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Blood flow characteristics in the ascending aorta after aortic valve replacement—a pilot study using 4D-flow MRI☆,☆☆

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ABSTRACT

Background: Aortic remodeling after aortic valve replacement (AVR) might be influenced by the postoperative blood flow pattern in the ascending aorta. This pilot study used flow-sensitive four-dimensional magnetic resonance imaging (4D-flow) to describe ascending aortic flow characteristics after various types of AVR.
Methods: 4D-flow was acquired in 38 AVR patients ($n = 9$ mechanical, $n = 8$ stentless bioprosthesis, $n = 14$ stented bioprosthesis, $n = 7$ autograft) and 9 healthy controls. Analysis included grading of vortex and helix flow (0–3 point scale), assessment of systolic flow eccentricity (1–3 point scale), and quantification of the segmental distribution of peak systolic wall shear stress (WSS_{peak}) in the ascending aorta.
Results: Compared to controls, mechanical prostheses showed the most distinct vorticity (2.7 ± 0.5 vs. 0.7 ± 0.7; $p < 0.001$), while stented bioprostheses exhibited most distinct helicity (2.6 ± 0.7 vs. 1.6 ± 0.5; $p = 0.002$). Instead of a physiologic central flow, all stented, stentless and mechanical prostheses showed eccentric flow jets mainly directed towards the right-anterior aortic wall. Stented and stentless prostheses showed an asymmetric distribution of WSS_{peak} along the aortic circumference, with significantly increased local WSS_{peak} where the flow jet impinged on the aortic wall. Local WSS_{peak} was higher in stented (1.4 ± 0.7 N/m^2) and stentless (1.3 ± 0.7 N/m^2) compared to autografts (0.6 ± 0.2 N/m^2; $p = 0.005$ and $p = 0.008$) and controls (0.7 ± 0.1 N/m^2; $p = 0.017$ and $p = 0.027$). Autografts exhibited lower absolute WSS_{peak} than controls (0.4 ± 0.1 N/m^2 vs. 0.7 ± 0.2 N/m^2; $p = 0.003$).
Conclusions: Flow characteristics in the ascending aorta after AVR are different from native aortic valves and differ between various types of AVR.

1. Introduction

After aortic valve replacement (AVR), thoracic aortic remodeling is observed, which includes progression, stagnation or regression of aortic dilatation and mainly occurs in the aortic root and mid-ascending aorta [1,2]. The mechanism of interaction between AVR and ascending aortic remodeling is unknown, yet certainly multifactorial. The known parameters related to this process include genetic predisposition, aortic wall morphology, atherosclerotic risk profile, as well as nature of the original valvular lesion [3]. In addition, ascending aortic hemodynamics after AVR and their possible connection to aortic remodeling are of interest. Post-stenotic regions or asymmetries in the local geometry create a highly dynamic flow environment where wall shear stress (WSS) is characterized by abrupt changes in magnitude and direction during the cardiac cycle. A non-uniform distribution of wall shear stress with abnormally high levels at the flow impingement site is the driving force behind wall degradation and predispose to aneurysm formation and growth. Low levels are associated with inflammation and endothelial cell dysfunction and promote atherosclerotic changes [4,5].

Local flow measurements and flow visualizations are possible with time-resolved three-dimensional flow-sensitive cardiovascular magnetic resonance (4D-flow CMR). Helicity and vorticity can be visualized, and the distribution of aortic WSS can be estimated [6–8]. The feasibility of 4D-flow adjacent to various aortic heart valve prostheses has been demonstrated in a flow phantom [9]. In the present pilot study, 4D-

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flow was applied in patients after various types of AVR and in healthy controls to describe the ascending aortic flow characteristics after AVR in order to generate hypotheses for future research in larger samples.

2. Methods

2.1. Study sample

The local ethics committee approved the study and written informed consent was obtained from the individuals. Fifty consecutive patients with surgical AVR and 9 healthy controls were prospectively enrolled. The types of AVR included mechanical prostheses, stented and stentless bioprostheses, as well as autografts (Ross procedure: replacement of the native aortic root by the pulmonary root). Transapically/transfemorally implanted prostheses were not included. Mechanical and stented prostheses were implanted in the supra-annular position. Twelve patients were excluded: in 8, extensive respiratory motion hindered efficient navigator control, 2 presented with atrial fibrillation, 1 interrupted the exam due to claustrophobia and 1 did not fit into the scanner due to obesity. The status "healthy" of the controls was based on: i) uneventful medical history, ii) absence of any symptoms indicating cardiovascular dysfunction, and iii) normal cardiac dimensions and function, normal morphology and function of the aortic valve and normal sized thoracic aorta on CMR cine imaging. In total, 38 patients with surgical AVR and 9 controls comprised the final study sample. Their characteristics are summarized in Table 1.

2.2. Image acquisition protocol

All subjects underwent CMR at a 1.5 T MR system (Avanto, Siemens Healthcare, Erlangen, Germany). Image acquisition settings and protocols were identical in all participants. A 12-channel body array coil was used for reception and the body coil for transmission. No contrast agent was administered.

Time-resolved 3D phase contrast CMR with three-directional velocity encoding (4D-flow) was acquired in a sagittal oblique volume covering the thoracic aorta using prospective ECG gating and a respiratory navigator placed on the lung–liver interface [6]. The phase contrast data were acquired with a Cartesian sampling pattern. Typical scan parameters were: echo time [TE] = 2.3 ms, repetition time [TR] = 4.8 ms, bandwidth = 440 Hz/pixel, acceleration mode GRAPPA with factor 2 and 24 reference lines, flip angle $\alpha = 9°$, temporal resolution 38.4 ms, field of view [FOV] 400 × 375 mm, matrix 192 × 158, voxel size 2.1 × 2.4 × 2.2 mm^3, 1 slab, phase encoding direction a-p, number of slices 26, slice thickness 2.2 mm, and slab thickness 57.2 mm. Velocity encoding was set to 2.5 m/s based on empirical data of the peak velocity in the ascending aorta after AVR to provide appropriate signal-to-noise at least during systole while omitting significant aliasing. The navigator acceptance window was set to 14 mm, navigator search window

Table 1
Characteristics of the study participants.

Parameter	Controls	Autograft	Mechanical	Stentless bio	Stented bio	*p*
n	9	7	9	8	14	–
Sex (females/males)	1/8	2/5	0/9	2/6	4/10	–
Age (years)	55 ± 16	47 ± 17	61 ± 11	62 ± 20	77 ± 4	<0.001*
Native valvular lesion	–	Stenosis ($n = 3$), regurgitation ($n = 1$), mixed ($n = 3$)	Stenosis ($n = 3$), regurgitation ($n = 5$), mixed ($n = 1$)	Stenosis ($n = 5$), regurgitation ($n = 3$)	Stenosis ($n = 7$), regurgitation ($n = 2$), mixed ($n = 5$)	–
Time since valve surgery [years]	–	6.0 ± 4.2	7.9 ± 3.6	2.7 ± 4.8	3.6 ± 2.6	0.014*
Labeled valve size	–	–	24.3 ± 2.5	26.0 ± 1.5	23.6 ± 2.0	0.029*
Orifice area [cm^2]	4.0 ± 0.8	4.6 ± 0.9	1.8 ± 0.5	2.0 ± 0.5	1.5 ± 0.4	<0.001*
Orifice area index [cm^2/m^2]	2.0 ± 0.4	2.3 ± 0.4	0.9 ± 0.2	1.1 ± 0.3	0.8 ± 0.2	<0.001*
Prosthetic types	–	–	Only bileaflet valves. Levibio ATS ($n = 1$), Sorin Carbomedics ($n = 1$), Medtronic Advantage ($n = 1$), St. Jude Regent ($n = 6$)	Porcine: Vascutek Elan ($n = 1$), Shelhigh ($n = 3$); St. Jude Toronto ($n = 1$); bovine: Sorin Freedom Solo ($n = 2$); Medtronic Freestyle ($n = 1$)	Porcine: Medtronic Hancock ($n = 6$), Labcore ($n = 1$); bovine: Edwards Perimount ($n = 3$), Sorin Mitroflow ($n = 2$), unknown ($n = 2$)	–
LV end diastolic volume [ml]	140 ± 41	176 ± 34	186 ± 98	165 ± 64	147 ± 58	0.459
LV stroke volume [ml]	92 ± 28	98 ± 22	76 ± 51	98 ± 40	84 ± 31	0.585
LV ejection fraction [%]	66 ± 6	57 ± 13	50 ± 14	60 ± 10	59 ± 11	0.049*
Aortic diameter [mm]	31 ± 5	37 ± 4	40 ± 8	37 ± 7	38 ± 4	0.009*

Results are given as frequencies or as mean ± SD. The *p*-value relates to the Kruskal–Wallis multiple group comparison. Further inter-study relations are outlined in the text.