Flow-sensitive four-dimensional magnetic resonance imaging:
flow patterns in ascending aortic aneurysms

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Abstract

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Keywords: Aorta/aortic; Aortic root; Aneurysm; Imaging (all modalities); Magnetic resonance imaging (MRI)

1. Introduction

Blood-flow patterns and haemodynamic force parameters such as fluid shear-stress (FSS) and circumferential wall tension (CWT), and their role in vascular remodelling and vascular disease development are subjects of current discussion [1]. Altered haemodynamics are assumed to be associated with pathological processes of the vessel wall, leading to the development of atherosclerotic plaques, loss of elastic lamellae, media degradation and the accompanying loss of vessel wall integrity. Pathological haemodynamics may be one of the factors leading to increasing vessel wall dilatation, aneurysm formation and vessel wall dissection [2]. However, there is evidence that changes in vessel morphology in the context of aneurysmatic vessel disease or after surgical repair correlate with local vortical and helical flow formations and flow acceleration [3,4]. Several studies have demonstrated initial detailed information about local changes in haemodynamic parameters in patients with different aortic diseases as revealed
in flow-sensitive four-dimensional (4D) magnetic resonance imaging (MRI) investigations. These included patients with aortic aneurysms [5,6], aortic dissections and partial thrombosis [7], patients after aortic root replacement [8,9], after ascending—descending aortic bypass surgery [10] and with a persistent ductus arteriosus [11].

It remains widely unknown under which circumstances pathologically complex flow appears and how it is characterised in detail. Furthermore, its influence on local vessel wall physiology, including loss of elastic fibres and other pathological processes affecting aortic wall integrity, has not been thoroughly investigated to date. Little is known about the impact of changes in flow patterns on the pathogenesis and progression of vascular diseases in general, and especially of diseases affecting the thoracic aorta.

In this context, the investigation of individual pathological flow patterns in thoracic aortic aneurysms is of particular interest. Non-invasive MRI and its intrinsic sensitivity to tissue movement and velocity enable us to acquire time-resolved three-dimensional (3D) data sets containing information about vessel morphology (magnitude images) and spatially co-registered haemodynamic information (flow images). State-of-the-art MRI data acquisition techniques combined with advanced computer-aided flow visualisation methods facilitate highly detailed imaging of individual local flow-patterns in healthy individuals and patients [12].

The rationale of this study was to characterise individual local pathological flow patterns in detail in a case series of six patients with ascending aortic aneurysms [13—15] using flow-sensitive 4D MRI and computer-aided flow analysis. Two patients had undergone previous aortic valve or ascending aortic operations. The pathological findings were compared to physiological aortic flow patterns in a healthy individual and to pathological flow patterns of the dilated ascending aorta described in current literature [6].

2. Materials and methods

2.1. Data assessment

All measurements were performed on a 3 T MRI-System (Trio, Siemens, Germany) using 3D morphological imaging in combination with flow-sensitive MRI, i.e. the spatially registered acquisition of three-directional velocity information. Data were acquired using a sagittal oblique 3D volume covering the entire thoracic aorta including the supra-aortic branches. ECG gating was used to assess blood-flow information as a function of the cardiac cycle and tissue movement [12]. To reduce artefacts such as image ghosting and/or image blurring due to respiration, flow-sensitive 4D MRI was combined with navigator gating [12]. The temporal evolution of the patient’s lung—liver interface was monitored by executing a navigator pulse at the end of each cardiac cycle. Respiratory control was done by gating MR measurements to the respiratory motion, i.e. by acquiring data whenever the lung—liver interface was within a predefined data acceptance window. None of the patients or healthy controls received contrast agents. The technique of improved navigator-gated data assessment has already been described by our group [12].

2.2. Computer-aided data analysis

Data sets were pre-processed using fully automated noise filtering and eddy current correction to minimise image noise for sources of error such as eddy currents. All reconstructed data were loaded in a commercially available software package (EnSight; CEI, Apex, NC, USA) for interactive 3D data analysis [5]. In every dataset six 2D emitter planes were created and put carefully in the dataset; one directly above the aortic valve, one in the middle of the ascending aorta, one proximal to each supra-aortic branch, and one in the descending thoracic aorta. The planes served as origin for 3D particle traces and 3D streamlines visualising local flow patterns during peak systole. The 3D streamlines represent traces tangent to the velocity field according to an individual timeframe and are colour-coded according to local flow velocities, while red colour represents the highest velocities up to 1 m/s. The 3D particle traces resemble paths of massless particles emitted during peak systole, and the same colour coding was used as in 3D streamlines. For these results we used the two most proximal 2D emitter planes, above the aortic valve and in the middle of the ascending aorta, as specific emphasis was put on the ascending aorta [5].

2.3. Healthy volunteers

Representative material from one healthy volunteer (male, age 32) is presented (Fig. 1, Video 1). The findings in a group of healthy volunteers (n = 19) were reported earlier [3,5,12].

2.4. Patients

This study was performed at the University Medical Center of Freiburg, Germany. All patients gave written informed consent prior to the investigations and the study was approved by the local ethics committee. All of the six patients (one female) suffered from an aneurysm of the ascending aorta with an average diameter of 5.6 cm (range: 4.8—7.6 cm). The patient mean age was 45.5 years (range 20—60 years).

Inclusion criteria for this study were previously diagnosed aortic root dilation, aneurysm of the aortic root or dilation/aneurysm of the ascending aorta. There were no exclusion...
criteria with respect to aetiology or age. All patients were recruited between July and December 2006.

Two patients presented an aortic aneurysm involving the sinuses of Valsalva (patient A: 4.7 cm; patient B: 5.5 cm) resulting in minimal (patient A) and mild (patient E) aortic valve insufficiency. Aortic valve insufficiency was also found in patient B (minimal to mild). Minimal mitral valve insufficiency was observed in patients A and E. Only two patients had arterial hypertension (B and D).

Development of an ascending aortic aneurysm was related to Marfan syndrome in one case (patient A), and in another, a pseudo-aneurysm occurred at the proximal suture site of a preceding supracoronary aortic replacement (patient B). Other aetiologies were degeneration (patients C and F) and atherosclerosis (patients D and E). In one case, (patient F) the ascending aneurysm was associated with a bicuspid aortic valve.

Two patients had undergone previous valve or ascending aortic operations. Patient B underwent supracoronary aortic replacement, developing an ascending aneurysm 12 years later, while patient C had undergone a commissurotomy during childhood related to a valvular aortic stenosis; he presented with an ascending aneurysm 18 years later. An overview of the demographic data of all patients is shown in Table 1.

### Table 1: Demographic data

<table>
<thead>
<tr>
<th>Patient</th>
<th>Aneurysm diameter (cm)</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Aetiology</th>
<th>AVI</th>
<th>Dilatation of SoV (cm)</th>
<th>Arterial hypertension</th>
<th>Previous operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.6</td>
<td>M</td>
<td>20</td>
<td>Marfan syndrome</td>
<td>Minimal</td>
<td>4.7</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>B</td>
<td>7.6</td>
<td>M</td>
<td>63</td>
<td>Pseudo-aneurysm</td>
<td>Minimal/mild</td>
<td>5.5</td>
<td>Yes</td>
<td>Supracoronary aortic replacement, 12 years ago</td>
</tr>
<tr>
<td>C</td>
<td>4.8</td>
<td>M</td>
<td>20</td>
<td>Degeneration</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Commissurotomy, 18 years ago</td>
</tr>
<tr>
<td>D</td>
<td>5.3</td>
<td>F</td>
<td>54</td>
<td>Atherosclerosis</td>
<td>—</td>
<td>—</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>E</td>
<td>4.8</td>
<td>M</td>
<td>60</td>
<td>Atherosclerosis</td>
<td>Mild</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>F</td>
<td>5.5</td>
<td>M</td>
<td>56</td>
<td>Degeneration, BAV</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>


Minimally vortical flow was seen in the sinuses of Valsalva (Fig. 1, Video 1).

The observed flow pattern in a typical onion-shaped Marfan-linked ascending aneurysm (patient A) featured considerably increased vortex formations within the sinuses. In this patient flow acceleration along the small curvature within the distal ascending aorta and proximal arch was evident (Fig. 2, Video 1).

Patient B developed an extensive ascending aortic aneurysm after preceding supracoronary aortic replacement at the proximal suture site. One large vortical flow

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**3. Results**

Healthy volunteers showed mainly undisturbed flow patterns throughout the thoracic aorta. Highest flow velocities up to 1.3 ms were seen in ascending and descending aorta and a right-handed helical flow pattern beginning in the distal ascending aorta and extending into the arch. Slow, minimally vortical flow was seen in the sinuses of Valsalva.

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**Fig. 2.** Patient A. Ascending aneurysm in a patient with Marfan syndrome. Arrows: prominent vortex formations within sinuses of Valsalva.

**Fig. 3.** Patient B. Upper: arrows indicate local flow acceleration in the middle of the ascending aorta, and extensive vortical flow formation within the large sac of the pseudo-aneurysm. Lower (1—4): development of the pathological flow pattern is more obvious over time in the same patient, as seen from left anterior. Yellow arrow: level of aortic valve. Note that the flow is divided and forced, with high energy into the ascending aorta or in the sac of the pseudo-aneurysm on the left.
formation could be observed, filling the complete extensive aneurysmal lumen. The 3D particle traces visualisation shows the development of this pathological pattern more clearly (Fig. 3, Video 1).

In patient C, commissurotomy due to valvular aortic stenosis had been performed in childhood, and he developed an ascending aortic aneurysm 18 years later. The 3D streamline visualisation of local flow revealed a large circumferential flow pattern with flow acceleration along the anterior aspect of the ascending aorta. In the middle of the ascending aorta we observed a helical flow pattern that was evident during the complete cardiac cycle, reaching its full extent in late diastole. The time-resolved, 3D particle-trace visualisation revealed that this flow pattern’s development started within early systole and that helical flow was directed in a retrograde fashion during diastole (Fig. 4, Video 1).

Patients D and E had ascending aortic aneurysms based on atherosclerotic aetiology, however, their local flow patterns differed significantly (Figs. 5 and 6, Video 2). Patient D showed an extensive increase in right-handed helical flow compared to flow patterns seen in healthy volunteers. Entrance of blood-flow into this helix was further proximal to the valve compared to the physiological right-handed helical pattern covering ascending aorta and the proximal arch. The number of revolutions rose to 3, and blood-flow accelerated along the entire great curvature of the ascending aorta. Patient E showed an extensive vortical flow pattern with a nearly sagittal orientation in the middle of the ascending aorta and increased vortical flow in the sinuses of Valsalva area. Flow acceleration was evident between these two vortices along the great curvature of the ascending aorta, although less extensively than in patient D.

Patient F had an ascending aneurysm linked with a bicuspid aortic valve, revealing a large vortical flow pattern directly above the valve. The spatial orientation of this vortex was not observed in any of the other individuals. Blood-flow velocity along the middle of the ascending aorta was slower, while flow along the ascending aorta’s right lateral wall was markedly faster (Fig. 7, Video 2).

4. Discussion

These flow-sensitive 4D MRI data reveal a marked variety of pathological local blood-flow patterns within the ascending aortic aneurysms that have been investigated. There are clear differences in pathological local flow patterns, not just when compared to the aortic flow situation in healthy volunteers, but among the patients themselves as well.

Klipstein et al. [16] reported on a series of healthy individuals in 1987 using magnetic resonance velocity mapping, describing diastolic retrograde flow along the posterior left aortic wall. This is consistent with the recent findings of Hope et al. [6] in healthy volunteers, revealing the development of two opposing systolic helices and diastolic retrograde flow in between the locations of these helices. In their series of volunteers, 80% showed right-handed helical flow in the ascending aorta. Bogren and Buonocore [17] reported on a series of 16 healthy volunteers, focusing on
differences in healthy thoracic aortic flow patterns between young and elderly patients and using a similar 4D MRI technique. All of the patients in the young group (30–34 years, n = 5), which matches the healthy volunteer presented in this study (Fig. 1, Video 1) and those already described (n = 5) [3,5,12] exhibited a clockwise (right-handed) helix with 1 revolution in the ascending aorta and aortic arch. Three volunteers in the young group also exhibited systolic, counterclockwise flow in the ascending aorta and/or arch. Maximum flow velocities reached 1.2 ms in these patients, and 1.3 ms in the volunteers in this study. The volunteers we reported on earlier (age range 20–40, mean 27 years) also featured a clockwise helix through the ascending aorta and a late systolic retrograde flow channel along the posterior left aortic wall, which corresponds to the findings of Bogren and Buonocore [17]. Interestingly, their group found severe disturbances such as uncoordinated flows in the ascending aortic patterns of elderly patients (over 75 years), due to stiffening, widening and elongation of the aorta with age. These patterns however were markedly different from our findings in patients with ascending aortic aneurysms, who all exhibited increased helical or vortical flow patterns.

Patient A suffered from Marfan syndrome and presented the typical onion-shaped ascending aorta shape, including dilated sinuses of Valsalva in particular. The 3D streamline visualisation however revealed extensive changes mainly in the sinuses' haemodynamics, indicating a possible correlation between extensive local vortical flow and vessel wall dilation in this case. The region of highest flow velocity within the ascending aorta had shifted to a more distal spot, the proximal arch, and closer to the small curvature than in healthy volunteers. Patient B, who, similar to patient A, developed an ascending aneurysm after an earlier aortic replacement, showed a conspicuous connection between extensive change in the local flow pattern at the distinctive vessel-dilatation site, as the vortex was located exclusively within the aneurysm sac. This finding also underlines a possible causal link between pathological vortical flow, which can change local forces affecting the vessel wall, and vessel dilation and aneurysm development. Patients C, D, E and F showed more general dilation of the complete ascending aorta. Flow visualisation in those patients showed less distinct locations with pathological flow patterns. Instead, the complete ascending aortic flow pattern was changed markedly, including mid-luminal helical flow (patient C), increased and accelerated helical flow along the vessel wall (patient D) and multiple vortex formations (patient E). Mid-luminal helical flow in patient C might be due to changes in cusp anatomy after valvular surgery in childhood, while the extensive circular pattern within the ascending aorta could be artefact-related. Patient F was the only patient in our series with a bicuspid aortic valve, showing an extensive local vortex within the ascending aorta with a spatial orientation differing significantly from our findings in the other patients. Causes behind the development of post-stenotic aortic dilatation and the linkage between a bicuspid aortic valve and dilation of the ascending aorta remain controversial [18,19]. However, the disk-shaped appearance of the vortex and its extent, covering nearly the entire ascending aortic lumen, suggests a possible direct connection to the aortic valve pathology in this particular case. This finding corresponds to earlier results in a study performed in patients with bicuspid aortic valves using echocardiography [20], in which distinctive flow acceleration was demonstrated along the antero-lateral ascending aortic wall.

Hope et al. [6] recently reported on 4D MRI investigations in patients suffering from ascending aortic aneurysms. Their report describes how anatomical changes in ascending aortic aneurysms can skew normal flow patterns, changing physiologically observed retrograde and helical flow patterns. The vortices in patients with ascending aortic aneurysm were significantly larger in diameter (48.5–53.1% of the lumen diameter in volunteers as opposed to 77.1–99% of the same in patients) and they also lasted longer. The average flow velocity in patients was lower in the ascending aorta (0.2 ms) than the velocities in the transverse arch and descending aorta (0.4 ms). This was not the case in healthy volunteers, whose velocities throughout the complete course of the aorta were between 0.38 ms and 0.52 ms, respectively. We identified five different flow patterns in dilated ascending aortas in this series. The most common pattern (54% of included patients) included initial systolic flow along the right anterior aortic wall, infolding before entering the transverse arch, in turn creating a large area of retrograde flow in the left coronary sinus area. This pattern appears as one prominent vortex in the ascending aorta and resembles our findings in patient E (Fig. 6, Video 2). However, patient E exhibited an additional second vortex, minor in size, around the right coronary sinus.

The second common pattern in Hope’s series (43% of patients) featured fast, right-handed circumferential flow and slower-moving helical flow in the aneurysm’s centre, which is consistent with our findings in patient D (Fig. 5, Video 2). One patient in Hope’s series showed a largely undisturbed flow pattern similar to the most common patterns in healthy individuals, and another showed an accentuated right-handed helix while the flow was entering the transverse arch. Neither of these patterns was present among our patients.

In Hope’s series, one patient with annuloaortic ectasia featured a considerably slower flow at the level of the ascending aorta and a pattern similar to a helical ring around the systolic central jet in the aneurysm. Our patient A, also suffering from a dilated aortic root, showed a largely unchanged ascending aortic flow pattern, while increased vortical flow was evident in both sinuses. We also observed a systolic helical ring around the central jet in patient C who did not have a dilated root. Patients B and F (Figs. 3 and 7, Videos 1 and 2) in our series exhibited patterns differing from the above-mentioned, which is most likely due to patient B’s specific aetiology in pseudoaneurysm and to the bicuspid nature of patient F’s aortic valve.

Artificial aneurysm models indicate that haemodynamics and wall mechanics play an important role in aortic disease development [21]. In particular, the kinetic energy occurring during turbulence was found to have a significant effect on pressure distribution along aneurysmatic vessel walls, considered an important factor in aneurysm growth and rupture [18]. Several studies have included attempts to define mathematical models to predict aneurysm growth and rupture and different computer models for estimating vessel wall forces [22]. It was shown that wall shear-stress is one of the most important factors contributing to aneurysm rupture [23]. Changes in local mechanical forces can lead to...
acceleration and aggravation of pathological processes including atherosclerotic plaque development, loss of elastic fibres within the vessel wall [2, 24] and finally, wall dilatation and dissection.

Presumably, the individual aneurysm’s morphology thus plays a role in generating different levels of mechanical forces on the vessel wall, thereby completing some kind of vicious cycle in aneurysm development and progression. In this context, others have demonstrated that asymmetric aneurysms are exposed to higher stress levels than those with more fusiform morphology [25].

It remains unclear as to what extent and how exactly pathological flow effectively initiates or aggravates aneurysm development. However, our results do suggest that aneurysms should be interpreted as not just a change in vascular geometry, but as an individually developing complex of diseased anatomy in conjunction with impaired function. The development of pathological flow within pathomorphologically changed vessel segments should be subjected to further investigation. Better knowledge of these interrelations will help us to better understand the development and progression of aortic disease. Future research should focus on defining certain pathological flow patterns, and on the question as to whether, and if so how, they influence the natural course of aortic aneurysms. This might lead to the identification of distinct pathological flow patterns serving as haemodynamic predictor factors for thoracic aortic disease, and might help to improve therapy planning and management of those patients affected by aortic aneurysms.

References