Integrated morphologic and functional assessment of the aortic root after different tissue valve root replacement procedures

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Objectives: This study was undertaken to explore aspects of the hemodynamic function of different biologic tissue aortic valve root replacements. We set out to image and display the spatiotemporal distributions of axially directed blood velocity through the aortic root.

Methods: The flow velocities through a plane transecting the aortic root were measured by 2-dimensional cine phase-contrast magnetic resonance velocity mapping in 44 subjects: 29 patients who had undergone aortic root replacement approximately 10 years previously (13 autografts, 10 stentless xenografts, and 6 homografts) and 15 healthy control subjects. With cine as well as velocity images, aortic sinus dimensions, effective orifice area, and several velocity parameters were measured. Color-coded plots of velocity relative to the sinus cross sections and velocity-time plots were used to compare spatiotemporal distributions of velocity.

Results: Peak flow velocity was similar between the autografts (102 ± 28.0 cm/s) and control valves (119 ± 20.0 cm/s) but was higher in xenografts (167 ± 36.0 cm/s) and homografts (206 ± 91.0 cm/s). These measurements showed an inverse relationship with the effective orifice area (7.27 ± 0.20, 4.24 ± 0.81, 3.37 ± 0.32, and 3.28 ± 0.87 cm^2, respectively). Autograft peak flow velocity showed no significant difference from control valve peak flow velocity, despite larger root dimensions ($P < .001$). The graphic displays provided further spatiotemporal information.

Conclusions: Peak velocities and spatiotemporal flow patterns depend on the type of valve substitute. In the parameters measured, autograft replacements differed least from normal aortic valves. (J Thorac Cardiovasc Surg 2012;143:1422-8)

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A number of surgical procedures to replace the aortic root and valves are currently being used. These include valve-sparing operations, aortic homograft, xenograft, and autograft root.[1-4] The influences of different types of valve operations on the size of the root and the pattern of flow in the aortic root have not been examined in detail. Recent studies have shown that the normal aortic root and valve perform sophisticated functions[5,6] that can influence patterns of blood flow in different parts of the aorta, coronary circulation, and systemic circulation, as well as influencing left ventricular function and endothelial functions of the ascending aorta and arch.[7,8] Cardiovascular magnetic resonance (CMR) imaging with phase-contrast velocity mapping allows noninvasive measurement of the spatiotemporal distribution of the components of velocity in the aortic root,[9-11] which can be used in the investigation of several clinical conditions.[12] The purpose of this investigation was to use this approach to characterize the spatiotemporal patterns of the flow directed through the aortic root after 3 different types of aortic root replacement and to compare these with flow conditions in healthy subjects.

MATERIALS AND METHODS

Study Population

Written consent was obtained from all subjects. The study protocol was approved by the local ethics committee, and the study complied with the Declaration of Helsinki. The study group comprised 44 subjects, including 29 patients who had undergone aortic root replacement more than 10 years before imaging with either an autograft (n = 13), a homograft (n = 6), or a xenograft (n = 10; Medtronic Freestyle; Medtronic Inc, Minneapolis,

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Abbreviations and Acronyms
CMR = cardiovascular magnetic resonance
SSFP = steady-state free precision

Minn). All patients had normally functioning valves, with no significant stenosis or regurgitation according to echocardiographic assessment at the time of analysis. Fifteen healthy volunteers without previous history of cardiovascular disease or associated risk factors were studied as a control group. Relevant demographic information about the study subjects is summarized in Table 1.

CMR Image Acquisition

All patients' studies were performed on a 1.5-T Siemens Avanto magnetic resonance scanner (Siemens Medical Solutions USA, Inc, Malvern, Pa) approximately 10 years after valve surgery as a part of clinical follow-up at Royal Brompton and Harefield Hospitals (London, UK). The healthy volunteers were scanned at Alfa Scan Radiology Center (Cairo, Egypt) with a Philips Achieva 3.0-T scanner (Royal Philips Electronics, Amsterdam, The Netherlands). Multislice anatomic images of the heart and great vessels were obtained with single-shot steady-state free precession (SSFP) sequence. Cine SSFP imaging in the left ventricular outflow tract from an appropriate transaxial section was then obtained, and this was followed by a left ventricular outflow tract crosscut cine acquisition. Cine SSFP was then acquired in the short-axis plane of the aortic valve positioned in the 2 left ventricular outflow tract views at midsinus level of the aortic root (Figure E1). Through-plane, breath-hold, retrospectively gated phase-contrast flow mapping was then acquired above the aortic valve at midsinus level, with care taken to avoid the valve plane, which moves during the cardiac cycle. For each subject, images (pairs of magnitude and phase images) were obtained at 20 equally distributed phases throughout the cardiac cycle with breath-holding, retrospectively electrocardiographically gated sequence. Typical matrix size was 256 × 176, with typical in-plane spatial resolution of 1.25 mm and slice thickness of 6 mm. Phase-contrast encoding velocity ranged from 150 to 430 cm/s. Detailed imaging parameters are summarized in Table E1.

Image Analysis

Each pair of acquired images (magnitude and phase images) was first segmented to obtain through-plane velocity maps over the cross section; a magnitude image was segmented to obtain an anatomic cross section of the aortic root, and then the through-plane velocity map on the cross section was calculated with the corresponding phase image in reference to encoding velocity. Volumetric flow was then calculated by integrating the velocity map over the cross section. By temporally interpolating 20 phases through the cardiac cycle, the time-varying volumetric flow curve (waveform) was also obtained. Morphologic and hemodynamic parameters were calculated on the basis of the reconstructed flow data. The parameters included stroke volume, ejection time, temporal maximum flow rate, mean flow rate throughout the cardiac cycle, spatial maximum velocity at peak flow rate, spatial mean shear rate ($\sqrt{(dv/dx)^2+(dv/dy)^2}$) over the cross section, cross-sectional area of the aortic sinus, and effective orifice area at peak flow rate. In addition, the diameter of the sinus (as determined from the cross-sectional area, $d = 2\sqrt{A_{sinus}/\pi}$) was derived from the cine SSFP images for the valve substitute groups and from phase-contrast images for healthy subjects. The parameters were compared among the subject groups, as were the velocity profiles. In this study, the effective orifice area was determined as the area in which velocities were higher than the mean velocity over the cross section. All analysis was carried out with an in-house MATLAB program (The MathWorks, Inc, Natick, Mass). An example of image data analysis is shown in Figure E2.

Statistical Analysis

Data are expressed as mean ± SD. Comparisons between groups of the demographic data and of the morphologic and hemodynamic parameters were carried out with the use of 1-way analysis of variance first. The morphologic and hemodynamic parameters for root substitute groups were also compared against control data with an unpaired, 2-tailed Welch *t* test. All statistical analyses were performed with a statistics software environment R version 12.2 (http://www.r-project.org/).

RESULTS

Morphologic and hemodynamic parameters derived for the 4 groups are summarized in Table 2. A statistical comparison of key data is shown in Figure 1.

Morphologic Parameters

The sinus cross-sectional area and diameter were larger for the autograft group than for the control group ($P < .001$), whereas the other 2 groups showed values comparable to those in the control group. When the ratio of

TABLE 1. Study population demographic characteristics

Variable	Autograft (n = 13)	Xenograft (n = 10)	Homograft (n = 6)	Control (n = 15)	*P* value*
Age (y, mean ± SD)	42.8 ± 8.5	73.5 ± 7.9	67.3 ± 10.8	30.9 ± 5.1	<.001
Sex (no. male)	11/13 (85%)	6/10 (60%)	4/6 (67%)	11/15 (73%)	.63
Time since operation (y, mean ± SD)	10.3 ± 1.1	8.2 ± 0.7	7.6 ± 0.7	N/A	<.001
Heart rate (beats/min, mean ± SD)	71.6 ± 15.7	75.8 ± 18.1	67.8 ± 19.9	72.1 ± 10.2	.79
Systolic BP (mm Hg, mean ± SD)	135.5 ± 18.0	126.6 ± 16.6	130.3 ± 11.3	110.7 ± 12.8	<.001
Diastolic BP (mm Hg, mean ± SD)	68.3 ± 14.4	73.7 ± 10.1	76.5 ± 3.1	72.7 ± 8.8	.42
⊿BSA	1.006 ± 0.08†	1.02 ± 0.05	1.002 ± 0.03‡	—	.82
Indication for surgery (no.)					
Aortic stenosis	2	2	2	—	
Aortic regurgitation	7	4	1	—	
Aortic stenosis and regurgitation	4	3	1	—	
Structural valve abnormality	0	1	1	—	
Postoperative LV mass index (g/m^2, mean ± SD)	94.7 ± 33.0	131.4 ± 63.1	120.5 ± 36.6	—	.21

BP, Blood pressure; *⊿BSA,* ratio of body surface area (time of cardiovascular magnetic resonance scan to time of operation); *LV,* left ventricular. *Comparisons by 1-way analysis of variance. †n = 11. ‡n = 5.