Evaluation of 3D Blood Flow Patterns and Wall Shear Stress in the Normal and Dilated Thoracic Aorta using flow-sensitive 4D MRI.

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Introduction: Thoracic aortic aneurysms are a frequent and life-threatening disease [1], involving the aortic root and ascending aorta [2]. Dissection or rupture is an often lethal complication with a significantly higher lifetime risk when the aortic diameter exceeds 6 cm [1]. The mean growth rate of thoracic aneurysms is low with an average of 0.1 cm/year [3] but there is substantial variation in individual aneurysm progression. Predicting aneurysm progression is nearly impossible [4] and dissection and rupture also occur at diameters smaller than 6 cm [3]. The assessment of aortic hemodynamics and the presence of altered flow patterns and their association with changes in aorta size may provide further regarding how aneurysms develop and the assessment of dissection risk. Previous studies have investigated the distribution and changes in wall shear stress (WSS) and the oscillatory shear index (OSI) in the aorta [5]. These factors can play an important role in the development of vascular pathologies such as aneurysms or atherosclerosis [6]. Time-resolved 3D phase contrast MRI with 3-directional velocity encoding (flow-sensitive 4D MRI) can provide comprehensive information on aortic hemodynamics [5]. It allows for simultaneous visualization of 3D blood flow and quantitative analysis of blood flow and regional wall shear forces with full volumetric coverage of the thoracic aorta. The purpose of this study was to investigate 3D flow patterns and vessel wall parameters (WSS and OSI) in the ascending aorta in correlation to the vessel geometry in patients with ascending aortic aneurysm, age-matched subjects, and young healthy volunteers.

Methods: Aortic hemodynamics were assessed in a study with n=63 subjects. Aneurysm patients (n=33, 3 female, age 60±16years) had a dilated or aneurismal AAo ≥4mm. For comparison, 15 healthy young volunteers (3 female, age 23±2years, aortic diameter = 30 ± 4mm) and 15 age-matched normal controls (3 female, age 67±8years, aortic diameter = 28 ± 4mm) were also included. All examinations were performed on a 3T MR System (Siemens, Germany) using flow-sensitive 4D MRI with three-directional velocity encoding. Data were acquired in a sagittal oblique 3D slab encompassing the aorta with prospective ECG gating and during free breathing using navigator respiratory gating (venc=150m/s, α=7-15°, TE=2.7- 3.5ms, TR=5.1-6.1ms spatial res.=1.6-2.2 x 2.1-2.5 x 2.4-3.0mm^3, temporal res.=40.8-48.8ms). A 3D phase contrast angiogram (3D PC-MRA) was used to manually position eight analysis planes (EnSight, CEI, Apex, USA) at defined anatomical landmarks normal to the aorta in the ascending aorta, arch, and proximal descending aorta (Fig.1,2). For each analysis plane the aortic lumen contours were manually delineated for all time-frames using a home built tool programmed in Matlab (Matlab, The Mathworks, USA). Velocity-time curves, peak systolic velocity, time-to-peak (TTP) systolic velocity, and retrograde flow were calculated. WSS estimation was based on a direct interpolation of the local velocity derivative on the segmented vessel lumen contour using b-splines. Regional time-resolved WSS vectors were mapped onto a standardized 8-quadrant model representing 8 angular segments of the aortic wall: outer and inner curvature, right outer and left outer curvature, right inner and left inner curvature, right and left (Fig. 2). For each analysis plane and each segment the time-averaged absolute WSS and peak systolic absolute $WSS_{systole}$ and the oscillatory shear index (OSI) were calculated.

Results: Dynamics of absolute WSS over the cardiac cycles for the eight analysis planes in the thoracic aorta are shown in Figure 1. Peak systolic values of patients and age-matched controls were clearly reduced and delayed compared to young healthy volunteers. Moreover, patients with dilated AAo and age matched controls demonstrated a number of significant ($p<0.05$) differences in regional flow velocities and wall parameters. Systolic time to peak (TTP) velocity and retrograde flow were significantly increased in patients in comparison to age matched controls in nearly all and four of the analyzed planes, respectively. In addition, peak systolic WSS in patients was systematically decreased in the ascending aorta and entire aortic arch. Conversely, OSI was significantly higher in patients at similar locations in the thoracic aorta. Correlation analysis revealed a significant relationship between the degree of aortic dilation and prolonged TTP systolic velocities in all eight analysis planes (r=0.30-0.53, p<0.04). Similarly, increased OSI clearly correlated with increase AAo diameter in all analysis planes expect for the proximal AAo (r=0.33-0.49, p<0.02). In addition, peak systolic WSS demonstrated weak but significant negative correlations with increased AAo diameter in three analysis planes in the aortic arch and descending aorta (r=0.32-0.40, p<0.03). Figure 2 shows the segmental distribution of peak systolic WSS in the entire thoracic aorta in patients with dilated AAo compared to age-matched controls. In patients, a significant decrease of regional peak systolic WSS was found which was mainly located in the right and outer curvature in the AAo and proximal arch (planes 1-4). The segmental distribution of peak WSS corresponded well with the frequently encountered eccentric shape of the dilatation in 14 of 33 (42 %) patients in our study cohort. In these, a clear majority (12/14, 86%) presented with an eccentric dilatation towards the outer curvature (i.e. regions with reduced systolic WSS) while only two patients demonstrated dilation eccentricity towards the inner curvature.

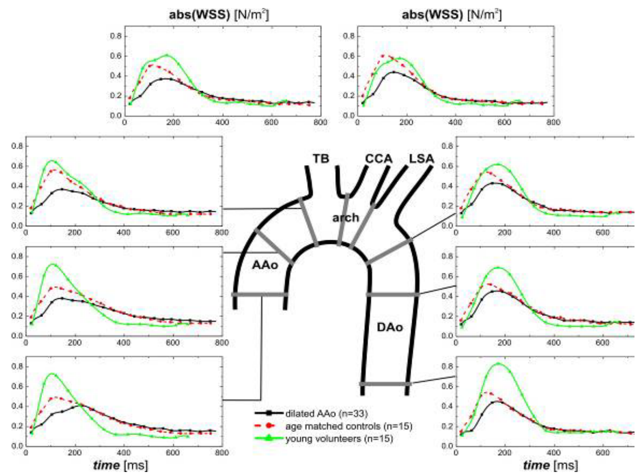

Fig.1: Temporal evolution of absolute wall shear stress (abs. WSS) averaged over the lumen circumference for each analysis plane. Graphs depict WSS at each location over the cardiac cycle averaged for healthy volunteers (green curves), AAo patients (black curves) and age-matched controls (red curves).

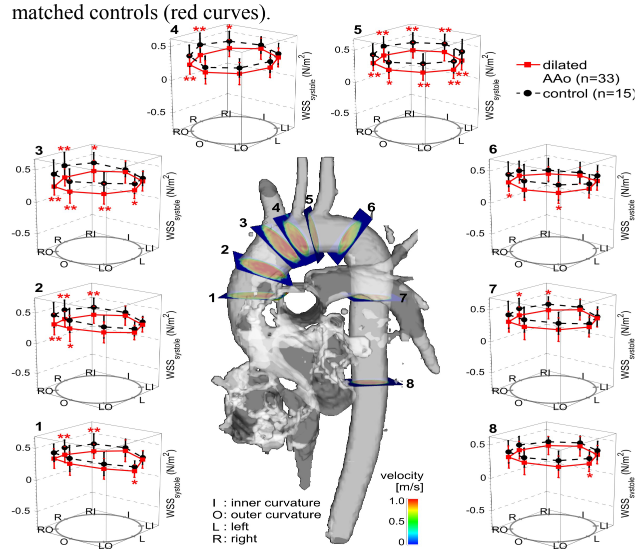

Fig. 2 Distribution of regional peak systolic wall shear stress (WSS) in aneurysms of the AAo (n=33) compared to age-matched controls (n=15). I = inner curvature, O = outer curvature, L = left, R = right. * / ** indicate significant differences with p<0.05 / p<0.01

Discussion: The results of this study demonstrate that flow-sensitive 4D MRI is able to quantify geometry dependent flow and vessel wall parameters alterations in the thoracic aorta. The decrease in systolic WSS and increase in OSI in patients with dilated AAo observed in this study is well in line with previous studies identifying low WSS and high OSI as critical wall parameters indicative of vascular remodeling in atherosclerosis and aneurysm development [6,7]. Notably, significant regional reductions in peak systolic WSS were centered along the right outer aortic wall, corresponding well with the asymmetric shape of dilatation and resulting eccentricity of the right outer wall often seen in our study cohort and in the predominant location of intimal fenestration in aortic dissection [8]. These findings indicate that peak systolic WSS may be a risk factor for aortic dilation in regions with low WSS. In addition, vessel wall parameters in patients with dilated AAo were altered at the dilation level as well as in the vessel segments distal to the dilation, highlighting that an enlarged AAo influences vessel wall parameters in adjacent normal segments. Follow-up studies of patients and age-matched controls are now necessary to evaluate the predictive value of the flow and WSS alterations we have detected regarding further dilatation and/or aneurysm development.

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