Flow patterns in the aortic root and the aorta studied with time-resolved, 3-dimensional, phase-contrast magnetic resonance imaging: Implications for aortic valve-sparing surgery

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Objective: Sparing the aortic valve has become a surgical option for patients who require repair of aortic root ectasia and have normal valve leaflets. Surgical approaches to valve sparing differ with regard to preservation of the native sinuses of Valsalva. The role of the sinuses and the importance of maintaining them remain controversial.

Methods: By using a time-resolved, 3-dimensional, phase-contrast magnetic resonance imaging technique, aortic root and aortic blood velocity data were acquired from 2 patients with Marfan syndrome 6 months after aortic valve-sparing surgery with straight Dacron grafts and contrasted with data from 6 normal volunteers.

Results: In normal aortas vortical blood flow became apparent in the individual sinuses after peak systole. The vortices filled the available space behind the valve leaflets and persisted until diastole, expanding and moving inward during aortic valve closure. In contrast, no vortices were observed in the postoperative patients with Marfan syndrome with negligible sinuses.

Conclusions: Changes in supralvalvular flow accompany loss of sinus architecture. Whether the presence, size, and velocity of supralvalvular vortices affects the function or durability of the preserved aortic valve remains to be studied.

Operations for aortic root disease that spare the aortic valve have become more frequent during the last decade.¹ The most familiar procedure, composite graft and valve implantation, has acceptable long-term results.²⁻⁴ This approach comprises the long-term risks of anticoagulation, however, as well as the potential for noise from the mechanical valves that are incorporated in most conduits.⁵

An alternative to the composite valve conduit approach is to preserve the native aortic valve. Sarsam and Yacoub⁶ have presented a method in which they conserve

the native aortic valve and its sinuses by connecting the annulus to a tailored graft. Another technique, advocated by David and Feindel,⁷ consists of a reconstruction in which the valve is mounted within a straight Dacron graft. The main difference between the 2 techniques is how the annulus is treated and whether the sinuses are preserved.

The importance of the sinuses of Valsalva in the function of the aortic valve has been debated since the time of Leonardo da Vinci.⁸ Modern investigators have theorized that the sinuses and their vortices adapt the valve for closure, thereby facilitating early closure and improving coronary blood flow.^{9,10} The dynamic and intricate function of the sinuses and of the blood flow within them has not been well studied in human subjects.

The aim of the present study was to investigate the in vivo flow patterns in the normal aortic root and sinuses of Valsalva by using magnetic resonance imaging (MRI) and to contrast them with flow patterns associated with valve-sparing aortic surgery with straight Dacron grafts.

Material and Methods

Data were acquired from 6 male volunteers (mean age, 34 ± 14 years; age range, 25–61 years) without a prior history of cardiovascular disease and with normal electrocardiographic results and normal aortic valve morphology, as determined by means of echocardiography. Data were also collected from 2 male patients with Marfan syndrome (29 and 30 years of age) who had had valve-sparing aortic root replacement with straight Dacron grafts for aortic root ectasia. One patient had concomitant aortic arch reconstruction for aortic dissection. No postoperative complications occurred in either patient, and they were examined 6 months after the operation. The study was approved by the Regional Ethics Committee for Human Research at the Faculty of Health Sciences, Linköping University; written informed consent was obtained from all volunteers and patients.

We used 3-dimensional (3D) phase-contrast MRI data to visualize the flow pattern in the aortic root and ascending aorta. Velocity vector information was obtained by using a retrospectively gated 3D phase-contrast pulse sequence.^{11,12} We used a 1.5 T scanner (Signa LX EchoSpeed; GE Medical Systems, Milwaukee, Wis) and the following acquisition parameters: TR of 18 ms; TE of 7 ms; velocity encoding range (VENC) of 100 cm/s for healthy subjects; VENC of 180 cm/s for patients; and field of view (FOV) of $300 \text{ (SI)} \times 300 \text{ (AP)} \times 128 \text{ (RL)} \text{ mm}$ with a spatial resolution of $1 \times 4 \times 4 \text{ mm}$. Thirty-two time frames were reconstructed. The phase contributions from concomitant gradient (Maxwell) terms and eddy current effects were subtracted.¹³

The acquired velocity data were transferred to the Ensign visualization program (CEI Inc, Research Triangle Park, NC). Streamlines, on the basis of the velocity information from a single time frame, were generated to visualize the instantaneous 3D flow field in systole. Streamlines were calculated by using a fourth-order Runge-Kutta numeric integration technique.¹²

Timing during the cardiac cycle was obtained from the flow velocity for each time step at a reference point within the aortic lumen near the aortic valve. Stroke volume was estimated from

Figure 1. A schematic drawing of the blood flow curve in the ascending aorta demonstrates the systolic-phase parameters.

velocity vectors perpendicular to a circular grid positioned within the aortic lumen a few centimeters above the aortic valve. Integration of this volume for each time step over the entire systolic time interval was taken as the stroke volume. Figure 1 shows a schematic drawing of the blood flow curve in the ascending aorta. S1 is the time from upstroke of the aortic flow curve to peak flow, and S2 is the time from peak flow to the end of ejection.

Results

Systolic Phase

Streamlines originating near the aortic valve at peak systole demonstrate the contours of the proximal aorta for a healthy subject and for a patient with Marfan syndrome after root replacement with a straight graft (Figure 2). Systolic-phase measurements, including the peak velocity near the aortic valve, the total duration of the systolic aortic flow, the duration from the start of the upstroke to peak systolic velocity (S1), and the time from peak systolic velocity to diastole (S2) for the 6 healthy volunteers and the 2 patients with Marfan syndrome are shown in Table 1. All measurements from the 2 patients fell within the range defined by the healthy subjects.

Supravalvular Vortices

Normal aortic root. Vortical flow was detected in the 3 sinuses of Valsalva of all of the normal aortas, beginning after the peak systolic ejection velocity. The vortices are clearly seen in the individual sinuses and persist into early diastole (Figure 3). As the late systolic period progresses, the vortices expand and occupy incrementally more of the aortic cross-sectional area, and the central zone for forward flow diminishes (Figure 4).

Aortic root replacement. The patients with straight aortic root replacement did not have conservation of sinus architecture. No supravalvular vortices were demonstrable in either patient (Figures 3 and 4).

Figure 2. Streamlines released at peak systole from a grid above the aortic valve in a healthy volunteer (A) and in an operated patient with Marfan syndrome (B) show the contours of the proximal aorta and neck vessels.

TABLE 1. Systolic-phase measurements

	Healthy subjects (n = 6)	Patient 1	Patient 2
Heart rate (beats/min)	64 ± 7 (range, 56-76)	50	73
Total systole (ms)	0.38 ± 0.03 (range, 0.33-0.40)	0.39	0.39
S1 (ms)	0.17 ± 0.01 (range, 0.15-0.19)	0.18	0.18
S2 (ms)	0.21 ± 0.02 (range, 0.18-0.23)	0.21	0.20
Peak velocity (m/s)	1.2 ± 0.2 (range, 1.0-1.6)	1.3	1.7
Stroke volume (mL)	77.1 ± 10.3 (range, 67.7-92.1)	92.1	79.4

S1, Duration from onset of systole to time of peak systolic velocity; S2, duration from time of peak systolic velocity to return to presystolic velocity.

Discussion

In 1968, Bellhouse and colleagues^{9,10} used in vitro flow modeling to predict the importance of the sinuses of Valsalva and the sinotubular ridge in the normal function of the aortic valve. They proposed that the sinus ridge promoted vortex formation within the sinuses that initiated early and smooth closure of the aortic valve and promoted coronary blood flow. Recent publications on the basis of mathematic models have suggested that the flow patterns in the aortic root might affect aortic valve function by allowing load and stress sharing between the valve leaflets and the aortic wall.¹⁴ MRI has previously shown the vortices in the sinuses of Valsalva in 2 dimensions.¹⁵ In our healthy volunteers 3D visualization of the magnetic resonance data clearly demonstrates the development of vortices within the individual sinuses during late systole. The sinus vortices

increase in size as aortic velocities decrease and persist until diastole. The direction of flow rotation in the sinus vortices is from superior to inferior along the lateral confines of the sinuses and then turns toward the central aortic orifice at the base of the sinuses. This direction of vortical blood flow in the sinuses at end-systole might exert inward pressure on the aortic leaflets and facilitate rapid valve closure.

Of interest, the apparent size of the vortical flow differed for the 3 sinuses, with relatively larger vortices associated with the right and noncoronary sinuses. This might reflect asymmetry of the aortic root, the swirling quality of the ejected blood, or both.¹⁶ Whether the volume or velocity of the supravulvar vortical blood flow affects the specific closing behavior of the individual leaflets has not been studied.

Figure 3. Examples of the flow pattern in the aortic root of a healthy volunteer (*upper row*) and an operated patient with Marfan syndrome (*lower row*) visualized in an oblique anterior posterior direction. The *white dotted line* in the first image from the left in both the upper and lower rows is an approximation of the aortic outline superimposed on the velocity data sets. *Red dots* identify the approximate location of the sinotubular junction in the healthy subject. The first images on the left correspond to peak systole; subsequent images moving to the right represent 30-ms intervals. *RC*, Right coronary sinus; *NC*, noncoronary sinus; *RPA*, right branch of the pulmonary artery.

Leyh and colleagues¹⁷ demonstrated that composite aortic grafts that incorporate a sinus portion result in a more normal pattern of aortic valve opening and closure. In contrast, they found that the normal gradual inward motion of the aortic leaflets during systole was impaired after aortic root replacement with a straight graft without sinuses. Others have also concluded that incorporation of sinuses in aortic root grafts promotes more normal function of the valve.^{18,19}

We did not observe supra-ventricular vortices in our 2 patients who did not have sinuses because of their aortic root replacement with a straight graft. Possible explanations for the absence of vortical flow in our patients include a relative lack of space, lack of appropriately curved architecture to promote circular flow, and changes in aortic compliance. These discrete changes in supra-ventricular flow behavior might explain earlier observations of delayed valve closure.¹⁷

It has been proposed that smooth and rapid aortic valve closure might minimize the stress on the valve leaflets.^{20,21} Perturbation of the normal valve closure mechanisms might

contribute to long-term leaflet degeneration.²² In addition, it has been suggested that the normal aortic root, consisting of the aortic valve, corresponding sinus, and the sinotubular junction, provides a “pull and release” function. Loss of this function after root replacement might lead to stress overload on the aortic leaflets and eventual cusp fibrosis and calcification.²³ Medium-term results from the Toronto and Hannover experiences with straight aortic root replacement have not demonstrated a trend toward valve dysfunction, however.^{24,25}

Options for aortic root replacement with compliant sinuses are available. Homografts preserve normal geometry and compliance early on. They have been shown to have progressive calcification over time, however, and this is often associated with progressive aortic valve dysfunction.²⁶ A second option is a conduit that incorporates compliant sinuses.^{19,27} Whether this type of conduit will retain its elasticity in the long term is uncertain.

The temporal resolution of these data is limited to 72 ms. This interferes with the assessment of rapid acceleration and

Figure 4. Examples of the flow pattern in the aortic root of a healthy volunteer (*upper row*) and an operated patient with Marfan syndrome (*lower row*) visualized in a superior inferior direction. The images correspond to the last 4 time steps of late systole at 30-ms intervals, moving from left to right. The *white dotted lines* in images from the healthy subject outline the effective aortic orifice. *LC*, Left coronary sinus; *RC*, right coronary sinus; *NC*, noncoronary sinus.

very short-lived events. In the case of our measurements, the exact timing of peak systole and the measurement of the true peak velocity might have been affected by this. Another limitation relates to the optimization of the range of measured velocities. The VENC of the MRI scanner has to be matched to the individual's particular hemodynamics to capture the highest velocities in the aorta. The patients with aortic root replacement were therefore imaged with a higher VENC than the normal subjects. A higher VENC limits low-velocity sensitivity.²⁸ A numerical simulation of the 2 VENC settings was performed to assess whether the higher VENC might interfere with recognition of vortices. In addition, a normal subject was imaged with both the higher and lower VENC settings. In both simulated and in vivo conditions, the higher VENC setting did not impair the recognition of vortical flow.

In conclusion, our findings provide new insight into the function of the aortic sinuses and of the flow within them. There is theoretic support for the concept that prompt and smooth closure of the valve might rely on the presence of normal aortic root flow. In our patients without sinuses undergoing root replacement, vortices were not demonstra-

ble above the aortic valve. This phenomenon might explain some of the changes in aortic valve motion that have been observed in patients undergoing valve-sparing surgery. The effect of the presence, size, and velocity of supravulvar vortices on the function or durability of the aortic valve will require future investigation with methods that can describe their dynamic behavior in 3 dimensions.

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