Time-resolved 3-dimensional magnetic resonance phase contrast imaging (4D Flow MRI) analysis of hemodynamics in valve-sparing aortic root repair with an anatomically shaped sinus prosthesis

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ABSTRACT

Objective: The anatomically shaped sinus prosthesis (Uni-Graft W SINUS; Braun, Melsungen, Germany) used in valve-sparing aortic root replacement promises physiological hemodynamics believed to grant physiologic valve function. Using time-resolved 3-dimensional magnetic resonance phase contrast imaging (4D Flow MRI), we analyzed sinus vortex formation and transvalvular pressure gradients in patients with sinus prosthesis compared with age-matched and young healthy volunteers.

Methods: Twelve patients with sinus prosthesis (55 ± 15 years), 12 age-matched and 6 young healthy volunteers (55 ± 6 years, 25 ± 3 years, respectively) were examined at 3T with a 4D flow magnetic resonance imaging sequence. Sinus vortices visualized by streamlines and time-resolved particle paths were graded on a 4-point Likert scale. Time resolved pressure differences of the left ventricular outflow tract and the ascending aorta to a reference point in the aortic bulb as well as the transvalvular pressure gradient were evaluated.

Results: 4D flow visualizations revealed a propensity of the sinus prosthesis toward intermediate (50%) and large (28%) vortices compared with age-matched volunteers with small (61%) and intermediate (36%) vortices. Vortices in sinus prostheses had a similar configuration compared with those in volunteers. The peak transvalvular pressure gradient did not vary significantly between patients and age-matched volunteers (4.0 ± 0.9 mm Hg, 3.8 ± 0.7 mm Hg, $P = .373$), its temporal evolution resembled that of volunteers with a prolonged positive phase in patients.

Conclusions: Hemodynamics closely relating to those of volunteers were confirmed in sinus prostheses, believed to grant physiological valve function. Minor differences are presumably attributed to graft compliance and temporal resolution of the acquisition. Nevertheless, long-term deterioration of valve function as it was described for straight grafts could potentially be decelerated using sinus prostheses. (J Thorac Cardiovasc Surg 2016;152:418-27)

Sinus vortices in a patient with valve-sparing aortic root replacement with sinus prosthesis (male, 60 years).

Central Message

Time-resolved 3-dimensional magnetic resonance phase contrast imaging (4D Flow MRI) confirmed sinus vortex formation and transvalvular pressure gradients in patients with valve-sparing aortic root replacement with an anatomically shaped sinus prosthesis closely relating to those of age-matched volunteers.

Perspective

Hemodynamics in patients with valve-sparing aortic root replacement with a sinus prosthesis closely relate to those of age-matched volunteers. This is believed to preserve native aortic valve function. Long-term deterioration of valve function as it was described for straight grafts could potentially be decelerated. Future studies are warranted to substantiate the link between postoperative hemodynamics and long-term outcome.

See Editorial Commentary page 428.

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Abbreviations and Acronyms

AAO	= ascending aorta
BULB	= aortic bulb
ΔP	= pressure difference
4D Flow MRI	= time-resolved 3-dimensional magnetic resonance phase contrast imaging
LVOT	= left ventricular outflow tract
MRI	= magnetic resonance imaging
SP	= sinus prosthesis
SV	= stroke volume
$t_{\max+/-n}$	= time point of peak systole plus/minus n heart phases
VOL-A	= age-matched volunteers
VOL-Y	= young volunteers
VSARR	= valve-sparing aortic root replacement

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During the past 2 decades, valve-sparing aortic root replacement (VSARR)^{1,2} has predominated alternative procedures in aortic root aneurysm repair in patients with intact aortic valve cusps. By preserving the native aortic valve, shortcomings of valve replacement such as the need for anticoagulation in mechanical valves or early degeneration of biological valves are avoided. More than the avoidance of shortcomings, however, native valve function in patients with aortic root replacement seems to be crucial.

The aortic valve forms the center of an intricate system consisting of the 3 cusps with the corresponding sinuses of Valsalva and the sinotubular junction.³ Leaflet movement is dependent strongly on the 3 sinuses. In the 16th century, Leonardo da Vinci stated that vortices in the aortic sinuses facilitate valve closure.^{4,5} Recent studies confirmed the importance of aortic sinuses and the vortex formation within them. They were found to contribute to proper valve opening and closure^{3,6} and to minimize leaflet stress⁷ and transvalvular pressure gradients.⁸ The recirculating blood is further suspected to facilitate smooth closure of the valve,⁹ to promote coronary flow, and to stabilize the leaflets in open position during systole,¹⁰ thereby protecting the aortic valve and potentially enhancing its longevity.

The implantation of a straight cylindrical graft as described by David and Feindel² deprives the patient of the aortic sinuses. Frequent contact of the valve leaflets

with the prosthesis wall and large bending deformation of the leaflets were observed on echocardiography and cinematography.^{11,12} Transvalvular pressure gradients were elevated,¹¹ and finite element studies revealed an increased mechanical stress for the leaflets.⁷ Although these findings seem to have no clinical significance in the mid-term follow-up,¹³ they might possibly lead to preterm degenerative changes of the valve in the long term.³ Initial long-term follow-up studies suggest a slow but progressive deterioration of valve function.¹⁴

In light of these physiological blood flow properties, the introduction of the sinus prosthesis (Uni-Graft W SINUS; Braun, Melsungen, Germany) in aortic root aneurysm repair is of special interest. Its 3 separate, physiologically teardrop-formed sinuses hold the promise of preserved hemodynamic properties (Figure E1). Details on the prosthesis and the operative procedure can be found elsewhere.^{15,16}

Time-resolved 3-dimensional magnetic resonance phase contrast imaging (4D Flow MRI) has emerged as a diagnostic technique that allows for noninvasive in vivo measurement and visualization of blood flow. Vector visualization of sinus vortices in vivo was first achieved by Kilner et al¹⁷ using 4D Flow MRI. Since then, applications have expanded from blood flow quantification, visualization, and its parametric characterization to derivation of hemodynamic and rheological properties, including the calculation of pressure differences.¹⁸

Therefore, it was the aim of this study to characterize aortic bulb hemodynamics in patients after VSARR with a sinus prosthesis (SP) by means of 4D Flow MRI. The aim of this work was 2-fold: (1) to compare the presence and extent of sinus vortices in patients with age-matched and young healthy individuals, and (2) to compare transvalvular pressure gradients between groups. In light of the physiologically shaped SP, we hypothesized that there were no differences for both vortex formation and pressure gradients.

METHODS**Study Design**

Thirty-two subjects were included in this HIPAA (ie, Health Insurance Portability and Accountability Act)-compliant study after approval of the local ethics committee and written informed consent. Table 1 provides a full demographic description. Fourteen patients had undergone surgical treatment of an aortic root aneurysm with SP as described previously¹⁵ and participated in the context of routine follow-up examinations (solely root replacement, n = 7, replacement of root and ascending aorta, n = 7). Twelve healthy age-matched volunteers (VOL-A) and 6 young volunteers (VOL-Y) were enrolled for reference. Exclusion criteria generally were accepted contraindications against magnetic resonance imaging (MRI), failure to provide consent for the study, and arrhythmia precluding completion of 4D Flow-MR examination. Hence, 2 patients dropped out because of intermittent arrhythmia during the MRI scan preventing proper cardiac gating.

MRI Scan

A 3-dimensional, 3-directionally velocity sensitive, time-resolved phase contrast sequence was performed as part of a clinical cardiovascular

TABLE 1. Demographics and clinical data

	SP		VOL-A		VOL-Y		P value		
							SP vs VOL-A	SP vs VOL-Y	VOL-A vs VOL-Y
Age, y	55 ± 15	(26-73)	55 ± 6	(47-69)	25 ± 3	(23-30)	.416	.002*	<.001*
Weight, kg	89 ± 9	(76-100)	69 ± 13	(53-92)	69 ± 10	(61-85)	.001*	.005*	1.000
Sex ratio, M:F	11:1		2:10		1:5		<.001*	.002*	1.000
Height, cm	183 ± 10	(160-200)	171 ± 7	(161-183)	173 ± 9	(163-190)	.005*	.049*	.572
BMI, kg/m ²	27 ± 4	(21-32)	24 ± 3	(20-30)	23 ± 2	(21-26)	.030*	.031*	.888
Months since surgery	19 ± 11	(6-39)	—	—	—	—	—	—	—
Bicuspid valve, n	3		0		0		.078	.218	1.000
Marfan syndrome, n	1		0		0		.359	.556	1.000
Antihypertensive medication, n	11		5		0		.012*	<.001*	.080
Blood pressure, mm Hg	147 ± 21/ 81 ± 9	(115-180/ 60-95)	127 ± 19/ 80 ± 10	(110-160/ 70-100)	121 ± 10/ 79 ± 7	(110-135/ 70-90)	.024*/.501	.015*/.567	.887/.887
Heart frequency, bpm	68 ± 11	(52-87)	63 ± 9	(49-76)	66 ± 6	(60-72)	.884	.962	.925

SP, Sinus prosthesis; VOL-A, age-matched volunteers; VOL-Y, young volunteers. M, male; F, female; BMI, body mass index. *Significant; values are given as mean ± standard deviation (range).

MRI protocol at 3.0 Tesla (Achieva; Philips, Amsterdam, The Netherlands) with a 20-channel surface coil. The sequence was retrospectively electrocardiogram-gated. To compensate for breathing motion, respiratory gating with a 7- to 12-mm acceptance window placed on the liver-lung interface was applied to achieve a gating efficacy of approximately 65%. The velocity encoding sensitivity was adapted to the expected maximal velocities and set to 180 cm/s in all 3 spatial directions. Typical imaging parameters included isotropic voxels ($2.6 \times 2.6 \times 2.6$ mm³, interpolated to

$2.0 \times 2.0 \times 2.6$ mm³) and a field-of-view of 380-400 mm × 277-400 mm × 67-94 mm (feet/head × anterior/posterior × right/left) with 25-36 slices in oblique sagittal orientation, carefully adapted to each individual's anatomy to depict the aortic arch including the aortic root. Further scan parameters were repetition time 3.6 ms, echo time 2.3 ms, Cartesian k-space sampling, flip angle 6° in studies without contrast agent, and 12° in studies with contrast agent. Contrast agent (0.1 mL/kg body weight, Gadobutrol, Gadovist [Bayer Vital, Leverkusen, Germany]) was administered in

FIGURE 1. Grading of sinus vortices. A, Sinus vortices displayed as streamlines color-coded with respect to the acquired flow velocities. Vortices were graded according to their size and maximal retrograde velocity at the time point of their maximum intensity. B, The majority of sinus vortices in patients was graded medium or large whereas volunteers mostly developed small- and medium-sized vortices. SP, Sinus prosthesis; VOL-A, age-matched volunteers; VOL-Y, young volunteers; V_{max} , peak velocity.

12 of 12 SP and 2 of 12 VOL-A as part of a clinical protocol containing contrast-enhanced magnetic resonance angiography that was not part of this study. Image acquisition acceleration was achieved with SENSE (effective reduction factor = 2.1). Data were reconstructed to 20 heart phases resulting in an effective temporal resolution of 35–62 ms, depending on heart rate. Typical scan time was 12 ± 3 minutes (range, 7–21 minutes), depending on respiratory and heart rate as well as navigator efficacy. As part of the clinical cardiac imaging protocol, cine short-axis balanced steady-state free precession sequences were acquired in patients and VOL-A.

Processing of MRI Data

Offline reconstruction of raw data included automated correction of eddy currents and Maxwell terms. Data were transferred to an onsite computer equipped with a commercially available software GTFlow (v2.1.4; GyroTools LLC, Zurich, Switzerland) used for visualization and the scientific software MEVISFlow (v9.1b; Fraunhofer MEVIS, Bremen, Germany) used for semiautomated pressure difference estimation.¹⁹ In 5 patients, data processing included aliasing correction with PhaseUnwrappingTool (v1; Fraunhofer MEVIS).

For blood flow visualization, a 2-dimensional contour transecting the aortic bulb in a fashion that all sinuses could be differentiated was carefully placed in GTFlow. From this contour, hemodynamic parameters such as stroke volume (SV), peak velocity, and flow volumes were derived. To visualize hemodynamics, particle paths and instantaneous streamlines, color-coded to the acquired flow velocity, were emitted in 3-dimensional mode from the predefined contour. Streamlines and time-resolved particle paths passing the contour during the heart cycle were visualized downstream to the contour as well, so-called forward and backward tracing, so that small flow patterns that developed directly distal or at the same level as the contour were visualized. Further details on visualization approaches can be found elsewhere.^{20–22}

For sinus vortex analysis, streamlines and time-resolved particle paths were used. Sinus vortices form in the aortic sinuses behind the opened valve cusps and are defined as recirculating blood deviating from main flow direction.²³ Each vortex in the left, right, and noncoronary sinus was graded visually according to its size and maximal retrograde velocity at the time point of its maximal intensity on a 0–3 scale, with “0” indicating no vortex was detected. A maximal retrograde velocity of 30 cm/s or 60 cm/s was considered a small or intermediate vortex, and greater retrograde velocities than 60 cm/s indicated a large vortex (Figure 1, A). To describe the temporal evolution of sinus vortex formation, the number of heart phases between peak systole and maximal vortex intensity was noted as well as a persistence into diastole.

Pressure difference (ΔP) calculation was achieved with MEVISFlow after semiautomatically segmenting aorta and left ventricular outflow tract (LVOT; Figure 2, A). First, a relative pressure map was calculated solving the Navier-Stokes equation based on the acquired time-resolved velocity fields assuming blood as a viscous, incompressible fluid. Viscosity was set at 0.0045 Pa·s and density at 1055 kg/m³. A reference point (aortic bulb [BULB]) was positioned at the level of the vena contracta, the location of the narrowest flow jet downstream of the aortic annulus, where pressure at peak systole (t_{max} , defined as the time point of peak velocity in the aortic bulb) dropped to a minimum. The reference value in the aortic bulb was set to 0 mm Hg. To calculate ΔP , 2 contours were positioned 3 cm upstream in the LVOT and 4 cm downstream the aortic valve in the ascending aorta (AAO). ΔP of the contours relative to the reference point was measured in every phase of the cardiac cycle. The transvalvular pressure gradient $\Delta P(LVOT, AAO)$ was calculated by subtracting $\Delta P(AAO)$ from $\Delta P(LVOT)$. Its maximum value, the peak transvalvular pressure gradient, was noted in every subject.

Ejection fraction and SV were determined from short-axis SSFP cine sequences following clinical standard by use of the Extended MR Workspace

(v2.6.3.5; Philips). Healthy young volunteers without a history of cardiovascular disease were defined to have a normal ejection fraction.

Statistics

Results with continuous values are given as mean $\pm$ standard deviation (range). Results of sinus vortex grading and time of maximal vortex intensity are given as median [25%, 75% percentile]. For comparison between groups, a Mann-Whitney *U* test was performed. A value of $P < .05$ was considered statistically significant. Correction for multiple testing was not performed because equality was to be proven; hence, second-order error was of greater concern than first order error.

RESULTS

Quantification and Visualization of Hemodynamics

Patients with SP and VOL-A had a normal ejection fraction, although patients with SP had a lower ejection fraction than VOL-A ($P = .022$). SV, heart rate, and cardiac index did not differ significantly between SP and VOL-A (Table 2).

Sinus vortices were confirmed in the sinuses of Valsalva of all subjects (Figure 3, Video 1, A–C) except for a non-coronary sinus of 1 VOL-A. In patients, sinus vortices were predominantly intermediate or large (median grading: 2, [2, 3]) compared with small- and intermediate-sized vortices in VOL-Y and VOL-A (median grading: 1 [1, 2] for both groups; for all, $P < .05$; Figure 1, B). There was no significant difference between VOL-Y and VOL-A ($P = .56$). Vortex intensity in the left, right, and noncoronary sinus did not differ significantly (for all, $P > .05$). Time of maximal sinus vortex intensity was 0 [0, 1] heart phases after peak systole in SP compared with 1 [0, 1] and 1 [0.75, 1.25] in VOL-A and VOL-Y, respectively, and did not differ significantly between SP and VOL-A ($P = .3$). All sinus vortices persisted into early diastole.

Pressure Differences

With 4D Flow MRI, the temporal evolution of pressure gradients across the aortic valve was analyzed successfully in all subjects. In 2 patients, the pressure minimum at peak systole was not detected in the aortic bulb but in the ascending aorta, where flow velocities were greater than in the vena contracta (Figure 4). These 2 patients were excluded from statistical analysis. Overall, physiological changes could be confirmed in all groups as described for each location in the following paragraphs.

Peak pressure gradients across the aortic valve $\Delta P(LVOT, AAO)$ in early systole were 4.0 ± 0.9 mm Hg in patients compared with 3.8 ± 0.7 mm Hg in volunteers (VOL-A, 3.5 ± 0.6 mm Hg; VOL-Y, 4.3 ± 0.6 mm Hg). The difference between patients and volunteers did not prove significant. Differences between VOL-Y and VOL-A revealed statistical significance ($P = .028$; Figure 5).

FIGURE 2. Relative pressure differences. A, A reference point (blue circle) for ΔP calculation was positioned at the level of maximum systolic flow velocity, where the diameter of the flow jet reaches its minimum in the aortic bulb (BULB). Two contours were positioned in the left ventricular outflow tract (LVOT, green) and the ascending aorta (AAO, red). Three pressure gradients were derived: $\Delta P(\text{LVOT, BULB})$, $\Delta P(\text{BULB, AAO})$, and the transvalvular

The transvalvular pressure gradient was positive while flow velocity increased in early systole. It decreased rapidly until it became negative just after peak systole, when velocity started to decrease as well. Fundamentally, aortic pressure exceeded ventricular pressure in late systole while blood was still being ejected from the ventricle. With 4D Flow MRI, the evolution of transvalvular ΔP [$\Delta P(\text{LVOT}, \text{AAO})$] was ascertained in all volunteers. Pressure gradient development in patients resembled that of volunteers except for a deceleration of the decrease of transvalvular ΔP in patients (Figure 2, E). This results in a longer phase of positive relative pressure in the LVOT and a shorter phase of positive relative pressure in the AAO. Considering a delay of 1 heart phase in patients for the first part of systole, there was no significant difference between patients and volunteers except for a greater ΔP at the time frame after peak systole in patients (Figure 2, E).

Relative pressure in the LVOT was increased relative to the bulb in early systole, promoting blood ejection into the aorta. $\Delta P(\text{LVOT}, \text{BULB})$ peaked at maximum blood flow velocity (Figure 2, C). Subsequently $\Delta P(\text{LVOT}, \text{BULB})$ decreased rapidly until leveling out with relative bulb pressure in diastole. Patients revealed an increased $\Delta P(\text{LVOT}, \text{BULB})$ (SP vs VOL-A, $P < .05$ from $t_{\max-1}$ to $t_{\max+2}$, as seen in Figure 2, C).

$\Delta P(\text{BULB}, \text{AAO})$ initially was negative but rapidly exceeded the pressure of the bulb between $t_{\max-1}$ and $t_{\max}$, reaching its maximum after peak systole, then plateauing until slowly decreasing until the end of systole (Figure 2, D). After peak systole, patients had a less-pronounced pressure increase than volunteers with a significant difference at $t_{\max+1}$ and $t_{\max+2}$ between SP and VOL-A ($P = .007$ and $.010$, respectively).

DISCUSSION

This study carries 2 messages we believe to be important. First, anatomically shaped aortic root prostheses exhibited hemodynamics that closely relate to those of age-matched volunteers with a tendency towards more pronounced sinus vortex formation. Second, transvalvular pressure gradients were of comparable amplitude but revealed a slight temporal delay. The results substantiate the high potential of 4D Flow MRI to evaluate postoperative hemodynamics in the aorta simultaneously with confirming the hypothesized physiological hemodynamics of an anatomically shaped aortic root prosthesis.

Sinus vortices persisted into early diastole, consistent with previous works.^{5,24} Sinus vortex formation is congruent with previous ultrasound studies confirming that valve leaflets do not collide with the wall of the SP during systole.^{15,16} In detail, vortices developed in early systole with maximum intensity about 1 heart phase after peak systole, concordant between groups. While in general there were larger vortices in patients, the per-sinus analysis across all participants did not show differences in vortex strength between sinuses. This result differs from those of both Kvitting et al,²⁴ who found that vortices developed only *after* peak systolic ejection velocity with relatively larger vortices in right and noncoronary sinuses, and Markl et al,²⁵ who described more pronounced vortices in the left and right coronary sinus. This difference might be explained by smaller volunteer collectives, differing scan parameters, and foremost by different analysis strategies. Frequently, streamlines and particle paths are emitted from a particular contour only. In contrast, our analysis additionally included streamlines and particle paths starting upstream to the contour and passing through it; therefore, a denser and probably more reliable visualization can be achieved.²⁶ The comparison of visualization strategies, however, warrants further investigation.

Although the clinical relevance of sinus vortex size is not yet clear, one can state that too small vortices bear the risk of collision of the valve leaflets with the vessel wall, whereas too large vortices bear the risk of energy dissipation, which may lead to an increased strain of the left ventricle. Vortices in SP patients were larger than those in volunteers. There were no significant differences in aortic bulb diameters between patients and VOL-A that were able to justify the increased vortex formation. We hypothesize that, next to differences in cardiac output, the reduced compliance¹⁶ and Windkessel effect of the prosthesis not only contributes to increased bending deformation of the valve leaflets¹⁶ but induces an augmented resistance and backward flow and thus increased vortices.

In addition, the administration of contrast agent in patients may have prompted an increased signal and thus better visualization quality. To at least partially compensate for such effects, the flip angles were adapted to the absence of contrast agents. Further mitigating the potential influence of contrast agent are data in 2 volunteers with a sinus vortex intensity comparable to the other volunteers who did not receive contrast agent. Because the retrograde velocity of sinus vortices is dependent on the flow velocity

pressure gradient $\Delta P(\text{LVOT}, \text{AAO})$. B, Flow profile in the aortic bulb over the course of time (20 heart phases: $t_{\max-2}$ to $t_{\max+17}$ with $t_{\max}$ as peak systole). Pressure differences (ΔP) between C, LVOT or D, AAO and BULB as well as E, the transvalvular pressure gradient $\Delta P(\text{LVOT}, \text{AAO})$ in patients with sinus prosthesis (SP: red) and age-matched and young volunteers (VOL-A: dark blue and VOL-Y: light blue, respectively) reveal physiological behavior. The transvalvular pressure gradient is positive in early systole and gets negative after peak systole while blood is still being ejected from the ventricle. Examples for each group at defined time points in the boxes on the right. [*SP vs VOL-A: $P < .05$]. AAO, Ascending aorta; BULB, aortic bulb; LVOT, left ventricular outflow tract; ΔP , pressure difference; $t_{\max} \pm n$, time point of maximum systole plus/minus n heart phases; SP, sinus prosthesis; VOL-A, age-matched volunteers; VOL-Y, young volunteers.

TABLE 2. Hemodynamic parameters and bulb diameter

	SP	VOL-A	VOL-Y	P value		
				SP vs VOL-A	SP vs VOL-Y	VOL-A vs VOL-Y
Diameter						
Bulb, cm	3.6 ± 0.2 (range, 3.3-3.9)	3.3 ± 0.4 (range, 2.8-4.1)	3.3 ± 0.1 (range, 3.1-3.4)	.105	.010*	.925
Heart function						
EF, %	58.4 ± 7.4	65.4 ± 2.8	—	.022*	—	—
Stroke volume, mL	100.6 ± 23.7	81.7 ± 10.5	—	.069	—	—
Cardiac output, L/min	6.6 ± 0.9	5.1 ± 1.0	—	.002*	—	—
Cardiac index, (L/min)/m ²	3.1 ± 0.4	2.8 ± 0.4	—	.093	—	—
Hemodynamic parameters						
Stroke volume, mL	102 ± 22	91 ± 19	111 ± 10	.225	.206	.019*
Peak average velocity, mL	59 ± 8	50 ± 7	62 ± 6	.009*	.280	.006*
Peak maximum velocity, cm/s	177 ± 54	130 ± 15	136 ± 13	.002*	.031*	.542
Peak net flow, mL/s	512 ± 78	372 ± 78	477 ± 41	<.001*	.425	.022*

SP, Sinus prosthesis; VOL-A, age-matched volunteers; VOL-Y, young volunteers; EF, ejection fraction; BMI, body mass index. *Significant; values are given as mean ± standard deviation.

in the center of the aortic bulb,²⁷ greater maximal flow velocities in the bulb of SP patients may contribute to larger sinus vortices.

Similarly, 4D Flow MRI was able to characterize the not entirely intuitive temporal evolution of transvalvular ΔP , consistent with results from invasive measurements^{28,29}:

ventricular pressure exceeds aortic pressure only in the first part of systole, promoting left ventricular outflow into the aorta. Transvalvular ΔP rapidly decreases until aortic pressure exceeds ventricular pressure in the second part, just after peak systole, while blood is still being ejected from the ventricle into the aorta.

FIGURE 3. Sinus vortices. *Top row:* particle paths at peak systole delineate hemodynamics in the thoracic aorta of 60-year-old patient with SP (A), of a healthy 53-year-old VOL-A (B), and a 30-year-old VOL-Y (C). *Bottom row:* sinus vortices in the right and left coronary sinus as visualized by instantaneous streamlines. Sinus vortices develop behind the opened valve cusp in each coronary sinus during systole and persist until early diastole. Vortices in patients had a similar configuration than those in volunteers. *Dashed lines* are used to emphasize sinus borders and *dotted lines* to underline vortex direction. SP, Sinus prosthesis; VOL-A, age-matched volunteers; VOL-Y, young volunteers; V_{max} , peak velocity.

VIDEO 1. Sinus vortices. Particle paths of sinus vortices in A, a 60-year-old patient with sinus prosthesis; B, a healthy 53-year-old age-matched patient; and C, a 30-year-old young volunteer. Sinus vortices develop behind the opened valve cusp in each coronary sinus during systole and persist until early diastole. Vortices in patients had a similar configuration than those in volunteers.

FIGURE 4. Patients with pressure drops in the ascending aorta. In 2 patients, the pressure minimum was not detected in the bulb but in the ascending aorta. In the first (male, 57 years) a secondary helix developed distal to a kinking of the prosthesis (1A) resulting in a pronounced pressure drop in the ascending aorta (1B). The second patient (female, 61 years) had a stenotic bicuspid aortic valve causing a vortex in the ascending aorta (2A) with an accompanying pressure drop (2B). Prostheses were delineated retrospectively as *dotted lines*. A, particle paths; B, pressure map. ΔP , Pressure difference.

FIGURE 5. Peak transvalvular pressure gradients. Peak transvalvular pressure gradients did not differ significantly between patients with SP and volunteers. In contrast, differences between VOL-Y and VOL-A were statistically significant. SP, Sinus prosthesis; VOL-A, age-matched volunteers; VOL-Y, young volunteers. *Statistical significance, $P < .05$.

A pressure gradient in an elastic pipe is almost proportional to the acceleration or deceleration of a fluid.²⁸ The ascending aorta with its Windkessel effect is such an elastic pipe. Positive transvalvular ΔP triggers the steep upslope of the velocity curve in the first part of systole. The more gradual decrease of blood flow velocity in the second part of systole is a result of negative transvalvular ΔP . It allows for a gradual initiation of valve closure and thus contributes to physiological valve function.³⁰

SP demonstrated a prolonged positive transvalvular pressure gradient as a result of an increased LVOT pressure and a significantly reduced aortic pressure. In SP there was neither a reduction of aortic blood flow nor an elevation of transvalvular ΔP . The prolonged positive transvalvular ΔP may be attributed to the reduced compliance of the synthetic prosthesis and hence increased resistance compared with the natural aortic bulb. In noncompliant vessels, pressure waves travel faster, thus getting reflected earlier, and consequently leading to a systolic pressure increase in the ascending aorta. Secondary flow patterns in the ascending aorta could influence aortic pressure as well; however, this was not within the scope of this study and will have to be addressed in following investigations.

Peak transvalvular pressure gradients did not differ significantly between volunteers and patients further underlining the close correlation of hemodynamics in sinus prostheses and volunteers. Findings are consistent with echocardiographic measurements^{15,16}; however, the absolute level of 4D Flow MRI-derived pressure differences (4.0 ± 0.9 mm Hg) is markedly lower than those described in previous in vivo studies with echocardiography (8.1 ± 3.6 mm Hg)¹⁵ and invasive measurements in phantoms (8.9 ± 1.1 mm Hg).¹⁶ We attribute this difference to the fact

that pressure gradients were derived from the velocity field of the entire vessel cross section in contrast to the peak velocity in the center of the vessel. 4D Flow MRI has been demonstrated previously to be both reliable and accurate.^{18,31,32} In general, it shows a tendency to underestimate peak flows and pressure gradients, presumably explained by spatiotemporal averaging during MRI acquisitions.¹⁸

As part of the ΔP characterization, both the Venturi effect and Bernoulli's principle, the first describing a reduction of pressure when a fluid passes a constricted section of a pipe, the second proposing an increase in velocity after the decrease of pressure, was affirmed. At peak systole, increased relative pressures in LVOT and AAO compared with the center of the aortic bulb were verified. Deducting that valve closure is promoted by the Venturi effect would profit from an analysis of pressure differences across a vessel cross section, which was limited by the acquired spatial resolution.

In 2 patients, the pressure minimum at peak systole was not detected in the aortic bulb but was displaced further downstream in the ascending aorta (Figure 4). In the first patient, both the aortic bulb and ascending aorta were replaced. In consequence, a kinking between both grafts had developed, promoting a secondary helix within the prosthesis. Similarly, the second patient presented with a stenotic bicuspid aortic valve and a postprosthetic dilatation, which resulted in a large ascending aortic vortex. We consider the aforementioned secondary flow patterns responsible for a restricted forward flow to the respective small part of the vessel lumen resulting in a displaced pressure minimum.

Shortcomings of this work are the relatively small collective of patients and long acquisition and postprocessing times. As of now, there is a limited number of patients with SP from which to recruit. Therefore, the presented results have to be understood as promising pilot data on which to expand a clinical study in which the connection between hemodynamics and long-term outcome not only in SPs but also in other VSARR prostheses needs to be analyzed. This will also help to discriminate flow patterns induced by the prosthesis or surgery itself. Moreover, potential characteristic features of patients with connective tissue disorders need to be investigated.

First mid-term-outcomes of a Valsalva graft with pseudosinus are promising.³³ The relatively long acquisition times that may lead to patient discomfort on one hand and averaging of small cyclic flow patterns on the other hand will be overcome by optimized parallel data acquisition techniques.^{34,35} At the time of the study, however, these techniques were not available. Lastly, long postprocessing may limit clinical practicability. Although modern imaging centers provide postprocessing services, the applied software is of scientific nature and not approved by the Food and Drug Administration and postprocessing is time-consuming, which hampers its clinical applicability. As 4D Flow MRI increasingly contributes to clinical research, however, this missing step may be overcome in future as well.

CONCLUSIONS

Although flow patterns within the sinuses and pressure gradients were both confirmed to be closely related to those of age-matched volunteers (VOL-A), future studies are necessary to clarify whether sinus prostheses have an impact on the long-term outcome of patients compared with straight grafts. Sinus vortex formation was comparable with those of volunteers believed to enable physiological valve function and thus decreased stress on the valve leaflets. Together with physiological pressure gradients, this could possibly lead to less valve deterioration in the long term, which seems especially relevant in particular for younger patients, eg, with Marfan syndrome.

Conflict of Interest Statement

Prof. Sievers receives royalties from B. Braun Melsungen AG. All other authors have nothing to disclose with regard to commercial support.

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Key Words: sinus prosthesis, 4D Flow MRI, 4D flow cardiovascular magnetic resonance, sinus vortices, sinuses of Valsalva, transvalvular pressure gradients, valve-sparing aortic root replacement, VSARR

FIGURE E1. The sinus prosthesis. Intraoperative view of an implanted sinus prosthesis. Note the sinus configuration and the straight pillars between the sinuses.