Opening and Closing Characteristics of the Aortic Valve After Different Types of Valve-Preserving Surgery

Rainer G. Leyh, MD; Claudia Schmidtke, MD; Hans-Hinrich Sievers, PhD, FETCS; Magdi H. Yacoub, PhD, FRCS

Background—The surgical approach to aortic root aneurysm and/or dissection remains controversial. The use of valve-sparing operations, which are thought to have many advantages, is increasing. We hypothesized that the particular technique and type of surgery could influence valve motion characteristics and function. Therefore, we studied the instantaneous opening and closing characteristics of the aortic valve after the main 2 types of valve-preserving surgery.

Methods and Results—In 20 patients (10 with tube replacement of the aortic root, group A; and 10 with separate replacement of the sinuses of Valsalva, group B) and 10 controls (group C), transthoracic and transesophageal studies on aortic valve dynamics were performed. Three distinct phases of aortic valve motion were identified. They were as follows: (1) a rapid opening, with a velocity of 20.9±4.2 cm/s in group C, 27.1±10.9 cm/s in group B (P<NS), and 58.3±18.4 cm/s in group A (group A versus group C, P<0.001; group A versus group B, P=0.001); (2) a slow systolic closure, with 12.5±6.6% and 10.8±2.2% of maximal opening in groups C and B, respectively (P=NS), and 3.8±1.6% in group A (group A versus group C, P=0.001; group A versus group B, P<0.001); and (3) a rapid closing movement, with a velocity of 26.3±5.6 cm/s in group C, 32.4±11.4 cm/s in group B (P=NS), and 21.8±3.5 cm/s in group A (group A versus group C, P=NS; group A versus group B, P=0.008). The pressure strain of the elastic modulus was different in groups C and B only at the commissures (682±145 g/cm² versus 1896±726 g/cm², respectively; P<0.001). At all root levels, the distensibility was reduced in group A (P<0.001). Systolic contact of aortic cusps and wall occurred only in group A.

Conclusions—Near-normal opening and closing characteristics can be achieved by a technique that preserves the shape and independent mobility of the sinuses of Valsalva. (Circulation. 1999;100:2153-2160.)

Key Words: aorta ■ valves ■ surgery ■ echocardiography

The surgical approach to aortic root aneurysm and/or dissection is still controversial. Replacing the diseased aortic root with a composite graft including a mechanical valve is commonly performed; with this procedure, patients must accept the disadvantages of lifelong anticoagulation and risks of thromboembolism, hemorrhage, endocarditis, and restricted hemodynamics in favor of defined, long-term function of the prosthesis.1-5 Because aortic disease leaves the aortic valve cusps largely unaffected, valve-preserving operations, with excision of all diseased tissue, have been developed and used in several series.6-13 The main 2 techniques used either replace the diseased sinuses of Valsalva by 3 separate, tongue-shaped extensions of the Dacron tube, thus maintaining the independent mobility of each sinus,6,7,13 or suture the mobilized aortic valve inside the cylindrical Dacron tube.8 The influence of the particular technique used on the opening and closing characteristics of the aortic valve, including the pattern of instantaneous movements of the cusps and aortic wall during the different parts of the cardiac cycle, has not been studied before. These movements could have important implications on the durability of the repair and, possibly, on coronary flow and left ventricular function and, thus, long-term results. The purpose of this study was to evaluate echocardiographically the opening and closing characteristics of the aortic valve after the 2 main types of valve-preserving surgery.

Methods

Patients

Between November 1992 and September 1997, 20 patients with aortic root disease underwent 2 different types of aortic valve-sparing operations. During the initial period, the David technique (group A; n=10) was performed; subsequently, the Yacoub technique (group B; n=10) was used.7,13 The inclusion criteria for both groups were identical and consisted of the absence of gross organic changes in the valve cusps, regardless of the size of the aneurysm, the duration of aortic insufficiency, ventricular function, or age. Patients with severe neurological abnormalities before the operation were excluded. The control group (group C) consisted of 10 healthy patients.
TABLE 1. Clinical and Operative Data

<table>
<thead>
<tr>
<th></th>
<th>Group A (n=10)</th>
<th>Group B (n=10)</th>
<th>Group C (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex, M/F</td>
<td>7/3</td>
<td>7/3</td>
<td>8/2</td>
</tr>
<tr>
<td>Age, y</td>
<td>48±17</td>
<td>58±13</td>
<td>41±14*</td>
</tr>
<tr>
<td>BSA, m²</td>
<td>1.92±0.15</td>
<td>1.89±0.23</td>
<td>1.82±0.21</td>
</tr>
<tr>
<td>Acute dissection, n</td>
<td>6</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Chronic aneurysm, n</td>
<td>3</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Marfan syndrome, n</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Follow-up, mo</td>
<td>23.2±8.5</td>
<td>4.1±1.8†</td>
<td></td>
</tr>
<tr>
<td>Bypass time, min</td>
<td>195±28</td>
<td>192±28</td>
<td></td>
</tr>
<tr>
<td>Ischemic time, min</td>
<td>143±12</td>
<td>134±17</td>
<td></td>
</tr>
<tr>
<td>Diameter of Dacron</td>
<td>28 mm: n=4</td>
<td>28 mm: n=3</td>
<td></td>
</tr>
<tr>
<td>Prostheses</td>
<td>30 mm: n=6</td>
<td>30 mm: n=7</td>
<td></td>
</tr>
</tbody>
</table>

BSA indicates body surface area.

*P<0.012, group C vs group B; †P<0.001, group A vs group B.

individuals in whom no abnormalities of the aortic valve, aortic root, or left ventricle were detected by medical history, standard clinical examination, and transesophageal echocardiography. The clinical characteristics of all groups are shown in Table 1. Informed written consent was obtained before echocardiography. The investigative procedures were performed in accordance with institutional guidelines. All patients were clinically evaluated at regular intervals at our hospital.

Operative Technique

Standard cardiopulmonary bypass with a membrane oxygenator (Hollow Fiber Oxygenator, Spiral Gold) at moderate hypothermia (28°C nasopharyngeal temperature) or deep hypothermic circulatory arrest (18°C nasopharyngeal temperature) was used, and cold crystallloid cardioplegia (St. Thomas Hospital solution) was used for myocardial protection. The operative techniques are described in detail elsewhere. In brief, the David technique is performed as follows: after excision of the diseased sinuses, the end of the sized Dacron tube is trimmed to produce 3 separate, tongue-shaped extensions, which are fixed to the aortic annulus at the line of attachment of the cusps; this is followed by reimplantation of the coronary ostia (Figure 1). The Yacoub technique, in brief, is as follows: after excision of the diseased sinuses, the end of the sized Dacron tube is trimmed to produce 3 separate, tongue-shaped extensions, which are fixed to the aortic annulus at the line of attachment of the cusps; this is followed by reimplantation of the coronary ostia (Figure 1). No reduction annuloplasties were performed, except for 1 in a patient with Marfan syndrome who needed plication of the intervalvular trigone between the noncoronary and left coronary sinus.

Echocardiographic Data Acquisition and Measurements

Echocardiograms were performed on a Hewlett Packard Sonos 2500 system with 2.5- and 5.0-MHz ultrasound transducers during routine follow-up investigations. All patients underwent transthoracic and transesophageal echocardiography at rest. Examinations were performed with the patients in the left lateral decubitus position. A modified ECG lead I was continuously recorded. Blood pressure was measured by cuff sphygmomanometry (Dinamap, Siemens). Echocardiographic measurements were performed while blood pressure was constant.

Root dimensions and valve-motion parameters were determined by 2 independent observers from video-recorded studies, and the average value of 5 consecutive beats in sinus rhythm was taken.

To evaluate the reproducibility of the echocardiographically determined aortic root diameters at base, sinus, and commissural levels, 3 patients were studied twice using transesophageal echocardiography within a period of 10 days. The range of variation of the sequentially measured diameters was 0% to 2.9%.

Two-Dimensional Echocardiography

First, the morphology of all 3 aortic cusps was examined in standard longitudinal and cross-sectional views. Then, the diameters of the aortic root at the level of the annulus, the sinuses of Valsalva, and the commissures were determined transesophageally by using the leading edge method, as described by Roman et al.15

By definition, the annulus level was circumscribed by the nadir hinge points of the aortic cusps, the sinus level was the largest root diameter between the annulus and the supraaortic ridge, and the commissural diameter was measured at the distal rim of the sinuses of Valsalva.

Measurements of diameters were made perpendicular to the long axis of the aorta in views showing the largest and smallest dimensions during 1 cardiac cycle. Left ventricular end-systolic and end-diastolic volumes were obtained from standard apical 4-chamber views. Diastole was defined as the beginning of the QRS complex on the simultaneous ECG recording. Left ventricular outflow tract diameter was obtained by freeze frame at maximum aortic valve leaflet opening in systole.

M-Mode Echocardiography

Tracings were recorded from transesophageal views at 100 mm/s paper speed on a strip chart and magnified. The purpose of these recordings was to analyze the intermittent systolic contact of an aortic cusp and the aortic wall, as well as the opening and closing movements of the aortic leaflets, as defined in Figure 2. Only views with the leaflet coaptation at the midline of the aortic root and a symmetrical configuration of the echocardiographic appearance of the valve motion pattern were analyzed.

Continuous-Wave and Pulsed-Wave Doppler

Maximum velocities across the aortic valve were obtained by continuous-wave Doppler using the apical 5-chamber view showing the aorta and left ventricular outflow tract. With pulsed-wave Doppler, the sample volume was placed just below the aortic leaflets and recorded at 0.5-cm intervals to the midventricular level, where the drop-off of aortic velocities occurred, to measure velocities and velocity time integrals in the left ventricular outflow tract. Pulsed-wave Doppler was also used for mapping the left ventricular outflow tract to assess aortic regurgitation.
Resting coronary artery blood flow velocity was determined by pulsed-wave Doppler exploration of the anterior descending coronary artery. The resting systolic and diastolic coronary flow velocity time integrals, defined as the area under the curve during systole and diastole, were measured. The ratio of resting systolic to diastolic velocity time integrals was then calculated.

Color-Flow Doppler

Aortic regurgitation was assessed by color-flow Doppler techniques in the standard transthoracic and transesophageal views and graded as follows using the ratio of jet height/left ventricular outflow tract height: ratio of 1% to 24%, Grade I; 25% to 46%, Grade II; 47% to 64%, Grade III; and 65%, Grade IV.

The following items were calculated with the indicated formulas.

Cardiac output (CO) was calculated using:

$$CO = HR \times SV$$

where HR indicates heart rate, and SV, stroke volume, which was calculated as follows:

$$SV = VTI \times (D/2)^2 \times \pi$$

where VTI indicates velocity time integral in the left ventricular outflow tract, and D, the diameter of the left ventricular outflow tract.

Ejection fraction (EF) was calculated as follows:

$$EF = \frac{EDV - ESV}{EDV} \times 100$$

where EDV and ESV indicate the end-diastolic and end-systolic volumes of the left ventricle, calculated according to the modified Simpson’s rule.

Peak systolic pressure gradient across the aortic valve (Δp) was calculated as follows:

$$\Delta p = 4V^2$$

where V indicates the peak systolic velocity across the aortic valve. Percent change in radius (PCR) was calculated using the following:

$$PCR = (\Delta R \times 100)/R$$

where ΔR indicates the difference between the largest and smallest diameter, and R, the average diameter.

Pressure strain elastic modulus (PSEM) was calculated as follows:

$$PSEM = (\Delta P \times R)/\Delta R$$

where ΔP is the difference between systolic and diastolic blood pressures.

Slow closing displacement (SCD) of leaflets was calculated using the following:

$$SCD = \frac{D_1 - D_2}{D_2} \times 100$$

where D1 indicates the maximal leaflet displacement, and D2, leaflet displacement before rapid valve closing (Figure 2).

Statistical Analysis

Data are given as mean±SD. To compare the continuous data of different groups, the H test according to Kruskal-Wallis was used. If significantly different, a Mann-Whitney ranked sum test (U-test) was applied. According to Bonferroni’s method for multiple pairwise tests, a 2-tailed P<0.016 (0.05/3) was considered significant. Relative frequencies were analyzed using the χ² test. Statistics were performed using statistical software (SPSS for Windows 6.0, SPSS Inc).

Results

No early or late deaths occurred in this series during the follow-up period of 2 to 42 months (mean, 13.7±11.6 months). No endocarditis or thromboembolic events occurred. No patient was on oral anticoagulants or antiplatelets. All patients were in New York Heart Association Class I at the latest follow-up. Clinically, all patients were judged to have good valve function throughout the follow-up period.

Heart rate, stroke volume, cardiac output, ejection fraction, blood pressure, and the transvalvular aortic pressure gradient were comparable in the 3 groups (Table 2).

A total of 50% of patients in group A (David procedure) and 70% of patients in group B (Yacoub procedure) had no aortic regurgitation. None of the patients had more than grade I aortic regurgitation. No calcifications, vegetation, or areas of thickening were observed on any leaflet.

Valve Opening and Closing Characteristics

Three distinct phases of aortic valve movement were observed: a rapid valve opening, a slow systolic closure, and a
Figure 3. Diagram of 3 distinct phases of aortic valve motion pattern derived from mean values of measured data. Note faster opening and reduced slow systolic closure in group A.

rapid valve closing movement (Figures 2 and 3 and Table 3). Valve opening and closing characteristics were largely similar in groups B and C (Figure 3, Table 3). The rapid opening of the valve in these groups was smooth, with a similar average speed of 27.1 cm/s in group B and 20.9 cm/s in controls. Maximal opening of the valve was achieved 14.5 ms later, on average, in controls compared with group B patients. Valve displacement was 21.1 mm smaller in group B than in group C (23.1 mm).

In contrast, the valves in group A opened faster, with an essentially increased speed of 58.3 cm/s and a shorter time (23.0 ms) for maximal opening. Valve displacement (Table 3) was largest (26.0 mm) in this group of patients.

The duration of valve opening as expressed as ejection time was shortest in group B. The decrease of valve displacement was largest (26.0 mm) in this group of patients.

Valve opening and closing characteristics were largely similar in groups B and C (Figure 3, Table 3). The rapid opening of the valve in these groups was smooth, with a similar average speed of 27.1 cm/s in group B and 20.9 cm/s in controls. Maximal opening of the valve was achieved 14.5 ms later, on average, in controls compared with group B patients. Valve displacement was 21.1 mm smaller in group B than in group C (23.1 mm).

Discussion

Coronary Artery Blood Flow Velocity

A biphasic pattern of coronary blood flow velocity in the left anterior descending coronary artery at rest with a greater diastolic component (9.02 cm in group B, 8.63 cm in group A, and 9.98 cm in group C) and a smaller systolic component (3.1 cm in group A, 3.48 cm in group B, and 3.98 cm in group C) was recorded (Table 5). No significant differences in coronary artery flow velocity were observed in the 3 groups.

TABLE 3. Valve Opening and Closing Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Group A (n=10)</th>
<th>Group B (n=10)</th>
<th>Group C (n=10)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVOT, ms</td>
<td>23.0±9.5</td>
<td>43.0±11.6</td>
<td>57.5±11.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>D1, mm</td>
<td>26.0±3.4</td>
<td>21.1±3.5</td>
<td>23.1±1.3</td>
<td>0.019</td>
</tr>
<tr>
<td>RVOV, cm/s</td>
<td>58.3±18</td>
<td>27.1±10.9</td>
<td>20.9±4.2</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ET, ms</td>
<td>319±48</td>
<td>254±54</td>
<td>329±63</td>
<td>NS</td>
</tr>
<tr>
<td>SCD, %</td>
<td>3.8±1.6</td>
<td>10.8±2.2</td>
<td>12.5±6.6</td>
<td>0.001</td>
</tr>
<tr>
<td>RVCT, ms</td>
<td>58.5±10</td>
<td>31.5±8.8</td>
<td>39.5±5</td>
<td>0.001</td>
</tr>
<tr>
<td>D2, mm</td>
<td>25.0±3.5</td>
<td>18.9±2.9</td>
<td>20.5±2.4</td>
<td>0.006</td>
</tr>
<tr>
<td>RVCV, cm/s</td>
<td>21.8±3.5</td>
<td>32.4±11.4</td>
<td>26.3±5.6</td>
<td>NS</td>
</tr>
</tbody>
</table>

RVOT indicates rapid valve opening time; D1, maximal leaflet displacement; RVOV, rapid valve opening velocity; ET, ejection time; SCD, slow closing displacement; RVCT, rapid valve closing time; D2, leaflet displacement before rapid valve closing; RVCV, rapid valve closing velocity; and NS, not significant.
that are thought to be important for the smooth functioning of the aortic valve. These changes have 3 distinct phases: a rapid valve opening, a slow systolic closure, and a rapid valve closing movement.

Using transesophageal echocardiography in control subjects, we found a pattern of movement of the cusps and the aortic root similar to that observed by Thubrikar et al\textsuperscript{20,22} and Higashidate et al\textsuperscript{21} in animal models.

After root replacement with separate reconstruction of the sinuses (group B), we measured an opening velocity of 27.1±10.9 cm/s, which was similar to that of the controls (group C; 20.9±42 cm/s). The aortic root distensibility in group B was also comparable to controls, except for a distensibility of a 2.7% change in radius at the upper part of the sinuses. This restricted distensibility, however, did not affect valve opening and closing characteristics, which were largely normal in this group of patients. In contrast, the distensibility of the aortic root was reduced in group A, with a maximal change in the radius of 2.2% at all levels; in this group, the velocity of valve opening was significantly faster (57.3 cm/s). This might be explained by the fact that the aortic root cannot change its shape during the cardiac cycle, as was suggested by the work of Higashidate et al\textsuperscript{21}, Thubrikar et al\textsuperscript{20,22} and Sievers et al\textsuperscript{23}. These authors observed that the semilunar valves start to open, without any forward flow, only because of root expansion during the beginning of systole in animal models. This interaction between the root and the leaflets leads to a stellate orifice of the valve that

<table>
<thead>
<tr>
<th>TABLE 4. Aortic Root Distensibility</th>
</tr>
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<tbody>
<tr>
<td>Group A (n=10)</td>
</tr>
<tr>
<td>PCR annulus, %</td>
</tr>
<tr>
<td>PCR sinus, %</td>
</tr>
<tr>
<td>PCR commissures, %</td>
</tr>
<tr>
<td>PSEM annulus, g/cm²</td>
</tr>
<tr>
<td>PSEM sinus, g/cm²</td>
</tr>
<tr>
<td>PSEM commissures, g/cm²</td>
</tr>
</tbody>
</table>

PCR indicates percent change in radius; PSEM, pressure strain elastic modulus; and NS, not significant.
becomes circular with increasing blood flow velocity. Thus, a gradual, smooth opening movement of the valve is achieved, which reduces stresses on the leaflets.

Also, left ventricular ejection parameters might have influenced valve-opening velocities. In our series, the ejection time was lower in group B compared to group A and group C. In conjunction with an equal stroke volume, this would lead to more abrupt changes in the valve-opening motion, which is contrary to what we observed. This emphasizes the importance of repair techniques on cusp movement. Furthermore, we observed contact of the leaflets with the aortic wall only in group A patients. This could be due to the rapid leaflet displacement during opening or due to the lack of sinuses in group A; this is supported by the echocardiographic appearance of 3 separate sinuses in controls and in patients in group B (Figure 6). In this context, Bellhouse et al. reported that the fully opened cusps are normally accurately positioned between the sinus wall and the bloodstream, with the sinus vortex adjusting the sinus pressure to balance that on the aortic side of the cusps. The lack of sinuses in group A probably prevents this mechanism from operating and, consequently, contributes to leaflet contact. Another reason for this phenomenon could be the lack of space in the Dacron tube, leading to a redundancy of cusp tissue.

Bellhouse and Bellhouse reported, in an in-vitro study, that a valve in a straight tube without the closing forces of the sinus vortices would increase regurgitation considerably during closure. We were, however, not able to confirm these results; only grade I regurgitation, without significant differences between groups A and B, occurred.

In the second phase of valve movement, the degree of slow closing motion was 10.8±2.2% of maximal opening in group B, which is comparable to that of controls (12.5±6.6%). In group A, we measured a slow closing motion of only 3.8±1.6%. Again, the missing sinus vortices impair the ability of leaflets to begin to close before the onset of flow deceleration in these patients. Furthermore, the lack of internal forces, which are stored by the displacement of the cusps after root distension and which initiate valve closure during flow deceleration (as described for normal valves by Thubrikar et al.), could have contributed to the reduced slow systolic valve closure with reduced root distensibility in group A.

During the third phase of valve movement, we observed differences in the valve closing velocity between groups A (21.8±3.5 cm/s) and B (32.4±11.4 cm/s), although both values are not different from that of controls (26.3±5.6 cm/s). This rapid valve closure is determined by the radial thrust of the sinus vortices on the sinus surface of the leaflets during the deceleration phase of aortic blood flow, and it is then completed by the reversal of aortic flow. The lower speed for this movement in group A patients is probably also related to the lack of sinus configuration and, thus, the closing forces of sinus vortices to push the leaflets to the midline.

In addition, Bellhouse et al. reported that sinus vortices not only initiate valve closure but also promote coronary artery blood flow. In our series, differences between groups in coronary artery blood flow at rest could not be detected during systole or diastole. Whether this holds true for exercise conditions remains to be established.

**Limitations**

This study has several limitations. (1) It could be argued that the resolution of the ultrasound technique is not sufficient to define accurate instantaneous movements of the aortic root and the leaflets. However, possibly more accurate techniques, such as high speed cineradiography or electromagnetic induction, are not applicable to humans and could interfere with valve movement. The ultrasound technique used in this study operates at a 900-Hz sampling frequency, providing an interval between 2 consecutive signals of 1.1 ms, which we believe is adequate to define aortic root motion. In addition, the technique produced reproducible results. (2) The fact that the aortic root moves during measurement could induce errors. However, these errors would apply to all groups and, therefore, should not affect comparative results. (3) Another limitation relates to the significantly longer period of follow-up in group A than in group B (23.2±8.5 versus 4.1±1.8 months) and the fact that this was not a randomized study. However, the 2 groups were well matched with regard to patient demographics and the size of the Dacron tube used.

In conclusion, we demonstrated important differences in valve opening and closing characteristics after valve-sparing operations, depending on the particular technique used. The near-normal pattern of valve movement and the preserved distensibility after the Yacoub technique could reduce stress on the valve. This is supported by the study of Reis et al., who showed that increased flexibility of a stented semilunar valve results in marked reduction of the measured stress on the cusps. Whether the observed differences in valve movement and distensibility between the 2 groups will affect...
Figure 6. Echocardiographic appearance of cross-section through aortic root at sinus level. A, group A; B, group B; and C, group C. Note near-normal shape of sinuses of Valsalva in group B in comparison with group A.
long-term valve durability, cardiac performance, and patient survival remains to be evaluated.

Acknowledgment

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References

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