Quantitative Flow sensitive 4D MRI: Detailed Flow and 3D Wall Shear Stress Analysis in the Entire Normal Thoracic Aorta

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Introduction: The importance of wall shear stress (WSS) and oscillatory shear index (OSI) is known since the introduction of the flow theory on atherogenesis [1] and arterial remodelling [2,3]. Recent reports further underline its importance [4]. Earlier reports on MR-based analysis of aortic hemodynamics were either based on 2D slices [5] or on visual description of visualized 3D flow patterns [6].

Flow-sensitive 4D MRI does not only provide 3D morphology but also acquires 3-directional blood flow data. Therefore, next to axial throughplane calculations of WSS, WSS can be determined as a vector quantity which can be decomposed into axial and circumferential WSS. As a result, the viscous drag of blood flow directed both along the vessel lumen (axial WSS) and the lumen circumference (circ. WSS) can be evaluated. The oscillatory shear index (OSI), representing the degree of WSS inversion along the cardiac cycle can be derived likewise. Therefore, the aim of this study was to apply those new parameters which may possibly reveal to be of predictive value with respect to arterial remodelling and atherogenesis and are new compared to previously reported studies.

Methods: MRT-experiments were performed on 11 healthy volunteers (mean age 23.6 years, range 20-34, 1 female) on a 3T MR-system (Magnetom TRIO, Siemens, Erlangen, Germany). 3D blood flow measurements covering the entire thoracic aorta were performed after written informed consent using time-resolved 3D CINE phase contrast MRI (flow sensitive 4d-MRI) using an eight channel body coil and an rf-spoiled gradient echo sequence with interleaved 3-directional velocity encoding (BW = ± 480 Hz/pixel, flip angle = 15°, TE / TR=3.67 / 48.8 ms, venc = 1.5 m/s, spatial resolution = (2.71 - 2.93 x 1.58 - 1.69 x 2.60 - 3.0) mm³, temporal resolution = 48.8 ms). The measurement was prospectively gated to the ECG cycle and utilized a previously reported adaptive navigator technique [7] to enable free breathing during the acquisition.

Data analysis and quantification: Eight 2D planes according to the schematic drawing in figure 2 (lower right) were interactively positioned in the 4D data sets(Ensight, CEI, NC, USA) and exported into a in-house software tool. Subsequent 2D segmentation permitted the detailed quantitative analysis of blood flow and vessel wall parameters in 12 segments. Specifically, wall shear stress (WSS) which is derived from the slope of the measured velocities at the arterial wall and which can be described using a deformation tensor, was derived from the measured 3-directional velocity vector field. As schematically illustrated in Fig. 1, WSS and the derived OSI were extracted from the data using B-spline interpolation of the local velocity onto the segmented vessel contours.

Results: MRI and quantifications were successful in all volunteers. Fig. 3 and 4 show that the mean circumferential WSS corresponds well to the known helical evolution of blood flow in the thoracic aorta. Fig. 3 underlines the aspect that max OSI closely follows min axial WSS but is substantially different from max axial WSS. Figure 4 shows the spatial distribution of mean axial WSS and OSI along the vessel wall in exemplary planes.

Discussion: Our results are in good agreement with WSS measurements results in the abdominal aorta derived from phase-contrast MRI reported in the literature based on 2D acquisitions [8-10], which delivered similar average WSS values over the course of the cardiac cycle (0.18 to 0.95 N/m2), as measured in the thoracic aorta. Further similar WSS values were also reported in a recent study of WSS in different segments of the descending thoracic aorta [5]. However, circumferential WSS and OSI measurements in true 3D datasets have not been shown before.

References: [1] Davies PF. Physiol Rev 1995;75:519-60; [2] Langille BL, Science 1986;231:405-7; [3] Glagov S, N Engl J Med 1987;316:1371-5; [4] Cheng C, Circulation 2006;113:2744-53; [5] Wentzel JJ, JACC. 2005;45:846-54; [6] Bogren HG, J Magn Reson Imaging. 1997;7:784-93; [7] Markl M, J Magn Reson Imaging 2006, in press. [8] Moore JE Jr., e. Atherosclerosis 1994;110:225– 40. [9] Pedersen EM et al. Eur J Vasc Endovasc Surg 1999;18:328 –33. [10] Oyre S, et al. J Am Coll Cardiol 1998;32:128 –34.

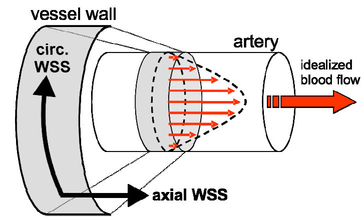

Fig 1: Schematic illustration of the decomposition of the measured wall shear stress into axial and circumferential components.

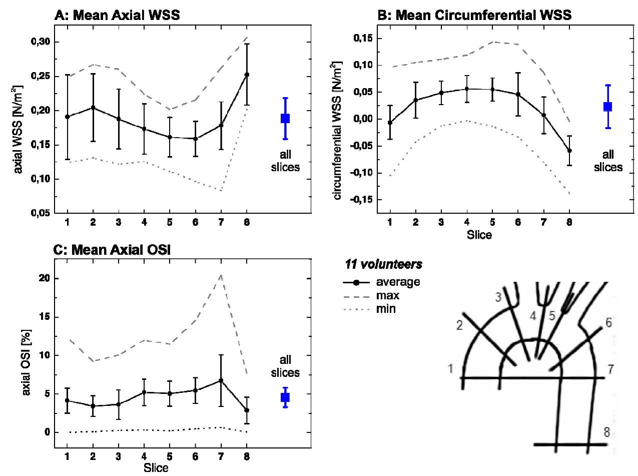

Fig. 2: Spatial and temporal mean WSS and OSI as a function of slice position. Error bars represent inter-individual variations in WSS and OSI. The blue data points on the right in each graph represent mean ± SD over all slices.

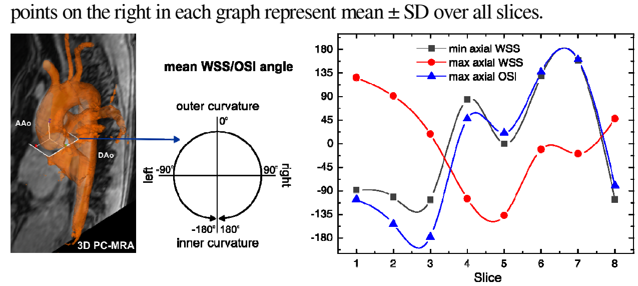

Fig. 3: Angular dependence of max and min WSS and max. OSI for 8 slices along the entire thoracic aorta. Slice locations are schematically illustrated in fig. 2, lower right. The definition of the angle of the max/min axial WSS and max axial OSI are exemplary illustrated for a particular plane in the ascending aorta (AAo).

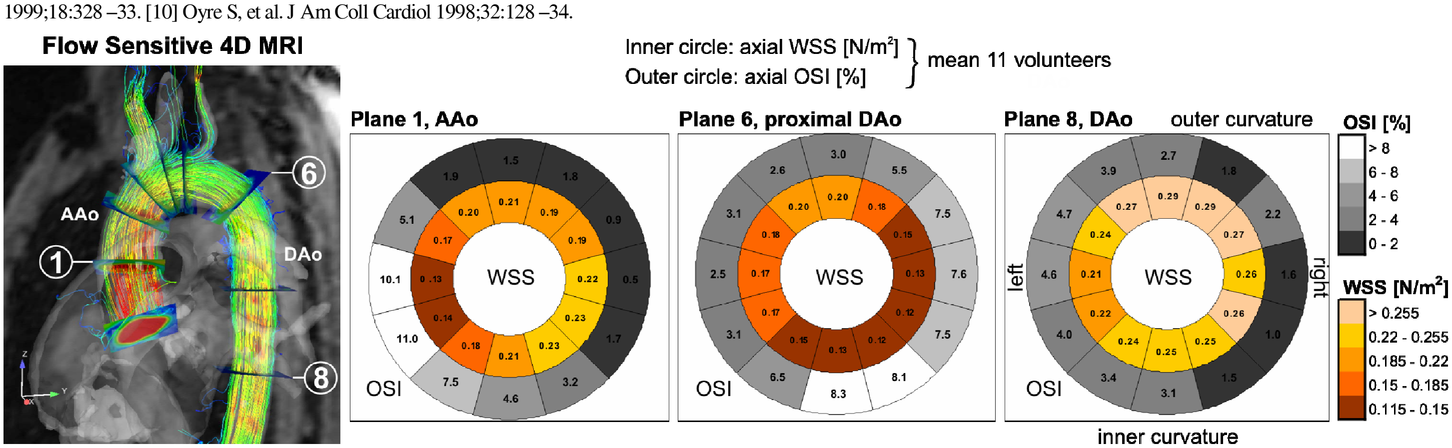

Fig 4: Detailed evaluation of local axial WSS and OSI in three slices in the AAo, proximal DAo and DAo. Axial WSS and OSI were derived from the measured blood flow velocities in 12 segments along the aortic lumen circumference. The orientation of the individual segments corresponds to the schematic illustration in fig. 3, left.