Hemodynamic Performance at Rest and During Exercise After Aortic Valve Replacement: Comparison of Pulmonary Autografts Versus Aortic Homografts

Isabelle Laforest, MS; Jean G. Dumesnil, MD; Martin Briand, MS; Paul C. Cartier, MD; Philippe Pibarot, DVM, PhD

Background—The Ross procedure and aortic homografts have both been shown to have superior hemodynamic performance after valve replacement, but there have been few comparisons.

Methods—Sequential Doppler echocardiograms were performed up to 5 years after aortic valve replacement in 132 patients with the Ross procedure and 111 patients with an aortic homograft (AH). Measurements included assessment of valvular regurgitation and calculations of valve effective orifice area (EOA) and mean transvalvular gradients; the same measurements were also performed at the level of the pulmonary homograft in the Ross patients as well as during maximum exercise in 20 Ross patients and 14 AH patients.

Results—Aortic valve hemodynamics were stable during follow-up for both procedures and values at 1 year showed larger indexed EOAs (1.77±0.45 versus 1.42±0.35 cm²/m², P<0.001) and lower gradients (2±3 versus 4±3 mm Hg) for the Ross procedure; similar findings were also observed during exercise (1.99±0.44 versus 1.36±0.39 cm²/m², P<0.001 and 7±3 versus 17±11 mm Hg). Prevalence and severity of aortic regurgitation were low in both groups, although 4 patients (1 Ross, 3 AH) underwent a second operation for this reason. Also, various degrees of pulmonary homograft stenosis were found in 20% of Ross patients, 4 of which underwent a second operation.

Conclusion—Both procedures provide continued excellent hemodynamics of the aortic valve. The Ross procedure has a slight advantage, but this is somewhat counterbalanced by the deterioration of the pulmonary homograft in up to 20% of patients. Further studies aimed at clarifying longer-term outcomes as well as preventing pulmonary homograft stenosis with the Ross operation are clearly needed. (Circulation. 2002;106[suppl I]:I-57-I-62.)

Key Words: valves ▪ stenosis ▪ homograft ▪ hemodynamics ▪ echocardiography

Pulmonary autografts (Ross procedure) and aortic homografts have both been shown to have superior hemodynamic performance after valve replacement compared with bioprosthetic and mechanical valves.1–3 There have been few comparisons of these 2 valve substitutes with regards to their hemodynamic performance.4,5 Moreover, these previous studies report only gradients and not valve effective orifice areas (EOAs) and they do not contain any hemodynamic data obtained during exercise.

Therefore, the objective of this study was to compare the hemodynamics of pulmonary autografts and aortic homografts at rest and during exercise. Also, because the Ross operation is a double-valve procedure, we also assessed the hemodynamic performance of the pulmonary homograft implanted in the pulmonary position.

Methods

Patients

Two-hundred and forty-three patients were followed up to 5 years after aortic valve replacement with either the Ross procedure (132 patients; age 20 to 59 years, mean: 40±11 years) or an aortic homograft (111 patients; age 21 to 85 years, mean: 50±15 years). The preoperative and operative data are summarized in the Table 1. The aortic valve substitute was implanted as a root replacement in 70% of the Ross patients and 88% of the patients with an aortic homograft. In these patients, the substitute was sutured to the aortic root using horizontal mattress sutures without any banding of the suture line. The substitute was implanted as a valve replacement in all other patients, except 1 patient with an aortic homograft who underwent a second operation for this reason. Also, various degrees of pulmonary homograft stenosis were found in 20% of Ross patients, 4 of which underwent a second operation.

A subgroup of 20 patients with the Ross procedure and 14 patients with an aortic homograft were also evaluated during upright exercise. Some of the data from the patients with the Ross procedure have been reported previously.6,7

Doppler Echocardiographic Measurements

Examinations were performed early (7 to 30 days), 3 to 6 months, 1 year after operation, and annually thereafter, as described previously.8 The number of patients at follow-up was as follows: 132 in the...
TABLE 1. Preoperative and Operative Data in Ross Patients and Patients With an Aortic Homograft

<table>
<thead>
<tr>
<th></th>
<th>Ross (n=132)</th>
<th>Aortic Homograft (n=111)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Male</td>
<td>82 (62%)</td>
<td>73 (66%)</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>50 (38%)</td>
<td>38 (34%)</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>40±11</td>
<td>50±15</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>BSA (m²)</td>
<td>1.79±.23</td>
<td>1.78±.22</td>
<td>NS</td>
</tr>
<tr>
<td>NYHA classification</td>
<td></td>
<td></td>
<td>0.036</td>
</tr>
<tr>
<td>I–II</td>
<td>76 (57%)</td>
<td>48 (43%)</td>
<td></td>
</tr>
<tr>
<td>III–IV</td>
<td>56 (43%)</td>
<td>63 (57%)</td>
<td></td>
</tr>
<tr>
<td>Dominant valvar dysfunction</td>
<td></td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Aortic stenosis</td>
<td>62 (47%)</td>
<td>35 (32%)</td>
<td></td>
</tr>
<tr>
<td>Aortic regurgitation</td>
<td>20 (15%)</td>
<td>52 (47%)</td>
<td></td>
</tr>
<tr>
<td>Mixed aortic disease</td>
<td>50 (38%)</td>
<td>24 (21%)</td>
<td></td>
</tr>
<tr>
<td>Etiology</td>
<td></td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Congenital</td>
<td>99 (75%)</td>
<td>39 (35%)</td>
<td></td>
</tr>
<tr>
<td>Failed prosthetic valve</td>
<td>11 (8%)</td>
<td>13 (12%)</td>
<td></td>
</tr>
<tr>
<td>Senile degeneration</td>
<td>8 (6%)</td>
<td>9 (8%)</td>
<td></td>
</tr>
<tr>
<td>Infective endocarditis</td>
<td>8 (6%)</td>
<td>25 (23%)</td>
<td></td>
</tr>
<tr>
<td>Myxomatous</td>
<td>7 (6%)</td>
<td>11 (10%)</td>
<td></td>
</tr>
<tr>
<td>Rheumatic</td>
<td>6 (5%)</td>
<td>7 (6%)</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>–</td>
<td>8 (7%)</td>
<td></td>
</tr>
<tr>
<td>Surgical technique</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Root replacement</td>
<td>93 (70%)</td>
<td>98 (88%)</td>
<td></td>
</tr>
<tr>
<td>Valve replacement</td>
<td>39 (30%)</td>
<td>12 (11%)</td>
<td></td>
</tr>
<tr>
<td>Mini-root inclusion</td>
<td>–</td>
<td>1 (1%)</td>
<td></td>
</tr>
<tr>
<td>Concomitant CABG</td>
<td>8 (6%)</td>
<td>8 (7%)</td>
<td>NS</td>
</tr>
</tbody>
</table>

Data are expressed as mean±SD or number of patients and percentage. BSA: body surface area; NS: non significant.

Ross group and 111 in the aortic homograft group early after operation, 124 and 104 at 3 to 6 months, 106 and 83 at 1 year, 84 and 65 at 2 years, 65 and 47 at 3 years, 66 and 32 at 4 years, and 42 and 22 at 5 years, respectively. The mean transvalvular pressure gradient of the aortic and pulmonary valves was calculated using the modified Bernoulli equation. The valve EOAs were determined by the standard continuity equation using the left ventricular (LV) stroke volume for the calculation of both the aortic and pulmonary valve EOAs. Cardiac index increased similarly in both groups, the EOAs did not change during exercise but because gradients at rest were better in the Ross patients. In both groups, the EOAs were smaller in the aortic homografts and gradients are a square function of EOAs, gradients increased to a larger extent during exercise in the homograft patients.

Exercise Protocol
The exercise protocol as well as the parameters measured during exercise have been described previously in detail. In summary, the patients are submitted to a maximum ramp upright bicycle exercise test with continuous increments between 15 and 35 Watts/min depending on subject’s physical condition. A 12-lead ECG is continuously recorded, and blood pressure is measured every 2 minutes. The patients are encouraged to exercise until exhaustion or the appearance of symptoms. Doppler echocardiographic measurements are performed with the patient sitting on the bicycle at rest and at maximum exercise either immediately before stopping the test or within 2 minutes after test termination.

Statistical Analysis
Data are presented as mean±SD and compared using a two-way Analysis of Variance for repeated measures to evaluate the effect of group (Ross versus aortic homografts) and the effect of either time since operation or exercise. Values of P<.05 are considered significant.

Results
Preoperative and Operative Data
Table 1 shows patients characteristics in the 2 groups. Ross patients were younger and had higher prevalences of predominant valvar stenosis and bicuspid congenital valve.

Aortic Valve Function
Figure 1 compares the prevalence of valvar regurgitation in the 2 groups. Severe (4/4) regurgitation was not observed, whereas moderately severe (3/4) regurgitation was a rare occurrence. Nonetheless, 1 patient with the Ross operation and 3 patients with an aortic homograft had to undergo another surgery for this reason within the first 4 years. The prevalence of moderate (2/4) regurgitation increased progressively during follow-up in both groups. It went from 2% early after operation to 17% after 5 years in the Ross patients and from 3% to 10% in the aortic homografts during the same period; the difference was not statistically significant. In fact, the only statistically significant difference (P=0.02) between the 2 groups was a higher prevalence of mild (1/4) regurgitation in the Ross patients early after operation (39% versus 21%), but this difference disappeared at subsequent follow-up intervals.

Aortic valve hemodynamics at rest are given in Table 2. EOAs and gradients did not change during follow-up in both groups, although they were slightly but significantly better in the pulmonary autografts at each interval. Consistent with our previous report, there was no significant difference between the root replacement and the valve replacement techniques in regards to the postoperative valve EOAs and gradients and the prevalence of regurgitation.

Table 3 gives the results for the exercise studies that were performed in 20 Ross patients and 14 patients with an aortic homograft. There was no significant difference between these 2 subgroups in regards to age, sex distribution, New York Heart Association functional class, and valvar etiology. The prevalence of predominant aortic stenosis was higher in the Ross subgroup (85 versus 50%; P=0.012). At peak exercise, cardiac index increased similarly in both groups (mean=219%). As in the larger cohort, the EOAs and gradients at rest were better in the Ross patients. In both groups, the EOAs did not change during exercise but because EOAs were smaller in the aortic homografts and gradients are a square function of EOAs, gradients increased to a larger extent during exercise in the homograft patients.

Pulmonary Valve Function
Figure 2 provides a comparison of the hemodynamics between the pulmonary homograft implanted in the pulmonary position in the Ross patients and the aortic homograft implanted in the aortic position in the other group. Consistent with our previous report, the hemodynamics of the pulmonary homografts deteriorated early after operation with a 33% decrease in EOAs and a 193% increase in mean gradients being observed during the first 2 years after operation; this
finding contrasts markedly with the very stable hemodynamics observed in the aortic homografts (Table 2 and Figure 2). However, it should be noted that the pulmonary homografts do not deteriorate uniformly in all patients. Hence, if pulmonary stenosis is defined as a valve having an indexed EOA $\leq 0.85 \text{ cm}^2/\text{m}^2$, the prevalence at 1 year is 20%. Nonetheless, 4 patients (3%) had to undergo a second operation because of symptoms and/or significant right ventricular dysfunction in relation to severe pulmonary stenosis (indexed EOA $\leq 0.65 \text{ cm}^2/\text{m}^2$). In contrast, an indexed aortic valve EOA $\leq 0.85 \text{ cm}^2/\text{m}^2$ was found in only 4% of the aortic homografts, and none of these patients required more surgery.

Also noteworthy are the pulmonary valve hemodynamics during exercise in the Ross patients (Table 3). Compared with the native pulmonary valve in the aortic homograft patients, the Ross patients had significantly lower pulmonary valve EOAs and markedly higher mean gradients both at rest and during exercise.

### Discussion

#### Aortic Valve Function

As in previous studies, this study confirms the excellent hemodynamic performance of both pulmonary autografts and aortic homografts in the aortic position.\textsuperscript{1-11} Nonetheless, the pulmonary autografts had significantly better resting and exercise hemodynamics than the aortic homografts. These differences are not readily explained by the differences in baseline characteristics between the 2 groups (ie, younger age and higher prevalence of valvular stenosis in the Ross patients). A plausible explanation could be that the root and valve leaflets of the autografts probably have greater flexibility than the homografts. Indeed, the autografts are fresh, highly viable, and completely immunoprivileged tissues whereas the aortic homografts are cryopreserved, partially viable, and less biologically active tissues.

LV mass was not measured in this study but it is unlikely that the small differences in hemodynamic performance...
observed between pulmonary autografts and aortic homografts would translate into significant differences in terms of LV mass regression. Indeed, Del Rizzo et al.\textsuperscript{12} observed a more important decrease in LV mass index 3 years after operation in patients with an indexed EOA \( \geq 0.8 \text{ cm}^2/\text{m}^2 \) compared with patients with an indexed EOA \( \leq 0.8 \text{ cm}^2/\text{m}^2 \) (\(-23\% \) versus \(-4.5\%\)). On the other hand, no difference was noted between patients with an indexed EOA between 0.8 and 1.0 cm\(^2/\text{m}^2\) and those with an indexed EOA >1.0 cm\(^2/\text{m}^2\) (\(-24\% \) versus \(-22\%)\). In the present study, the proportion of patients with an indexed EOA \( \leq 0.85 \text{ cm}^2/\text{m}^2 \) was 4\% in the aortic homografts and 1\% in the pulmonary autografts. Accordingly, both valve substitutes had low pressure gradients and the results are consistent with our previous demonstration that resting and exercise gradients become more important only when the indexed EOA is \(< 0.8 \text{ cm}^2/\text{m}^2\).\textsuperscript{13}

The prevalence and severity of aortic regurgitation found in the present study were relatively low, with no significant difference between groups except for a relatively higher prevalence of mild (2/4) regurgitation early after operation in the Ross patients. Also, the progressive increase in the prevalence of moderate (2/4) valvular regurgitation observed during follow-up tended to be more important in the Ross patients (\(+14\% \) from early to 5 years after operation) than in the aortic homograft patients (\(+7\%\)). As reported in a previous study, dilatation of the pulmonary autograft after the Ross procedure may occur because of an intrinsic abnormality of the pulmonary root in patients with congenital aortic valve disease.\textsuperscript{14} Given that 75\% of the Ross patients included in the present study had a congenitally abnormal aortic valve, it is possible that this phenomenon might have contributed to the tendency to have a slightly higher incidence of moderate regurgitation in this group. However, although the difference was not statistically significant, the number of additional operations for moderately severe (3/4) was higher in the aortic homograft group (3 versus 1). Obviously, longer-term studies are necessary to determine whether the severity of regurgitation and the rate of additional surgeries increase after 5 years in these 2 groups.

In most patients included in this series, the aortic valve substitute was implanted as a root replacement. In this context, David et al.\textsuperscript{14,15} have recently suggested the use of prosthetic materials or tanned pericardium to buttress the suture line at the sinotubular junction to limit dilatation in that location and thus reduce late progression of aortic regurgitation.

### Pulmonary Valve Function

Several studies have reported relatively high gradients at the level of the pulmonary homograft after the Ross procedure. In these studies, the incidence of peak gradients \( > 20 \text{ mm Hg} \) was not statistically significant, the number of additional operations for moderately severe (3/4) was higher in the aortic homograft group (3 versus 1). However, the difference was not statistically significant, the number of additional operations for moderately severe (3/4) was higher in the aortic homograft group (3 versus 1). Obviously, longer-term studies are necessary to determine whether the severity of regurgitation and the rate of additional surgeries increase after 5 years in these 2 groups.

### Pulmonary Valve Function

Several studies have reported relatively high gradients at the level of the pulmonary homograft after the Ross procedure. In these studies, the incidence of peak gradients \( > 20 \text{ mm Hg} \) was
patients with the Ross operation is due to an immune rejection, an inflammatory reaction, or other unknown factors.

The fact that only pulmonary homografts but not aortic homografts appear to be affected by this immune and/or inflammatory reaction is intriguing and largely unexplained. It has been hypothesized that pulmonary homografts might be more likely to trigger an immune reaction than aortic homografts, but this is largely negated by studies reporting a higher incidence of short-term failure in aortic homografts compared with pulmonary homografts when both are implanted in the pulmonary position. Other hypotheses that have been proposed are the following: 1) the distinctive anatomical and physiological features of the right ventricular outflow tract could contribute to a more pronounced immune/inflammatory reaction because of lower intraluminal shear stress in the right ventricular outflow tract, thus facilitating the adhesion of leukocytes at the surface of the homograft endothelium; and 2) the nature and prevalence of the immune and/or inflammatory reaction would be the same for homografts implanted in either position, but it would have less consequences in the aortic position because the higher pressure regimen on the left side would lessen the shrinkage of the lumen due to the immune and/or inflammatory reaction.

**Conclusion**

Aortic homografts and the Ross operation both provide continued excellent hemodynamics in the aortic position. The Ross procedure appears to have a slight advantage, but this is counterbalanced by the occurrence of varying degrees of pulmonary stenosis in 20% of patients undergoing this operation to the extent that a small number have to undergo additional surgery for this reason. Further studies are clearly needed to clarify long-term outcomes as well as to better understand and prevent the deterioration of the pulmonary homograft with the Ross operation.

**Acknowledgments**

This work was supported by grants from the Heart and Stroke Foundation of Quebec, Montreal, the Fonds de recherche en santé du Québec, Montreal, and the Canadian Foundation for Innovation, Ottawa, Canada. Dr. Pibarot is the recipient of a research scholarship from the Heart and Stroke Foundation of Canada. We would like to dedicate this article to the memory of Dr. Paul C. Cartier, who unexpectedly died on January 2, 2001. We thank Jacques Ménas, MD, Daniel Doyle, MD, FRCP, FACS, and Patrick Mathieu, MD, FRCP, for their constructive comments; Louise Côté, RN, and Jacinthe Aubé, RN, for the clinical follow-up of the patients; and Jocelyn Beauchemin, RT, for his technical assistance.

**References**


Hemodynamic Performance at Rest and During Exercise After Aortic Valve Replacement: Comparison of Pulmonary Autografts Versus Aortic Homografts
Isabelle Laforest, Jean G. Dumesnil, Martin Briand, Paul C. Cartier and Philippe Pibarot

Circulation. 2002;106:I-57-I-62
doi: 10.1161/01.cir.000032912.33237.bc

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/106/12_suppl_1/I-57

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/