Time-resolved 3-dimensional magnetic resonance phase contrast imaging (4D Flow MRI) reveals altered blood flow patterns in the ascending aorta of patients with valve-sparing aortic root replacement

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ABSTRACT

Objective: The aim of this study was to compare aortic flow patterns in patients after David valve-sparing aortic root replacement with physiologically shaped sinus prostheses or conventional tube grafts in healthy volunteers.

Methods: Twelve patients with sinus prostheses (55 ± 15 years), 6 patients with tube grafts (58 ± 12 years), 12 age-matched, healthy volunteers (55 ± 6 years), and 6 young, healthy volunteers (25 ± 3 years) were examined with time-resolved 3-dimensional magnetic resonance phase contrast imaging (4D Flow MRI). Primary and secondary helical, as well as vortical flow patterns, were evaluated. Aortic arch anatomy as a flow influencing factor was determined.

Results: Compared with volunteers, both sinus prostheses and tube grafts developed more than 4 times as many secondary flow patterns in the ascending aorta (sinus prostheses n = 1.6 ± 0.8; tube grafts n = 1.3 ± 0.6; age-matched, healthy volunteers n = 0.3 ± 0.5; young, healthy volunteers n = 0; P ≤ .012) associated with a kinking of the prosthesis itself or at its distal anastomosis. As opposed to round aortic arches in volunteers (n = 16/18), cubic or gothic-shaped arches predominated in patients (n = 16/18, P < .001). In all but 3 volunteers, 2 counter-rotating helices were confirmed in the ascending aorta and were defined as a primary flow pattern. This primary flow pattern did not develop in patients who underwent valve-sparing aortic root replacement.

Conclusions: In patients after valve-sparing aortic root replacement, there was an increased number of secondary flow patterns in the ascending aorta. This seems to be related to surgically altered aortic geometry with kinking. Because flow alterations are known to affect wall shear stress, there seems to be an increased risk for vessel wall remodeling. Compared with previous 4D Flow MRI studies, primary flow patterns in the ascending aorta in healthy subjects were confirmed to be more complex. This underlines the importance of thorough examination of 4D Flow MRI data. (J Thorac Cardiovasc Surg 2020;159:798-810)

Central Message

4D Flow MRI reveals altered hemodynamics distal to prostheses in patients after VSARR, whereas in the ascending aorta of healthy volunteers, 2 counter-rotating helices typically developed.

Perspective

Altered flow in the ascending aorta after VSARR is believed to influence wall shear stress, potentially inducing vessel wall remodeling. With kinking being the dominant factor for flow pattern changes in this work, surgical approaches to reduce geometric deviations in VSARR surgery should be pursued. Long-term follow up is necessary to determine the clinical impact.

See Commentary on page 811.

Valve-sparing aortic root replacement (VSARR) is the standard surgical therapy of aortic root aneurysms in patients with a normal aortic valve. Previously, near physiologic
changes in the thoracic aorta distal to the aortic bulb in patients who underwent VSARR with an anatomically shaped SP or a TG with those of healthy, young, and age-matched volunteers.

### MATERIALS AND METHODS

#### Study Design

A total of 36 subjects were included in this Health Insurance Portability and Accountability Act–compliant study after approval of the local Institutional Review Board and written informed consent. Eighteen patients had undergone surgical treatment of an aortic root aneurysm with an SP or a conventional TG (n = 6). They were consecutively recruited through the Department for Cardiac Surgery outpatient service and underwent routine follow-up MRI including an additional 4D Flow MRI scan. In each patient group, tubular graft replacement of the ascending aorta (AAO) was performed in half of the patients. For comparison, 12 age-matched, healthy volunteers (VOL-A) and 6 young, healthy volunteers (VOL-Y) were enrolled. Demographic details are given in Table 1. Patients with TG were added to a previously presented study collective focused on sinus flow. Previous data were reevaluated for the purpose of the presented hypotheses.

#### Magnetic Resonance Imaging Scan and Processing of Magnetic Resonance Data

A 3-dimensional, 3-directionally motion-sensitive, time-resolved, phase-contrast sequence (4D Flow MRI) was performed as part of a clinical cardiovascular MRI protocol at 3.0 Tesla (Achieva, Philips, The Netherlands) using a 20-channel surface coil, respiratory gating, and retrospective electrocardiogram gating. Sequence and acquisition set-up has been described. Data were analyzed using GTFlow software (GyroTools LLC, Zurich, Switzerland). In 7 patients, data processing necessitated aliasing correction using PhaseUnwrappingTool (Fraunhofer MEVIS, Germany).

#### Anatomy

To test for the cofounding influence of aortic geometry, the thoracic aorta was classified as round, gothic, or cubic (Figure 1, A). Kinking was defined as an abrupt angular deviation from the anatomically given course of the aorta and recorded if present. The diameters of the AAO and descending aortas (DAO), the prosthesis at the distal anastomosis, and the aorta 1 cm distal to the anastomosis were registered.

#### Hemodynamics in the Thoracic Aorta

For evaluation of flow patterns, the thoracic aorta distal to the aortic bulb was divided into 3 segments: AAO, ARCH, and DAO. Flow patterns were analyzed in 2-dimensional (2D) view and with 4D approaches to achieve a comprehensive analysis (Figure 2).

Step 1: In-plane vectors based on 2D contours in the 3 predefined segments were used to evaluate subtle helical flow patterns graded according to their maximum velocity.

Step 2: Mesh plots based on 2D cut-planes depicting through-plane flow allowed for detecting retrograde flow during systole.

Step 3: Strictly antegrade, helical flow patterns were defined as helix in which the blood column moves spirally in the main flow direction. 2D flow patterns with antegrade and retrograde flow were characterized as vortex, which are defined as recirculating blood deviating from main flow direction.

Step 4: 4D backward and forward traced particle paths and instantaneous streamlines were emitted from the predefined contours to analyze the flow field in total and confirm 2D measurements.
TABLE 1. Demographics and clinical data

<table>
<thead>
<tr>
<th></th>
<th>SP</th>
<th>TG</th>
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<tbody>
<tr>
<td>Age, y</td>
<td>55 ± 15 (26-73)</td>
<td>58 ± 12 (41-72)</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>89 ± 9 (76-100)</td>
<td>86 ± 16 (56-104)</td>
</tr>
<tr>
<td>Gender ratio, male/female</td>
<td>11:1</td>
<td>4:2</td>
</tr>
<tr>
<td>Height, cm</td>
<td>183 ± 10 (160-200)</td>
<td>180 ± 5 (172-186)</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>27 ± 4 (21-32)</td>
<td>26 ± 4 (19-30)</td>
</tr>
<tr>
<td>Blood pressure, mm Hg</td>
<td>147 ± 21/81 ± 9 (115-180/60-95)</td>
<td>138 ± 13/87 ± 7 (120-150/80-100)</td>
</tr>
<tr>
<td>Aortic valve</td>
<td>9 tricuspid/3 bicuspid</td>
<td>6 tricuspid/0 bicuspid</td>
</tr>
<tr>
<td>Heart rate, beats/min</td>
<td>68 ± 11 (52-87)</td>
<td>62 ± 6 (56-72)</td>
</tr>
<tr>
<td>Ejection fraction, %</td>
<td>58 ± 7 (43-66)</td>
<td>53 ± 15 (26-70)</td>
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SP, Sinus prosthesis; TG, tube graft; VOL-A, age-matched, healthy volunteers; VOL-Y, young, healthy volunteers; BMI, body mass index. *Significant; values are given as mean ± standard deviation (range).

All visualization strategies were color-coded according to the acquired flow velocity. Further details on visualization approaches have been described. A primary, physiologic helix filling complete vessel volume was graded 1 = moderate (<180° rotation) and 2 = marked helical flow (>180° rotation), adapted from Burk and colleagues. Particles in a right-handed helix move clockwise in the main flow direction as opposed to a left-handed helix where particles move anti-clockwise. In contrast, a secondary helix does not fill the complete cross-section and was graded according to a vortex.

Every vortex that was depicted in 4D visualization was marked with an additional 2D contour at its maximum diameter. Vortex’s maximum size was graded as 1 = less than 33%, 2 = 33% to 66%, and 3 = more than 66% of the vessel diameter. Vortices and secondary helices were defined to be “secondary flow patterns” because they differ from main flow as opposed to “primary flow patterns,” such as primary helices, which do not deviate from main flow. The spatial relation between secondary flow patterns, the graft or its anastomoses, and the sites of kinking was registered.

Statistics
Results with continuous values are given as mean ± standard deviation (range). Results of vortex and helix grading are given as median (25%, 75%). Normality was tested using the Shapiro–Wilk test. For comparison between groups, a Mann–Whitney U test was performed. Because equality was to be proven and second order error was of greater concern than first order, error correction for multiple testing was not performed.

RESULTS
Anatomy
Volunteers typically presented with a round ARCH (n = 16/18). In contrast, cubic and gothic forms dominated in patients undergoing VSARR (n = 16/18, P < .001; Figure 1, A). Irrespective of the operation procedure, all patients undergoing VSARR developed at least 1 kinking in the region of the prosthesis (n = 18/18). In all patients with an additional ascending aortic tubular graft, there was a kinking between the 2 prosthesis parts (n = 9/9). The majority of patients undergoing VSARR (11/12 SP and 5/6 TG) had a kinking at the distal anastomosis.

In comparison with volunteers, patients undergoing VSARR had increased diameters of the native AAO (if not replaced) and DAO (AAO: SP = 4.0 ± 0.3 cm; TG = 3.9 ± 0.3 cm vs VOL-A = 3.0 ± 0.4 cm; P = .002 and P = .030, respectively; DAO: SP = 2.9 ± 0.7 cm; TG = 2.5 ± 0.4 vs VOL-A = 2.4 ± 0.2 cm; P = .005 and P = .397, respectively). There was a relative dilatation of 0.7 ± 0.3 cm distal to all prostheses independent of prosthesis type (Figure 1, B).

Hemodynamics in the Thoracic Aorta
Quantitative hemodynamic parameters. SVs were comparable between groups (bulb: SP = 103 ± 23 mL, TG = 95 ± 20 mL, VOL = 97 ± 20 mL; all P > .05, except for arch (SP, VOL) P = .014; Figure E1, A). Peak velocities were higher in patients after VSARR in the entire aorta compared with volunteers with significant differences in SP’s AAO and ARCH (Figure E1, B). Differences in quantitative hemodynamic parameters between prosthesis types were not statistically significant.

Hemodynamics in the Thoracic Aorta
Ascending aorta. Step 1. In the time-resolved 2D in-plane vector graph analysis, there were 2 counter-rotating helices in the AAO of all study participants with the exception of 2 SP, 1 TG, and 1 VOL-A, in which only 1 helix was detected, respectively. One patient with SP presented with 2 concordant helices. In counter-rotating helices, blood in the vessel center moved to the outer curvature and along the vessel periphery back to the inner curvature (Figure 3). There were differences in helix strength and distribution of these helices in the entire aorta: predomination of the right posterior left-handed helix (n = 23 in 108 planes) or the left anterior right-handed helix (n = 49/108); in some, both helices were of equivalent size (n = 7/108) or there was no helical flow at all (n = 29/108) (Figure 4, A). The helices were significantly stronger in patients after VSARR than in volunteers (SP vs VOL-A P = .016; TG vs VOL-A P = .013; Figure 4, B).
counter-rotating, moderate 3D helices in the AAO of 6 of 6 VOL-Y and 9 of 12 VOL-A during systole. In diastole, the helices immersed into diastolic backward flow at the inner curvature (Figure 5). This flow pattern was defined to relate to primary helices. Two other VOL-A developed strong and long-lasting counter-rotating 2D helical flow graded as secondary helices. One VOL-A had a large helix in 2D planes caused by a 3D vortex with retrograde flow in peak systole.

In contrast, 12 of 18 patients did not develop primary helices (Figure 4, C and D). Only 1 SP and TG developed 2 counter-rotating helices comparable to those seen in healthy volunteers in 3D visualization (Figure 5). However, these 2 counter-rotating helices differed from those of healthy volunteers because there was profound reflux at the inner curvature already in early systole. Thus, all 2D helical flow patterns (n = 6) in patients were caused by secondary helices or vortices with pronounced retrograde flow already at peak systole. In every patient, at least 1 secondary flow pattern developed in direct spatial relation to a kinking of the prosthesis itself or at the distal anastomosis. In patients after VSARR, secondary flow patterns occupied more space of the vessel cross-section than in VOL-A. They were consequently scored with grade 3 more often (SP: n = 2.4 ± 0.8 per person; TG: n = 2.7 ± 0.8 per person vs VOL-A: n = 1.4 ± 0.8 per person; P = .008, P = .012, respectively) (Figure 6 and Videos 1-4). In contrast, none of the young volunteers developed any secondary flow pattern. There was no significant difference in the number of secondary flow patterns developing in the ARCH or DAO between groups. In contrast, there was a significant increase of secondary flow patterns in the AAO in patients after VSARR compared with VOL-A (SP P < .001, TG P = .012). In the AAO, patients with SP (TG) developed more than 5 (4) times as many secondary flow patterns as VOL-A.

Medium-sized flow patterns were found most often in all groups (Figure 6). Patients after VSARR developed more vortices than volunteers (SP: n = 2.2 ± 0.7; TG: n = 2.0 ± 0.7; VOL-A: n = 0.7 ± 0.7; P < .05). There was no significant difference in the number of secondary helices (SP: n = 0.8 ± 0.8; TG: n = 0.7 ± 1.0; VOL-A: n = 0.8 ± 0.6).

DISCUSSION
Secondary Flow Patterns
This study reveals a significant increase of secondary flow patterns distal to both an anatomically shaped SP and a TG in patients who underwent VSARR in comparison with volunteers concordant with previous studies with smaller patient collectives.26-29 In light of expected changes of the wall shear stress after increased secondary flow patterns, this might induce vessel wall remodeling and aneurysm growth.

### TABLE 1. Continued

<table>
<thead>
<tr>
<th>VOL-A</th>
<th>VOL-Y</th>
<th>SP vs VOL-A</th>
<th>TG vs VOL-A</th>
<th>SP vs TG</th>
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<tbody>
<tr>
<td>55 ± 6</td>
<td>25 ± 3</td>
<td>(47-69)</td>
<td>(23-30)</td>
<td>.416</td>
</tr>
<tr>
<td>69 ± 13</td>
<td>69 ± 10</td>
<td>(53-92)</td>
<td>(61-85)</td>
<td>.011*</td>
</tr>
<tr>
<td>2:10</td>
<td>1:5</td>
<td></td>
<td>.001*</td>
<td>.009*</td>
</tr>
<tr>
<td>171 ± 7</td>
<td>173 ± 9</td>
<td>(161-183)</td>
<td>(163-190)</td>
<td>.005*</td>
</tr>
<tr>
<td>24 ± 3</td>
<td>23 ± 2</td>
<td>(20-30)</td>
<td>(21-26)</td>
<td>.030*</td>
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<tr>
<td>12 tricuspid/0 bicuspid</td>
<td>12 tricuspid/0 bicuspid</td>
<td></td>
<td>.078</td>
<td>1.000</td>
</tr>
<tr>
<td>63 ± 9</td>
<td>66 ± 6</td>
<td>(49-76)</td>
<td>(60-72)</td>
<td>.884</td>
</tr>
<tr>
<td>65 ± 3</td>
<td>–</td>
<td>(61-69)</td>
<td>–</td>
<td>.022*</td>
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Although there were no significant differences in the ARCH and DAO between VSARR patients and volunteers, the number of secondary flow patterns in the AAO was more than 4 times higher in patients compared with age-matched volunteers. The development of secondary flow patterns seems to correlate not only with AAO diameter and age but also with aortic geometry and kinking. Concordant to the results of the study by Frydrychowicz and colleagues,16 round aortic forms were frequent in healthy volunteers developing only few secondary flow patterns. In all VSARR patients, a kinking was detected in the area of the prosthesis, which led to a frequent classification of cubic and gothic forms. A kinking of straight prostheses that are implanted into the curved aorta is frequent because prostheses are not dimensionally stable in physiologic pressure conditions.30 The kinking was regularly observed at the anastomosis between the 2 prosthesis parts of aortic bulb and AAO, as well as between the distal prosthesis and the native aorta. Apparently, anastomoses and differences in compliance between the synthetic prosthesis and native tissue are predilection sites for kinking. A kinking of the aorta seems to promote secondary flow patterns because at least 1 secondary flow pattern developed in direct spatial relation to each kinking. Moreover, the postprosthetic dilatation facilitates the development of secondary flow patterns. It can be assumed that there was a mismatch between the diameters of prosthesis and aorta at implantation, but it remains unclear whether the dilatation increases postoperatively. Long-term follow up studies are warranted to determine the risk of local dilatation.

Patients with SP revealed higher peak velocities in the AAO and the ARCH than age-matched volunteers. This correlates well with results from Gaudino and colleagues31 and Semaan and colleagues,4 who attributed higher flow velocities to a reduced compliance and Windkessel effect. Although peak velocities were constant throughout the thoracic aorta in VOL-A, and even increased in VOL-Y, there was a decrease of velocity in patients throughout the thoracic aorta. This indicates a nonphysiologic loss of kinetic energy in the course of the aorta in patients after VSARR. Probable reasons are the increased number and strength of secondary flow patterns and the sudden change of diameter distal to the prosthesis. Energy dissipation leads to a compensatory increase of work and strain of the left ventricle.27 Moreover, a reduced compliance of the prosthesis leads to increased systolic and pulsatile pressure that induced left ventricular hypertrophy in animal experiments.32,33

Primary Helical Flow Patterns
To analyze differences in primary flow patterns between VSARR cases and volunteers, physiologic primary flow patterns needed to be defined. In contrast to other

**FIGURE 1.** Geometric characteristics of the thoracic aorta. A, In VOL-A and VOL-Y, round aortic forms predominated. In contrast, patients receiving VSARR (SP, TG) presented with gothic and cubic forms. B, Significant diameter increase 1 cm distal to VSARR graft. Location of measurements at distal prosthesis and aorta 1 cm distal to the prosthesis are indicated as dotted lines. Typical sites of kinking between VSARR graft and replacement of the AAO (*) and distal to the ascending aortic graft (**). SP, Sinus prosthesis; TG, tube graft; VOL-A, age-matched, healthy volunteers; VOL-Y, young, healthy volunteers.
studies there was no single, most often right-handed helix detected in the AAO, but 2 counter-rotating helices were detected in 15 of 18 healthy volunteers. This phenomenon, well known to rheology as Dean vortices, was described by Hope and colleagues in 8 of 19 healthy volunteers and by Bogren and colleagues in 14 of 14 healthy volunteers. Concordant with our results, they found a right-handed helix at the left aortic wall and a left-handed helix at the right aortic wall. If one assesses helicity in the AAO only from the left ventral view, the right-handed helix is the only helix to see because it is situated left ventrally in the vessel. To evaluate helicity in the aorta comprehensively, streamline analysis has to be performed from all view angles. Of help is the in-plane vector analysis that easily reveals 2 counter-rotating helices at first sight. However, time-resolved 2D analysis alone is not sufficient.

because secondary vortices may contain helical flow but can be better identified in time-resolved 3D streamline analysis. The combination of time-resolved 3D streamline and particle path analysis, as well as 2D in-plane vector analysis, is essential for adequate assessment of helical flow patterns.

In fluid dynamics, the development of 2 counter-rotating helices in curved pipes is known as the “Dean vortex.”\textsuperscript{38,39} Apart from 4D Flow MRI studies\textsuperscript{17,36} Dean vortices in the AAO were also described in computational fluid design simulations.\textsuperscript{40} Because 2 counter-rotating helices were found regularly in the AAO of healthy subjects and they only passed into physiologic reflux at late systole or early diastole, we propose to define this flow pattern as “primary” flow pattern. Helical flow seems to stabilize the

FIGURE 3. 2D analysis of counter-rotating helices in the AAO. First line: anatomic orientation of planes. A, Schematic depiction of extent and variations of counter-rotating (so-called “Dean”) helices based on (B) in plane vector graphs and (C) through plane flow velocity as seen (A-C) from below and (D) in lateral view. L, Left-handed helical flow; R, right-handed helical flow. Capital letters indicate predominant flow direction.
FIGURE 4. 2D and 4D analysis of helical flow and primary flow patterns. Grading and directionality distribution of helical flow patterns in 3 aortic regions according to the graduation scheme proposed in Figure 2. A, Counter-rotating helices predominated in the AAO, and right-handed helical flow was frequently seen in the aortic arch. No helix or left-handed helical flow was typical for the descending aorta. Patients after VSARR (SP, TG) developed (B) stronger in-plane helical flow but (C, D) less primary flow patterns compared with VOL-A and VOL-Y. SP, Sinus prosthesis; TG, tube graft; VOL-A, age-matched, healthy volunteers; VOL-Y, young, healthy volunteers; AAO, ascending aorta; ARCH, aortic arch; DAO, descending aorta.
blood column: Flow separation and thus secondary flow patterns, especially vortices, develop more rarely in the AAO of healthy volunteers in whom primary helical flow patterns dominate. Helical flow seems to be an explanation for the low atherosclerotic burden in this area. In contrast, primary helical flow patterns are rarely found

**FIGURE 5.** Counter-rotating helices in the AAO of healthy volunteers and VSARR patients. Counter-rotating helices in (A) in-plane vector visualization, (B) through-plane mesh plot analysis, and (C) 3D particle paths of volunteers. At the inner curvature, both helices confluence to pass into early diastolic reflux. One patient with SP shows comparable, counter-rotating helices but with an early systolic reflux at the inner curvature. SP, Sinus prosthesis; o/i, outer/inner curvature. *Retrograde flow.

**FIGURE 6.** Grading and frequency distribution of secondary flow patterns. Secondary flow patterns were significantly increased in VSARR patients with focus on the site of prosthesis implantation, the AAO. AAO, Ascending aorta; ARCH, aortic arch; DAO, descending aorta; SP, sinus prosthesis; TG, tube graft; VOL-A, age-matched volunteers.
in the DAO of healthy volunteers, presumably explaining the higher incidence of atherosclerotic plaque. Primary flow patterns were found significantly less often in VSARR cases, concordant with the results of Semaan and colleagues. Differences between VSARR cases and volunteers were less pronounced in parts of the aorta where no prosthesis was implanted (ie, ARCH and DAO). A right-handed, primary helix predominated in the ARCH, whereas there was no or a left-handed helix in the DAO, consistent with Bogren and Buonocore.

Clinical Relevance

Postoperatively altered aortic geometry is correlated with increased secondary flow patterns that are closely linked to wall shear stress changes resulting in a potentially increased risk for developing atherosclerotic plaques and aneurysms. Guzzardi and colleagues showed the correlation between increased wall shear stress measured with 4D Flow MRI and the loss of elastin fibers in the affected areas of the vessel wall in patients with bicuspid aortic valves with aneurysm of the AAO. Moreover, there should be an increased load for the left ventricle due to the loss of kinetic energy through secondary flow patterns and loss of velocity during the course of the thoracic aorta. Whether the increased strain on the left ventricle is clinically important needs to be evaluated.

Physiologically curved prostheses might reduce kinking and thus reduce secondary flow patterns and related complications. The first results are promising. More research regarding prosthesis material with physiologic biomechanical properties, particularly compliance, is warranted.
Study Limitations

A potential drawback of this study is the relatively small patient cohorts through a limited number of patients receiving VSARR with SP from which to recruit. Consequently, the presented results should be considered as pilot data. Patients who underwent VSARR with other prosthesis types also should be included because the increased number of secondary flow patterns seems to be typical not only for the SP but also for the readily available TG.

Moreover, differences between patients with bicuspid and tricuspid aortic valves need to be considered in larger-scale studies. The a priori altered flow pattern in patients with bicuspid valves is likely to influence the development of secondary flow patterns in VSARR. In this study with only 3 patients with bicuspid valves who had undergone valve reconstruction, there were no significant differences compared with patients with tricuspid valves. The development of secondary flow patterns also may depend on the differing ejection fraction between cohorts. Patients revealed a lower left ventricular ejection fraction in comparison with age-matched volunteers. However, comparable SVs should have limited the influence of the cardiac function on flow patterns. Because of the pilot character of this study and the initial, small patient collective, it was not possible to adjust for different baseline characteristics. Moreover, there is limited knowledge of which factors are influencing the hemodynamics measured by 4D Flow MRI. Large studies need to identify relevant characteristics that need to be adapted for.

Long acquisition and postprocessing times still limit the application of 4D Flow MRI in large clinical studies. Faster acquisition techniques and automated software solutions that quantitatively assess vortex strength will be introduced to clinical routine. However, they were not accessible at the time of this study. Thus, only a semiquantitative analysis of flow patterns was possible.

CONCLUSIONS

Although near-physiologic sinus flow patterns were previously confirmed inside the SP, the current 4D Flow MRI examination revealed disturbed flow patterns distal to aortic root prostheses in general. Secondary flow patterns developed at sites of kinking of the prosthesis itself or at anastomoses. In contrast to occasional secondary flow patterns in older volunteers, young subjects did not develop any secondary flow patterns. Consequently, a small number of secondary flow patterns should be targeted because they seem to be associated with degeneration of the vessel wall.

Altered hemodynamics in patients after VSARR may have several disadvantages. First, they may accelerate vessel wall remodeling and induce aneurysm growth because they are known to affect wall shear stress. Second, inefficient blood transport is known to increase kinetic energy dissipation, which is reported to increase the strain for the left ventricle. The clinical relevance of the described secondary flow patterns needs to be determined in long-term follow-up and multicenter studies. Along with the development of more compliant prosthesis material with adequate durability, the adaption of the form of the prostheses to the geometric features of the ARCH seems to be essential. A first case study of an anatomically curved graft adapted to the curvature angle of AAO and arch was promising.

Conflict of Interest Statement

Dr Sievers receives royalties from B. Braun Melsungen AG. Dr Frydrychowicz receives nonfinancial support from Philips Healthcare, Research Agreement, and Personal Fees from Philips Healthcare, Speaker’s Bureau; Bayer Healthcare—Speaker’s Bureau. All other authors have nothing to disclose with regard to commercial support.

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References


Key Words: altered hemodynamics, 4D flow cardiovascular magnetic resonance, 4D Flow MRI, secondary flow patterns, sinus prosthesis, valve-sparing aortic root replacement, VSARR
FIGURE E1. Hemodynamic parameters. A, Except for the SV in the aortic arch, there were no significant differences between patients after VSARR (SP, TG) and VOL-A and VOL-Y. B, Peak velocities were increased in VSARR patients at the level of the aortic bulb and the AAO compared with volunteers. **BULB**, Aortic bulb; **AAO**, ascending aorta; **ARCH**, aortic arch; **DD**, ductus diverticulum; **DAO**, descending aorta; **SP**, sinus prosthesis; **TG**, tube graft; **VOL**, healthy volunteers.