Conclusions—Aortic valve replacement with either a pulmonary autograft or an aortic homograft leads to a degree of impairment,7 this question may have important relevance for function has always been difficult.8 Recently, echocardiographic measurement of the longitudinal movement of the tricuspid annulus (RV long-axis movement or tricuspid annular plane systolic excursion [SE]) has been advocated as a simple, objective measure of RV free wall function that has been shown to correlate with both exercise tolerance9 and ejection fraction10 in patients with ischemic heart disease. This measure has additional importance due to the fact that unlike LV ejection, longitudinal rather than short-axis movement is the predominant mechanism for RV ejection.11 Although echocardiography is effective for the measurement of long-axis movement of the RV, it is acknowledged that other methods are necessary for more detailed assessments of RV volumes. Currently, MRI is accepted as the noninvasive gold standard for the measurement of RV volumes.8

The aim of this study was to assess RV function after pulmonary autograft surgery with a combination of echocardiographic RV long-axis measurements and MRI assessments...
of RV volumes. These measurements were repeated with a similar cohort of patients who were undergoing aortic homograft replacement as part of a prospective randomized trial, to allow a comparison with a group who had a similar biological valve implanted but in whom no surgical procedure was carried out on the right side of the heart. The study involved 2 phases: (1) RV long-axis measurements were obtained in patients before and after either pulmonary autograft or aortic homograft surgery and (2) postoperative comparisons were made of RV long-axis results and MRI RV volumes in a separate cohort of patients who had undergone either pulmonary autograft or aortic homograft surgery.

### Methods

#### Patient Selection

Twenty-five patients in phase I were studied before surgery and at 6 months (range 3 to 12 months) after surgery. Eighteen patients in phase II were studied at 18 months after surgery (range 6 to 35 months). Patient demographics and preoperative variables are given in Table 1. Local ethical committee approval was obtained before the study was started, and full informed consent was obtained from each patient.

#### Operative Technique

All operations were performed by the same surgeon (M.Y.). Cardiopulmonary bypass with moderate hypothermia (30°C) was used. In both groups, myocardial protection was achieved with either antegrade crystalloid or cold blood cardioplegia. All patients underwent aortic root replacement with coronary reimplantation. In the autograft group, the RV outflow tract was reconstructed with the use of...
a large homovital or antibiotic-sterilized pulmonary homograft conduit inserted with the use of continuous 4-0 sutures without the inclusion of strips of prosthetic or autologous tissue for support. These suture lines were performed before release of the aortic clamp.

Echocardiographic Measurements

Transthoracic echocardiograms were performed with a Hewlett Packard Sonos 500 or 2000 machine. An M-mode trace was obtained through the tricuspid annulus from the apical 4-chamber view and printed at a paper speed of 100 cm/s (Figure 1). This trace was then digitized offline with customized software that allowed the calculation of SE, lengthening rate (LR), and shortening rate (SR). In each case, 3 consecutive beats were analyzed and averaged.

MRI Measurements

Imaging was performed with a Picker 0.5-T whole-body system with the use of prospective ECG gating and a jacket receiver coil. Ventricular volume measurements were achieved by imaging the heart from apex to base with the use of contiguous 10-mm slices in the short-axis plane. A series of transthoracic cross-sectional images allowed identification of the mitral valve and the apex. The vertical long-axis plane was aligned from these images, and the horizontal long-axis (HLA) plane was located perpendicular to the vertical long-axis plane with maintenance of the LV axis passing through the center of the mitral valve and the apex. The short-axis plane was finally identified from the HLA plane, with the most basal imaging slice located just below mitral and tricuspid valve insertions (Figure 2). Subsequent slices were parallel to the basal slice and repeatedly offset by 10 mm toward the apex until the entire heart had been imaged, usually involving 10 to 14 slices. Each slice of the volumetric study consisted of a series of 12 to 16 frames throughout the cardiac cycle. The end-diastolic and end-systolic frames could be identified by running the frames in sequence as a cine loop (Figure 3). The endocardial borders were identified for the LV and RV, and the enclosed areas were measured with the use of online software. The total areas for diastole and systole were summed and multiplied by the slice thickness (10 mm) to obtain left and right end-diastolic and end-systolic volumes. Other MRI parameters include field of view of 350 to 400 mm, slice thickness of 10 mm, 96 to 128 phase encoding lines, 2 signal averages, and repeat times of ~45 ms to enable 12 to 16 images to be made per cardiac cycle.

Statistical Analysis

Statistical analysis was performed with a commercially available software package (SPSS Inc). A comparison between groups of demographic and preoperative or postoperative data was performed with the use of an unpaired t test. A comparison of data over time was made with the use of a 1-way ANOVA. A P value of <0.05 was accepted as significant.

Results

At the time of their postoperative echocardiographic or MRI investigations, 37 (86%) patients were in NYHA class I and 6 (14%) were in NYHA class II. No patients were in class III or IV. No patient had significant aortic or pulmonary valve dysfunction (defined as more than mild valvular regurgitation or a peak transvalvular gradient of >30 mm Hg). Aortic cross-clamp times were significantly higher for the autograft group than for the homograft group (mean ± SD, 110 ± 20 versus 81 ± 17 minutes, P < 0.001).

Both preoperative and postoperative indices of RV function were analyzed according to whether the preoperative pathology was aortic regurgitation or stenosis. Analysis of patients with pure aortic stenosis or regurgitation preoperatively demonstrated no significant differences between the 2 groups (Table 2); therefore, the autograft and homograft groups were not further subdivided according to preoperative type of lesion.
Although phase 1 patients were studied at a mean interval of 6 months after surgery and phase 2 patients were studied at a mean interval of 18 months after surgery, the time period of analysis was wide (3 to 12 months for phase 1 and 6 to 35 months for phase 2). Therefore, in a subset of 7 patients for whom regular and extended follow-up was available, RV SE was analyzed at 6 weeks and 6, 12, and 24 months after surgery (Table 3). The postoperative depression in RV function did not alter according to time since surgery over this period. Given that only 1 patient was studied outside this time frame, this suggests that changes in postoperative RV function over time should not bias the results, despite the wide time range of analysis.

Phase I
In all patients studied, postoperative RV long-axis SE and both SR and LR were reduced compared with preoperative values (Figure 4 and Table 4). There were no significant differences between the autograft and homograft groups with regard to either preoperative or postoperative values. All patients who were studied had echocardiographic evidence of reversed ventricular septal motion on an M-mode parasternal long-axis recording.

Phase II
The ventricular volumes and RV long-axis SE measured for the 18 patients are summarized in Table 5. Stroke volume and ejection fraction as a percentage of end-diastolic volume were calculated. All parameters were similar for the 2 groups of patients. For RV volumes, end-diastolic volume ranged from 80 to 202 mL, end-systolic volume ranged from 38 to 116 mL, and ejection fraction ranged from 0.37 to 0.55. In patients with no regurgitant valves, LV and RV stroke volumes must be identical and therefore provide additional validation of volumetric analysis. LV and RV stroke volume correlation curves and Bland-Altman plots are given in Figures 5 and 6.

Discussion
The use of a pulmonary autograft as an aortic valve substitute has many potential advantages,12 including improved hemodynamics and durability, resistance to infection, and the ability to grow. Conversely, it is a longer and more technically demanding operation, and concern still exists over the effect of such surgery on RV function.13 The results of this study demonstrate that patients undergoing aortic valve replacement with either a homograft or an autograft valve substitute have evidence of persistent RV dysfunction after aortic valve replacement; however, the dysfunction is not more pronounced in those undergoing the Ross operation. A comparison of the RV volumes obtained in this study with other published “normal values”14,15 obtained with MRI shows that the end-diastolic and end-systolic values are increased by a factor of 10% to 30%, whereas the stroke

TABLE 3. Changes in RV SE With Time Since Surgery in a Subset of Patients for Whom Regular and Extended Follow-Up Was Available

<table>
<thead>
<tr>
<th>Time</th>
<th>SE, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preoperative</td>
<td>2.5±0.2</td>
</tr>
<tr>
<td>6 wk</td>
<td>1.5±0.3</td>
</tr>
<tr>
<td>6 mo</td>
<td>1.4±0.2</td>
</tr>
<tr>
<td>12 mo</td>
<td>1.4±0.3</td>
</tr>
<tr>
<td>24 mo</td>
<td>1.5±0.2</td>
</tr>
</tbody>
</table>

n=7.
Values are mean±SD.

TABLE 4. Phase I Results: RV Long-Axis Variables (Preoperative and 6 Months Postoperative)

<table>
<thead>
<tr>
<th></th>
<th>SE, cm</th>
<th>SR, cm/s</th>
<th>LR, cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autografts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preoperative</td>
<td>2.2±0.4</td>
<td>8.2±3.0</td>
<td>8.5±3.7</td>
</tr>
<tr>
<td>Postoperative</td>
<td>1.4±0.4*</td>
<td>5.8±3.0*</td>
<td>5.7±1.9*</td>
</tr>
<tr>
<td>Decrease, %</td>
<td>34.7±17</td>
<td>29.6±20</td>
<td>21.8±31</td>
</tr>
<tr>
<td>Homografts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preoperative</td>
<td>2.3±0.6</td>
<td>9.6±3.1</td>
<td>8.9±3.0</td>
</tr>
<tr>
<td>Postoperative</td>
<td>1.5±0.4*</td>
<td>6.8±2.1*</td>
<td>6.0±1.8*</td>
</tr>
<tr>
<td>Decrease, %</td>
<td>32.9±16</td>
<td>29.2±26</td>
<td>26.7±26</td>
</tr>
</tbody>
</table>

*P<0.05 for postoperative vs preoperative.

Figure 4. Preoperative and 6-month postoperative RV long-axis traces, demonstrating typical and striking reduction in both total amplitude and maximal velocities. PCG indicates phonocardiogram.
volumes appear to be similar to other normal published values. Although the numbers involved are too small for statistically significant comparisons, there does not appear to be any difference in either MRI or echocardiographic values according to the underlying disease process and reason for surgery. This 2-phase study appears to show that patients undergoing aortic valve replacement with biological valves have mild long-standing postoperative RV dysfunction, which preferentially affects the long-axis movement of the RV, given that the longitudinal movement falls to at least as great a degree as the absolute volumes. The mechanism of preservation of stroke volumes and, to a lesser degree, global volumes is unclear, but it seems likely that both increased short-axis movement of the RV and reversed ventricular septal motion play a role.16,17

Although altered cardiac geometry and movement of the heart in space may affect long-axis measurements immediately after surgery, such problems should not exist with transthoracic echocardiographic measurements from a fixed apical window 6 to 18 months after surgery, especially when they are backed up by similar changes in absolute volumes. Similar RV long-axis results, with preservation and improvement of LV indices, have been described in patients undergoing CABG.15 It therefore seems likely that the RV dysfunction is secondary to a common feature of both types of operation; possible factors include (1) pericardectomy and the loss of a lubricating surface between the anterior surface of the heart and the chest wall, (2) ischemic damage secondary to cardiopulmonary bypass and poor RV preservation,14 and (3) right atrial and pectinate muscle damage secondary to placement of the bypass cannulae. Further studies in patients undergoing beating heart coronary surgery and with different methods of myocardial protection should help to identify the underlying etiological factors. Thus, although persistent RV long-axis dysfunction should be recognized as an important entity after biological aortic valve replacement, patients undergoing pulmonary autograft surgery are similar in this regard to those undergoing simple homograft aortic valve replacement. Given that patients undergoing pulmonary autograft surgery have excision of part of the RV outflow tract, this implies that intact infundibular function is not a major contributor to RV function as assessed according to the methods in this study. Given the number of patients who were studied, it is possible that the degree of postoperative dysfunction seen in both groups may mask more subtle changes in RV function in the autograft group. However, any such changes appear to be less significant than the persistent longitudinal dysfunction seen in both groups. A similar group of patients undergoing mechanical valve replacement were not studied because the original goal was to examine the effect of pulmonary autograft surgery on RV function, and for this purpose, aortic homografts provide the best comparison. Further studies, including those in patients undergoing mechanical valve replacement and minimally invasive aortic valve replacement, are required to define the exact mechanisms involved in producing the RV dysfunction and the possible effects of our findings in terms of functional capacity and longevity. All of our patients had reversed septal motion, which almost certainly is an important interrelated physiological or anatomic postoperative effect that merits further study. It is hoped that these studies will stimulate the search for better methods of myocardial protection, focusing particularly on the RV and interventricular septum.

Acknowledgments

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