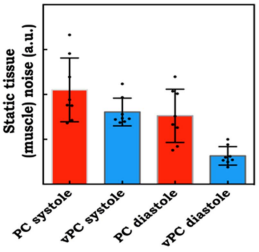

Figure 1: noise quantification for systolic and diastolic velocity in the back muscle.

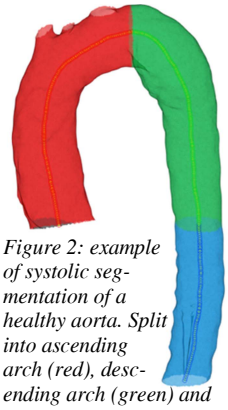

Figure 2: example of systolic segmentation of a healthy aorta. Split into ascending arch (red), descending arch (green) and descending aorta (blue)

Results: Flow quantification showed no difference in flow rates between 4DPC and 4DvPC. Both visual inspection and noise quantification (figure 1) showed a significant improvement in VNR for the 4DvPC sequence in diastole, but as expected not in systole. WSS was calculated on the entire vessel wall (see example in figure 3). Average WSS was 1.3 ± 0.2 Pa over the entire aorta in systole and 0.2 ± 0.1 Pa in diastole. No significant differences in WSS mean or standard deviation were observed between 4DPC and 4DvPC results in the separate aorta parts (figure 4). Visually, we did see a more smoothed appearance of the WSS patterns on the vessel wall. RI for systolic WSS was 6.8% for the entire aorta, and 8.6%, 8.7% and 8.1% for the ascending, descending arch and the descending aorta respectively.

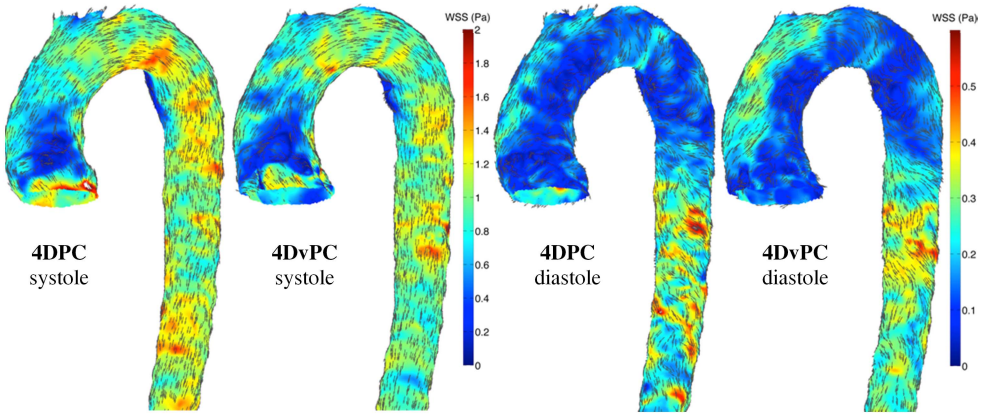

Figure 3: WSS visualization for systolic and diastolic WSS from the 4DPC and 4DvPC sequence. Colors depict the WSS magnitude. Arrows depict the direction of the WSS vectors. For clarity only 1/10 of the arrows was plotted.

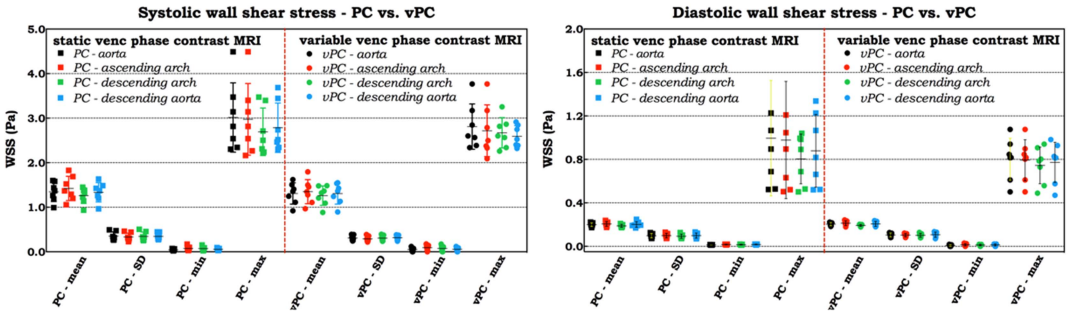

Figure 4: WSS results for all 7 volunteers (mean, standard deviation, minimum and maximum). Data shown is the full aorta (black) and the separate parts ascending arch (red), descending arch (green) and descending aorta (blue).

Discussion: The results we found in terms of flow are in accordance with existing literature on 4DvPC imaging. We found no differences in flow rate, but we did found a decrease in noise for the 4DvPC images. Our main hypothesis was that the improved VNR would also improve WSS quantification. Despite a better visual appearance of the WSS from 4DvPC data, we were unable to quantify this improvement by comparison of the (segmental) WSS standard deviations. The likely explanation is that the physiological variation of WSS and the limited WSS quantification accuracy exceed the gain from the decreased noise levels. Furthermore the increase in bandwidth may have limited (±15%) the VNR gain of the 4DvPC sequence, dampening the hypothesized effect. Comparing the values to literature, we found that both systolic and diastolic WSS are similar. We only used systolic segmentations, also for diastole, which may have induced WSS errors, especially near the aortic root in diastole.

We found no significant differences ($p>0.05$) in the systolic WSS values between 4DPC and 4DvPC. Regarding reproducibility, the regional differences in RI can be explained by the more complex patterns of the WSS in the arch.

Conclusion: WSS in systole and diastole can be calculated using both 4DPC and 4DvPC MRI data. The decrease in velocity noise did not result in a decrease of standard deviation in the WSS calculation, suggesting that the improvement does not exceed the physiological and methodological variation of calculated WSS. The reproducibility of the mean WSS using this method was found to be good.

References: **1.** Stalder et al., MRM 2008; 60:1218–1231. **2.** Bieging et al., JMRI 2011; 33:589–597. **3.** Nilsson et al. JMRI 2012; 36:1450-9. **4.** Potters et al. JCMR 2012; 14 Suppl 1:W5. **5.** Ooij et al. JMRI 2013:1–16.