Fate of the Aortic Root Late After Ross Operation

Giovanni Battista Luciani, MD; Gianluca Casali, MD; Alessandro Favaro, MD; Maria Antonia Prioli, MD; Luca Barozzi, MD; Francesco Santini, MD; Alessandro Mazzucco, MD

Background—The Ross operation is an alternative to mechanical aortic valve replacement in the young. Early dilatation of the pulmonary autograft root exposed to the systemic circulation has been reported. To define the prevalence of, risk factors for, and consequences of late autograft dilatation, outcome in all consecutive patients operated since May 1994 was reviewed.

Methods and Results—Ninety one patients, 77 males and 14 females, with at least 1 year of follow-up underwent cross-sectional clinical and echocardiographic examination. Age at operation was 27±10 years (range 6 to 49), and the indication was aortic regurgitation in 54 (59%) patients and bicuspid valve was present in 62 (68%). End-points of the study were freedom from autograft dilatation (root diameter >4 cm or 0.21 cm/m²), from (moderate) autograft regurgitation and from reoperation. Follow-up (4.0±1.9, range 1 to 8 years) autograft root diameters were anulus, 29±4 mm (18–39); sinus of Valsalva, 38±7 mm (24–53); sinotubular junction, 37±6 mm (23–54); and ascending aorta, 37±5 mm (27–54). Late autograft dilatation was identified in 31 (34%) patients and regurgitation in 13 (14%), 7 of whom had autograft dilatation. At 7 years, freedom from dilatation was 42±8%, freedom from regurgitation was 75±8%, and freedom from reoperation was 85±10%. Cox proportional hazard analysis identified younger age (P=0.05), preoperative sinus of Valsalva (P=0.02), root replacement technique (P=0.03), and absence of pericardial buttressing (P=0.04) as predictive of autograft dilatation, whereas female sex (P=0.002), follow-up sinus of Valsalva (P=0.003), and sinotubular junction diameter (P=0.02) as predictive of autograft regurgitation.

Conclusions—Autograft dilatation is common late after the Ross procedure, particularly in younger patients, in those with preoperative aortic aneurysm, and those having root replacement without support of anulus and sinotubular junction. Bicuspid aortic valve is not a risk factor. Significant autograft valve dysfunction affects a minority of patients, but it is more prevalent in those with autograft dilatation. (Circulation. 2003;108[suppl II]:II-61-II-67.)

Key Words: aneurysms ■ aorta ■ aortic valve ■ heart surgery ■ pulmonary valve

The pulmonary autograft was introduced in clinical practice as a substitute for the diseased aortic valve by Donald Ross in 1967.1 The original implant technique, namely subcoronary freehand grafting, was associated with substantial prevalence of early and late valve dysfunction, thereby limiting widespread adoption of the operation. More recent experience with pulmonary autografts used for complete or partial aortic root replacement allowed for satisfactory functional behavior of the valve.3 The ability to promptly obtain a fully competent graft and to more easily reproduce the operation explains the increasing popularity that the Ross procedure subsequently witnessed. The long-term fate of the pulmonary autograft when used as free-standing root or inclusion cylinder is largely unknown, particularly in adult patients. Concern has been growing over reports of progressive autograft root dilatation and valve dysfunction.4–9 However, the exact magnitude of the phenomenon and its clinical consequences are still matter of controversy.10–13 The present study was undertaken to define the prevalence of and risk factors for autograft root dilatation late after operation, and the relation, if any, with valve dysfunction.

Patients and Methods

Patients

From May 1994 to May 2002, 92 consecutive patients undergoing the Ross operation at our institution with at least 1 year of clinical and echocardiographic follow-up were identified. Demographic data are reported in Table 1. During the same time interval, a total of 98 patients underwent the Ross operation, with 1 (1%) operative death as a result of coronary complication.

Operative Techniques

Three operative techniques were used to implant the autologous pulmonary valve in aortic position (Table 1). Subcoronary freehand valve grafting was mostly applied during the early stage of the experience, followed by freestanding complete aortic root replacement and cylinder inclusion (mini-root) replacement. The latter two techniques currently represent the techniques of choice, root replacement being preferred in children (<18 years) and inclusion cylinder preferred in adults. Operations were performed with the aid of
TABLE 1. Demographic and Operative Data

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Mean±SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td>91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male/Female</td>
<td>77/14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>27±10</td>
<td>6–49</td>
<td></td>
</tr>
<tr>
<td>BSA (m²)</td>
<td>1.8±0.2</td>
<td>1.3–2.3</td>
<td></td>
</tr>
<tr>
<td>AR</td>
<td>54 (59%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS</td>
<td>12 (13%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS/AR</td>
<td>25 (28%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bicuspid valve</td>
<td>62 (68%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aortic aneurysm</td>
<td>18 (20%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prior aortic procedure</td>
<td>13 (14%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aortic crossclamp (minutes)</td>
<td>162±18</td>
<td>125–205</td>
<td></td>
</tr>
<tr>
<td>Cardiopulmonary bypass (minutes)</td>
<td>209±32</td>
<td>156–300</td>
<td></td>
</tr>
<tr>
<td>Root replacement</td>
<td>54 (59%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylinder inclusion</td>
<td>29 (32%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subcoronary grafting</td>
<td>8 (9%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Associated procedure</td>
<td>20 (22%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BSA indicates body surface area; AR, aortic regurgitation; AS, aortic stenosis.

moderately hypothermic (28°C) cardiopulmonary bypass, during a period of global myocardial ischemia. Myocardial protection was achieved by antegrade and retrograde cold (4°C) blood induction and maintenance cardioplegia with warm reperfusion. Approach to the aortic root was gained by a complete circumferential aortic transection 2 cm above the sinotubular junction. After inspection of the pulmonary valve, the autograft was harvested within a cylinder of right ventricular outflow tract. Subcoronary grafting, inclusion cylinder and freestanding root replacement were performed according to previously described techniques.1,3,5 Buttressing of inflow (anular) and outflow (ascending aortic) suture lines with strips of glutaraldehyde-fixed autologous pericardium was used during freestanding root replacement to improve hemostasis.1,6 This modification was abandoned after 1998, because it appeared irrelevant to postoperative bleeding. The right ventricular outflow tract was reconstructed with a cryopreserved pulmonary homograft in all but three patients, two of whom received an aortic homograft and one who received a porcine xenograft. Associated procedures were performed in 20 patients, including reductive tailoring aortoplasty in 16 and ascending aortic replacement in 2 patients all with aortic aneurysm, patch repair of membranous septal aneurysm in 1 patient and of atrial septal defect in 1 patient.

Echocardiographic Data and Measurements

All patients underwent transthoracic echocardiographic examinations at discharge and were scheduled on yearly basis thereafter. Because of the widespread geographic origin of patients, this program was inconstantly respected. For the latter reason and to eliminate interobserver variability, cross-sectional follow-up echocardiographic investigation was undertaken by the same experienced sonographer at our institution between June and August 2002 (mean follow-up 4.0±1.9, range 1 to 8 years). Transthoracic echocardiograms were performed with 2.5-MHz ultrasound transducers (Hewlett-Packard Sonos 2500 system) and recorded on VHS videotape. Average values of five consecutive beats were taken for dimensions and pressure gradients.

Two-Dimensional Echocardiography

Autograft dimensions were measured as described by Roman et al15 at 4 different levels: (1) aortoventricular junction (aortic anulus), at the level of the autograft leaflet hinges; (2) sinus of Valsalva, at the largest anteroposterior diameter; (3) sinotubular junction, at the distal rim of the sinuses of Valsalva; (4) proximal ascending aorta, 2 cm above the sinotubular junction. Because of the recognized tendency of autograft root to remodel after implant,4 the sinus of Valsalva and the sinotubular junction often assumed similar dimensions. In these cases, the sinus portion was arbitrarily measured 2 cm above the aortic anulus, the sinotubular junction 2 cm above the sinus and the ascending aorta 2 cm above the sinotubular junction. Measurements of diameters were made in the parasternal long-axis view of the aorta at end-diastole. Left-ventricular-aortic junction was measured by freeze-frame at the maximum aortic valve leaflet opening in systole. Diastole was defined as the beginning of the QRS complex on the simultaneous ECG recording.

Continuous-Wave, Pulsed, and Color-Flow Doppler

Aortic regurgitation was assessed by multiple techniques with the apical 5-chamber view: pulsed wave Doppler and color-flow Doppler imaging were used for mapping the left ventricular outflow tract, including determination of ratio of jet height to left ventricular outflow tract height; continuous Doppler imaging was applied to measure the deceleration slope and pressure half-time of the aortic regurgitant jet. Aortic insufficiency was graded with the use of standard criteria.16

Clinical Follow-up

All 91 patients (100%) were assessed by means of direct physical examination at our clinic between June and August 2002, in conjunction with echocardiographic evaluation.

Statistical Analysis

Categorical variables are reported as absolute numbers and percentage. Continuous variables are expressed as means±SD. Comparison of continuous variables was performed using the two-tailed Student t test for paired data and comparison of discrete using Pearson chi-squared test or Fisher exact, as appropriate. Time-related events were described using the Kaplan-Meier estimate. End-points of the study were survival, freedom from autograft dilatation (root diameter >4 cm or 0.21 cm/m² at any of the 4 levels examined), freedom from moderate or greater autograft regurgitation, and freedom from reoperation on the autograft. Multivariate analysis was performed using Cox proportional hazard method to identify risk factors for time-related occurrence of autograft dilatation and autograft regurgitation. Variables entered in the analysis included age, gender, body surface area, diagnosis (regurgitation, stenosis, mixed), bicuspid aortic valve, prior aortic procedure, operative technique (subcoronary, cylinder inclusion, root replacement), use of pericardial strip buttressing, associated procedure, length of follow-up, and preoperative and postoperative diameters of aortic anulus, sinus of Valsalva, sinotubular junction, and ascending aorta. Significance was inferred at a probability value <0.05.

Results

Survival and Cardiovascular Events

During follow-up, there was 1 sudden death at home 13 months after operation in a patient with moderate autograft regurgitation at latest echocardiographic evaluation. The overall survival was 99±1% at 1 and 98±2% at 5 and 7 years. No adverse cardiovascular events, other than reoperation on the autograft as described below, were recorded in any of the patients during follow-up, including congestive heart failure, myocardial ischemia, hemorrhage, thromboembolism, and endocarditis. Eighty nine patients (99%) are New York Heart Association class I and all have resumed normal lifestyles, including regular schooling (children and adolescents) or employment (adults).
**Autograft Dilatation**

Overall aortic root diameters showed only slight increase at follow-up when compared with preoperative values (left ventricular-aortic junction: 27±5 versus 29±4 mm; sinus of Valsalva: 35±8 versus 38±7 mm; sinotubular junction: 34±8 versus 37±6 mm; ascending aorta: 36±8 versus 37±5 mm). However, when the results were stratified according to operative technique, patients receiving freestanding root replacement demonstrated significant increase at all aortic root levels (Table 2). In this subset of patients, remodeling of the aortic root with equalization of sinus of Valsalva, sinotubular junction and ascending aortic dimensions was an almost uniform finding, as evident in Table 2. On the contrary, in patients undergoing the cylinder inclusion technique significant decrease in diameter at the sinus of Valsalva (40±8 versus 35±6 mm, *P*=0.01) and ascending aorta (42±8 versus 34±5 mm, *P*=0.002) level was identified (reverse remodeling). Thirty one patients (34%) showed significant aortic root dilatation: in 4 (4%) patients root diameters were compatible with aortic aneurysm (5.0 to 5.5 cm), which would ordinarily be dealt with by elective resection. Freedom from root dilatation was 99±1%, 65±7%, and 42±8% at 1, 5, and 7 years, respectively (Figure 1). Progression of dilatation could only be analyzed in a subset (n=44) of institutional patients who had longitudinal echocardiographic examination. Significant increase in follow-up ascending aortic diameter when compared with discharge value was shown in the overall population (35±4 versus 37±5 mm, *P*=0.002); this change was entirely because of an increase in patients having the root replacement technique (36±5 versus 38±6 mm, *P*=0.001). Univariate analysis showed younger age, larger preoperative dimensions of aortic root, use of root replacement technique, absence of pericardial strip buttressing, and length of follow-up (*P*=0.02) to be predictive of late autograft dilatation. All but the latter proved significant at multivariate analysis (Table 3). Accordingly, prevalence autograft dilatation at follow-up in patients presenting with preoperative aortic aneurysm was significantly higher than in patients without aneurysm (11/18=61% versus 20/73=27%, *P*=0.007).

**Autograft Dysfunction**

Autograft valve regurgitation was found in 13 (14%) patients. This appeared early in three patients, one each having subcoronary, cylinder inclusion, and root replacement operation. Because of the timing and progression of regurgitation, dysfunction was attributed to technical cause. Late dysfunction was identified in 10 patients, 9 with moderate and 1 with

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**TABLE 2. Preoperative and Follow-up Aortic Root Dimensions in Patients Undergoing Pulmonary Autograft Root Replacement**

<table>
<thead>
<tr>
<th></th>
<th>Preoperative</th>
<th>Follow-up</th>
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<tbody>
<tr>
<td></td>
<td>Mean±SD Range</td>
<td>Mean±SD Range</td>
</tr>
<tr>
<td>LV-Ao junction (mm)</td>
<td>27±4 17–40</td>
<td>29±4 18–39</td>
</tr>
<tr>
<td>LV-Ao junction index (mm/m²)</td>
<td>15±2 10–23</td>
<td>16±3 10–27</td>
</tr>
<tr>
<td>Sinus Valsalva</td>
<td>33±7 22–58</td>
<td>39±7 24–55</td>
</tr>
<tr>
<td>Sinus Valsalva index</td>
<td>17±3 10–27</td>
<td>21±3 12–32</td>
</tr>
<tr>
<td>Sinotubular junction</td>
<td>33±7 21–55</td>
<td>38±6 23–54</td>
</tr>
<tr>
<td>Sinotubular junction index</td>
<td>17±3 11–27</td>
<td>21±3 15–31</td>
</tr>
<tr>
<td>Ascending aorta</td>
<td>34±7 21–55</td>
<td>38±6 27–55</td>
</tr>
<tr>
<td>Ascending aorta index</td>
<td>18±3 13–27</td>
<td>20±3 14–29</td>
</tr>
</tbody>
</table>

LV-Ao indicates left ventricular-aortic.

*Figure 1. Actuarial freedom from autograft dilatation in long-term survivors after Ross operation. Error bars represent±SD values. Patients at risk are reported over the y-axis.*
severe autograft insufficiency. Seven of 13 (54%) patients with dysfunction had root dilatation at follow-up: 6 of 10 (60%) with late dysfunction had evidence of root dilatation. Freedom from hemodynamically relevant autograft regurgitation was 96\%/110062%, 85\%/110065%, and 75\%/110068% at 1, 5, and 7 years, respectively (Figure 2). Risk factors for late autograft dysfunction disclosed at univariate and Cox proportional hazards analysis included female sex, preoperative sinus of Valsalva diameter, follow-up sinus of Valsalva, and ascending aorta diameter (Table 4).

Reoperation
During follow-up, reoperation on the autograft was carried out on four patients (4%), two of whom had two procedures each. All three patients with suspected technical cause of graft dysfunction were eventually reoperated. Briefly, attempt at autograft root repair was done in two patients, who had undergone subcoronary grafting and full root replacement. Because of progression of valve insufficiency both patients subsequently required mechanical aortic valve replacement. A third patient having cylinder inclusion underwent repair of root false aneurysm causing severe regurgitation. The fourth patient required replacement of the aortic root for progressive insufficiency because of severe root dilatation. All patients survived reoperation. In conclusion, only one of seven patients with valve dysfunction as a result of root dilatation required reintervention. Three patients with root diameters in excess of 5.0 cm, but without evidence of severe regurgitation, were managed conservatively. Actuarial freedom from reoperation on the autograft was 98±2%, 96±3%, and 85±10% at 1, 5, and 7 years, respectively.

**Discussion**
After reports suggesting improved functional outcome of the Ross procedure with the root replacement technique when compared with subcoronary grafting,2,3 the operation became increasingly popular. Negligible valve-related morbidity, freedom from chronic anticoagulation, ability to accommodate growth and, most importantly, scarcity of alternative treatment options make it a valid therapeutic modality in the infant and child with aortic valve disease or complex left heart obstruction.3,17 Because of the excellent quality of life associated with the Ross operation,3,14 adoption of the procedure in adult and, sometimes, elderly patients with isolated aortic valve disease has increased. Because valid treatment options in this age group are many, some well-established, close scrutiny of adverse events associated with the Ross procedure is mandatory. Indeed, it has become apparent that prevalence of pulmonary homograft obstruction may be significant.18 In addition, reports of early and late dilatation of the autograft root are also gathering.4–13

The present study confirms that the Ross procedure is a safe treatment modality for the child and young adult with isolated valve disease and that it allows normal quality of life. However, the current work provides evidence that neo-aortic (ie, autograft) root dilatation is a common phenomenon late after the Ross operation, because it may affect nearly one-third of patients. Furthermore, incidence of autograft valve regurgitation increases with time and is more prevalent in patients with root dilatation.

**Autograft Dilatation**
Dilatation of the autograft has been reported with increasing frequency by several authors and it is likely the most common

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**TABLE 3. Risk Factors for Autograft Dilatation**

<table>
<thead>
<tr>
<th>Cox proportional hazard</th>
<th>Beta factor</th>
<th>Standard Error</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>-0.07</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Preoperative sinus Valsalva diameter</td>
<td>0.24</td>
<td>0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>Root replacement technique</td>
<td>2.80</td>
<td>1.27</td>
<td>0.03</td>
</tr>
<tr>
<td>Pericardial strip buttressing</td>
<td>-2.61</td>
<td>1.33</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**TABLE 4. Risk Factors for Autograft Dysfunction**

<table>
<thead>
<tr>
<th>Cox proportional hazard</th>
<th>Beta factor</th>
<th>Standard Error</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex (female)</td>
<td>3.51</td>
<td>1.14</td>
<td>0.002</td>
</tr>
<tr>
<td>Preoperative Sinus Valsalva diameter</td>
<td>0.34</td>
<td>0.16</td>
<td>0.04</td>
</tr>
<tr>
<td>Follow-up Sinus Valsalva diameter</td>
<td>0.63</td>
<td>0.21</td>
<td>0.003</td>
</tr>
<tr>
<td>Follow-up sinotubular junction diameter</td>
<td>0.77</td>
<td>0.32</td>
<td>0.02</td>
</tr>
</tbody>
</table>

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![Figure 2. Actuarial freedom from autograft dysfunction (moderate or greater valve regurgitation) in long-term survivors after Ross operation. Error bars represent±SD values. Patients at risk are reported over the y-axis.](image-url)
problem after the Ross procedure.\textsuperscript{4–13} Prevalence rates vary according to definition of significant dilatation (generally 4.0 cm or greater), methods used to identify it (one or more levels of the left ventricular outflow tract), technique used for operation, and duration of follow-up. The estimate found in the present study is greater than what originally reported by David and co-workers,\textsuperscript{7} however, it correlates well with recent observations by Simon-Kuplik and associates,\textsuperscript{13} who found a 7 year freedom from dilatation of 45%. In addition, absolute values of aortic root diameters at the aortic anulus and sinus of Valsalva level measured herein are perfectly concurrent with prior experience with autograft root replacement by Hokken, Carr-White, Simon-Kuplik, Elkins, and their associates.\textsuperscript{11–13,19} Although attention has been generally dedicated to aortic anulus and sinus portion, the present study shows that diameters at the sinotubular junction and proximal aortic level tend to equalize with the sinus of Valsalva, thereby realizing a root remodeling process. The phenomenon has been recognized before by others,\textsuperscript{5,12} albeit to a lesser extent, and it is most prominent in patients undergoing fee-standing root replacement. Practically, it results in loss of sinotubular junction and it imposes arbitrary definition of left ventricular outflow tract levels, when using echocardiographic imaging. Root dilatation seems to be a time-dependent event, therefore progressive, in agreement with previous work.\textsuperscript{5,7,11,13} In the present study, it was possible to demonstrate progression only in a subset of patients. However, very few are the studies with multiple echocardiographic observations. In fact, progression of autograft root dilatation has been challenged by studies reporting periodic ultrasound examinations.\textsuperscript{12}

In the series reported herein, younger age at operation is a risk factor for root dilatation. Possible explanations for this finding include wider adoption of root replacement technique, greater likelihood of geometric mismatch of aortic and pulmonary roots, and physiological dilatation (ie, root growth) in children undergoing the Ross operation.\textsuperscript{3,4} The latter hypothesis is supported by the relatively low prevalence of autograft insufficiency in the face of high prevalence of dilatation and by the observation of similar behavior of the autologous pulmonary root late after neonatal repair (arterial switch, Damus-Kaye-Stansel, or Norwood operations) of complex congenital lesions.\textsuperscript{20} Preoperative aneurysm of the aortic root or ascending aorta appears to be a risk factor for late autograft root dilatation. This observation has been previously reported by Elkins and colleagues\textsuperscript{4} and it has led to modification of the Ross operation to accommodate for associated aortic pathology.\textsuperscript{19} The results reported thus far, including the ones herein using reductive aortoplasty, appear suboptimal because late dilatation has proved more common among patients with preoperative aortic aneurysm. Therefore, ascending aortic replacement with vascular grafts seems advisable in the presence of coexistent aortic aneurysm. This should allow fixation of sinotubular junction and prevention of distal root dilatation. In addition, use of root replacement technique in this anatomic setting may be undesirable. In fact, the latter proves to be the third independent risk factor for late root dilatation after operation, in agreement with other authors.\textsuperscript{5,13} Although freestanding root replacement has turned the Ross procedure into a readily reproducible and successful operation, it may have altered the original physiological assumptions of Donald Ross.\textsuperscript{1} Accordingly, negligible prevalence of root dilatation and stability over time has been shown late after autograft implantation using the subcoronary technique.\textsuperscript{21} Nonetheless, impact of surgical learning curve remains substantial and competence of the autograft is often suboptimal, as originally reported by Chambers,\textsuperscript{2} even nowadays.\textsuperscript{22} Based on the present experience, as well as on the work of others,\textsuperscript{5} our institutional preference has since shifted toward cylinder inclusion or mini-root technique. Although geometric matching of aortic and pulmonary root may be critical and subtle differences may translate into autograft dysfunction, as attested by the case of aortic root false aneurysm herein, this technique associates reproducibility with potential protection from late dilatation. Whether the retained native aortic root also may be subject to progressive dilatation, particularly in bicuspid valve patients, remains highly speculative. Quite unexpectedly, a technical modification initially conceived to control postoperative hemorrhage after free-standing root replacement, namely buttressing of anular and ascending aortic suture lines with autologous pericardial strips, has proved to be protective against late dilatation. Therefore, in cases in which the inclusion technique may not be advisable (children, root mismatch), some form of support of anulus and sinotubular junction should be associated to freestanding root replacement. Finally, the present study confirms preliminary clinicopathologic work from our institution,\textsuperscript{23} and the clinical experience of others,\textsuperscript{7,12,13,21} showing no correlation between bicuspid aortic valve disease and increased prevalence of late root dilatation in Ross patients.

**Autograft Dysfunction and Reoperation**

Autograft valve dysfunction leading to regurgitation increases with time, though it affects a minority of patients 8 years after operation. This suggests that durability of the autograft may be limited, similar to observations made with aortic homografts.\textsuperscript{22} Prevalence of moderate or greater valve regurgitation is infrequently reported in previous series, because reoperation on the autograft is a more widely used end-point. In a recent multicenter review of the Dutch experience with the Ross operation, significant dysfunction was identified in nearly 10% of long-term survivors.\textsuperscript{6} Progressive appearance of moderate or greater valve insufficiency was also documented in up to 14% of patients 5 years after surgery by Briard and associates.\textsuperscript{24} Both results are in agreement with the results observed herein. Lower prevalence of dysfunction, however, has been reported by others.\textsuperscript{5,12,13,21} Actuarial freedom from dysfunction appears concerning in our series, though it lends support to prior estimate of 77% at 7 years by Dossche and colleagues.\textsuperscript{25}

The present work suggests that follow-up aortic root dilatation is associated with increased prevalence of autograft dysfunction at follow-up. Interestingly, both dilatation of sinus of Valsalva and of sinotubular junction are independently correlated with this event. This result is original and at variance with previous observations by David, Hokken, Carr-White, Simon-Kuplik, and associates,\textsuperscript{5,11–13} postulating...
that dilatation of the sinus of Valsalva does not cause valve insufficiency per se. Explanations for the findings herein include demonstration that the neoaortic root undergoes extensive remodeling late after operation. Therefore, loss of sinotubular junction and autograft root remodeling, in addition, although moderate degrees of dilatation (less than 5 cm) may be accommodated by the autograft valve, root aneurysm formation, as occasionally observed in our series, results in flattening and over-stretching of valve leaflets causing insufficiency. Preoperative sinus of Valsalva dimension is also associated with late autograft dysfunction. The correlation between preoperative and follow-up aortic root aneurysm identified above may account for this finding. The significance of female sex as incremental risk factor for valve regurgitation remains elusive, but it is likely a spurious association.

Freedom from reoperation in the present series is in line with prior work by David, Takkenberg, Willems, and associates, with estimates between 92% and 95% at 5 years and between 88% and 91% at 7 years. It must be emphasized that replacement of the autograft valve was clearly correlated to progressive root dilatation only in one of four patients undergoing reoperation. However, the observation that other six patients with progressive dilatation also have moderate regurgitation casts serious doubts on the long-term performance of the autograft. During the study period, we elected not to intervene on patients with root dilatation, even severe (greater than 5 cm), until concomitant severe valve insufficiency appeared. The rationale was that mechanical valve or composite root replacement, as needed, have proved a worse long-term treatment than autografts or homografts in adolescents and young adults in our experience. However, as failures of Ross procedure because of root dilatation are increasingly reported, anecdotal experience with aortic root replacement with autograft valve preservation using the Yacoub or the David technique is gathering. Accordingly, indication to autograft root aneurysm resection may need to be reconsidered and possibly advanced to patients with diameters in excess of 5 to 5.5 cm before severe regurgitation appears to successfully preserve the pulmonary valve.

Clinical Implications
Because root dilatation and autograft dysfunction seem to be progressive events, life-long periodic echocardiographic assessment is advised. Use of the cylinder inclusion technique is suggested in adults undergoing the Ross procedure. When concomitant ascending aortic aneurysm is present, replacement of the aorta with a vascular graft is warranted. However, if freestanding root replacement is required because of geometric mismatch of aortic and pulmonary roots, support of the anulus and sinotubular junction with pericardium is strongly advised. Indication to elective resection of autograft root aneurysm should be advanced to patients with moderate regurgitation to increase likelihood of autograft valve preservation.

Study Limitations
The current study presents several limitations. As a result of loss of sinotubular junction and autograft root remodeling,

left ventricular outflow tract diameters were often arbitrarily defined. In addition, longitudinal echocardiographic evaluation, which would have allowed demonstration of progression of root and valve pathology, was possible in only one half of the patients. Cross-sectional rather than longitudinal evaluation had to be used instead. Further, adoption of the three different operative techniques was not concurrent nor randomized, but rather subsequent. Lastly, some techniques were preferentially used in certain patients (ie, root replacement in children, cylinder inclusion in adults).

Addendum
Since submission of the manuscript, two additional patients who presented with root dilatation and autograft dysfunction at follow-up have undergone elective reoperation. The original procedure had been freestanding root replacement in both. One patient with sinus of Valsalva diameter of 6.3 cm and moderate valve insufficiency has received root remodeling with valve preservation. The other patient, with severe valve regurgitation and uniform aortic root dilatation of 4.7 cm, has undergone composite aortic root replacement. Thus far, a total of three of seven (43%) patients with valve dysfunction due to root dilatation have required reoperation.

References
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