Three-dimensional Assessment of Wall Shear Stress Distribution in the Atherosclerotic Aorta

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Introduction: Complex plaques of the aortic arch with thickness ≥4 mm or containing thrombi are considered high-risk sources of brain ischemia. [1]. In an autopsy study, ulcerated plaques were predominantly found in the superior wall of the aortic arch [2] while clinical experience reveals that plaques are typically located at the inner curvature of the proximal descending aorta. Since cardiovascular risk factors impact on the entire aortic wall this particular preference of plaque development must be induced by individual factors such as aortic anatomy including the outlet of supra-aortic arteries and the curved shape of the arch resulting in reduced wall shear stress (WSS) and increased oscillation of flow at this site. The association of low WSS and high oscillatory shear index (OSI) with atherosclerotic wall thickening was recently studied in an animal model and in patients [3, 7]. The three-dimensional distribution of WSS in 19 healthy volunteers using three-directional velocity encoding MRI was recently shown [4]. We present the first in-vivo study investigating the distribution of WSS and OSI in the entire thoracic aorta of stroke patients by three-directional velocity encoding MRI (flow sensitive 4D MRI) and compare findings with those of 32 healthy volunteers.

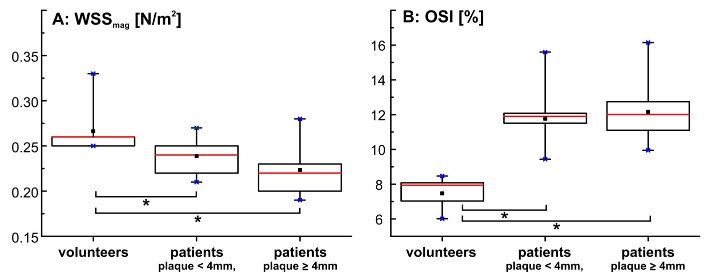

Fig. 2: Mean WSS (left) and OSI (right) averaged over all 8 analysis planes in young normal volunteers (n = 31) compared to patients with no or mild (n = 28) and with severe atherosclerosis (n=30). Small filled box = mean, red line = median; large box = lower and upper quartile; error bars = range of values within 5 - 95%, blue x = min and max values within 1 - 99 % (* = significant).

Methods: 58 acute stroke patients (60.5±12.9 years, 25 females) were prospectively included. All experiments were conducted on a 3T MR system (TRIO; Siemens, Germany). For the individual evaluation of 3D hemodynamics time-resolved flow-sensitive 4D MRI was employed. Respiration and wall motion artifacts were minimized by ECG and respiratory gating [5]. Imaging parameters were: *venc* = 150 cm/sec, spatial resolution = 2.1×3.2×3.5 mm^3 in a sagittal-oblique 3D volume with rectangular field-of-view (FOV) = 400×300 mm^2, flip angle = 15°, TE / TR = 3.5 / 6.1 ms, temporal resolution = 48.8 msec. Data processing included noise filtering, correction for eddy currents and velocity aliasing. A 3D phase contrast (PC) MR angiography was calculated from the 4D MR data and was used to extract eight analysis planes at defined anatomical landmarks normal to the aorta (Ensight, CEI, USA, figure 1 A). Planes were imported into an in-house analysis tool (MatLab, The MathWorks, USA). Vectorial WSS was directly derived from the flow-sensitive 4D MRI data using first order derivatives of measured velocities which were mapped directly onto the segmented lumen contours using cubic b-spline inter-polation as described previously [4]. After segmentation of all measured time frames, absolute shear stress (WSS_{mag}) and oscillatory shear index (OSI) reflecting the degree of WSS_{mag} inversion over the cardiac cycle were extracted for 12 segments along the vessel circumference. Mean WSS_{mag} and OSI (averaged over all 8 analysis plane, all segments, and time) were compared to findings in 32 young heal-thy volunteers (mean age = 23.7 years, 8 females) from a previous study [4, 6]. To evaluate the influence of the level of atherosclerosis on WSS, patients were sub-divided into 2 groups with no or mild atherosclerosis (max plaque thickness <4 mm, n =28) and patients with severe atherosclerosis (i.e. presence of complex plaques, n = 30). For segmental analysis and to identify areas at particular risk for plaque development or presence, the segments representing the individual 15% threshold of time-averaged min. WSS_{mag} and max. OSI were identified.

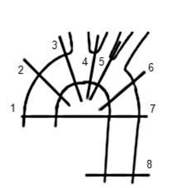

Fig. 1: Analysis plane orientation within the thoracic aorta. Planes 1 - 3 are located in the ascending, planes 4 and 5 in the arch, and 6 - 8 in the descending aorta.

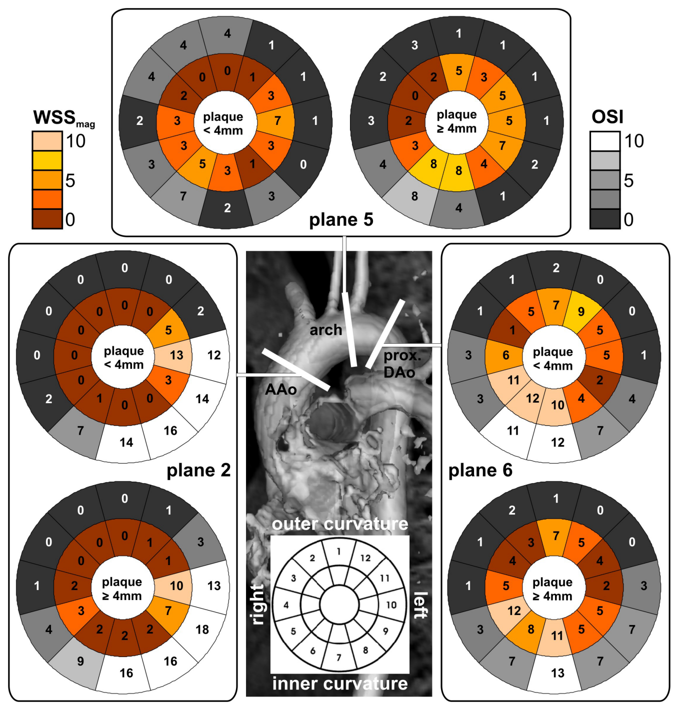

Fig. 3: Segmental distribution of the individual upper 15% of OSI and lower 15% of WSS_{mag} in patients with no or mild (n=28) and with severe atherosclerosis (n = 30). The segmental distribution shown for planes in the AAo (plan 2), arch (plane 5) and proximal DAo (plane 6) represents the number of patients with low WSS_{mag} or high OSI in the respective aortic region.

Results: For the entire aorta, mean WSS_{mag} systematically decreased with increasing age and plaque burden (figure 1). Similarly, OSI was different between young volunteers and patients (p<0.05) while differences between the patient groups were less pronounced. The segmental distribution of plaque promoting low WSS_{mag} (inner circles) and high OSI (outer circles) for three analysis planes is shown in figure 2. High OSI was very pronounced on the left-inner wall of the ascending aorta for both groups reflecting oscillating shear forces due to typical diastolic retrograde flow. Low ascending aortic WSS_{mag} was more frequently found in patients with atherosclerosis. A high incidence of low WSS_{mag} was found and at the dorsal wall/inner curvature of the aortic arch and proximal descending aorta (planes 5 and 6, segments 5-9). Additionally high OSI in similar segments indicated significant reverse flow along the inner curvature of the descending to the ascending aorta and showed a larger variance to the anterior and posterior aortic wall.

Discussion: The unique advantage of this MRI technique is the 4-dimensionality of flow analysis allowing for a retrospective and spatially non-restricted evaluation of segmental wall parameters in-vivo. Visual 3D information can be directly combined with absolute velocities or local wall shear stress at the individual site of interest. The markedly reduced wall shear stress at the inner curvature of the arch and proximal descending aorta in combination with high OSI at the same locations is well compatible with typical sites of plaque development. Future studies will investigate the correlation of individual plaque localization with these individual areas at risk. A clear and potentially atherogenic reduction of WSS_{mag} and increase in OSI could be demonstrated between the younger volunteer and older patient group. Age-related normal values are thus mandatory in order to perform future individual risk stratifications for the development and progression of aortic atherosclerosis. In addition, the inclusion of larger patient cohorts is necessary to evaluate the association of aortic anatomy and cardiovascular risk factors on wall shear stress.

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