Time course of resolution of pulmonary hypertension and right ventricular remodeling after orthotopic cardiac transplantation


ABSTRACT Most patients with severe congestive heart failure have secondary pulmonary hypertension (PHT). Elevation of pulmonary vascular resistance (PVR) to greater than 480 dynes·sec·cm⁻⁵ (6 Wood units) is currently the principle hemodynamic contraindication to orthotopic cardiac transplantation. We performed serial two-dimensional Doppler echocardiographic examinations and right heart catheterizations in 24 recipients (21 men, 14–58 years old) of orthotopic cardiac transplants to determine the time course of resolution of PHT and the concomitant remodeling of the donor right ventricle. Right and left heart filling pressures declined in parallel and reached the upper normal range in 2 weeks after the transplant procedure and remained unchanged at 1 year follow-up. Mean pulmonary arterial pressure (mm Hg) decreased from 38 ± 9 preoperatively to 22 ± 5 at 2 weeks and was 19 ± 5 at 1 year after the transplantation procedure. At 1 year after surgery, PVR had decreased from 202 ± 89 dynes·sec·cm⁻⁵ preoperatively to 99 ± 36 dynes·sec·cm⁻⁵ (p < .001), while cardiac output increased from 3.7 ± 1.2 to 6.3 ± 1.5 liters/min (p < .001). Echocardiographic analysis showed that transplant recipients had an enlarged right ventricle on day 1 after surgery, and a volume overload contraction pattern and tricuspid regurgitation was present in the majority. This increase in right ventricular size was maintained at 1 year follow-up while the incidence of tricuspid regurgitation decreased. We conclude that there is rapid resolution of moderately elevated pulmonary arterial pressures after cardiac transplantation. The donor right ventricle responds to the abnormal recipient pulmonary circulatory dynamics by developing early dilatation and tricuspid regurgitation that persists despite resolution of PHT.


PATIENTS with severe class IV congestive heart failure (CHF) have a very high mortality. Conventional medical therapies including diuretics, inotropes, antiarrhythmics, and afterload reduction have had little impact on survival in these patients. They often remain in a low-output state, despite trials of investigational inotropes, and often have an expected survival of less than 6 months. Currently, cardiac transplantation is the only intervention that has been shown to unequivocally prolong survival in this subset of patients with CHF.

Cardiac transplantation not only prolongs survival, but reestablishes a near-normal lifestyle in these patients. Since the introduction of cyclosporine for immunosuppression, survival is reported to be 85% at 1 year and 66% at 5 years after orthotopic cardiac transplantation. Before undergoing transplantation, the majority of these patients have pulmonary hypertension (PHT) secondary to chronic elevation of left ventricular filling pressures. Hemodynamics measured weeks to months after successful heart transplantation have documented normalization of resting right heart hemodynamics and pulmonary vascular resistance. No attempts have yet been made to assess right-sided hemodynamics serially immediately after transplantation to determine the time course of resolution of PHT.

The purpose of this study was (1) to determine the magnitude and time course of changes in pulmonary arterial pressures over the first year after orthotopic cardiac transplantation, and (2) to assess concomitant donor right ventricular remodeling.
Materials and methods

**Patient population.** The study population consisted of 24 consecutive recipients of orthotopic heart transplants at Brigham and Women’s Hospital in Boston. The patients ranged in age from 14 to 58 years (mean 42). The cause of CHF was idiopathic dilated cardiomyopathy in 13, ischemic heart disease in eight, and valvular heart disease in three. The mean follow-up period was 13 months (range 1 to 29) with 16 transplant recipients followed for at least 1 year.

**Methods.** All patients underwent right heart catheterization with a No. 7F balloon flotation pulmonary artery catheter placed through a No. 9F Cordis introducer sheath in the right internal jugular vein at the time of their scheduled endomyocardial biopsies for routine monitoring for rejection. Under fluoroscopic and hemodynamic guidance, the balloon catheter was advanced to the pulmonary capillary wedge position and the following pressures (mm Hg) recorded on a strip-chart recorder: mean right atrial (RAP, normal 2 to 8), right ventricular systolic (RVS, normal 15 to 30) and end-diastolic (RVD, normal 2 to 8), pulmonary arterial systolic (PAS, normal 15 to 30), diastolic (PAD, normal 4 to 12), and mean (PAM, normal 9 to 18), and pulmonary capillary wedge (PCWP, normal 2 to 10) pressures.\(^\text{10}\)

Serial hemodynamic measurements obtained at 1, 2, and 3 weeks and 1, 3, 6, and 12 months after transplantation were analyzed and compared with those obtained before surgery. At 1 year after the transplant procedure, cardiac output (CO, liters/min) was measured by the Fick method and pulmonary vascular resistance (PVR, dynes-sec-cm\(^{-5}\), normal 20 to 130) was calculated as

\[
PVR = \frac{PAM - PCWP}{CO} \times 80
\]

Pulmonary hypertension was defined by the presence of PAM greater than 20 mm Hg.

Two-dimensional and Doppler echocardiograms in the parasternal short- and long-axis, and apical two- and four-chamber views were obtained on the first postoperative day and within 24 hr of each of the hemodynamic measurements at 1 week and 1 and 12 months after the transplantation procedure. The echocardiograms were analyzed by one of us (S. B.) in a blinded fashion — the studies were analyzed without knowledge of the patient’s identity or time elapsed since transplantation. Furthermore, the serial echocardiograms were distributed for study in a random fashion. The two-dimensional images were analyzed to assess right ventricular size and wall thickness. The right ventricular end-diastolic area (RVEDA in cm\(^2\)) was assessed by planimetry the endocardial border from the apex to the level of the tricuspid valve annulus in the apical four-chamber view with a Diasonics Cardio Revue center (figure 1). End-diastole was identified by the maximum right ventricular size defined at the peak of the R wave on a simultaneous electrocardiogram. Right ventricular maximal end-diastolic dimensions (RVEDD in cm) was measured by electronic calipers as the largest transverse or minor-axis dimension of the right ventricle (figure 2). Three frames were analyzed and the average was computed. Right ventricular wall thickness (RVWT in cm) was measured from epicardium to endocardium with electronic calipers in three frames in the subcostal view and the average was calculated. The two-dimensional measurements were compared with those obtained from 10 normal volunteers (age 20 to 34 years).

Interventricular septal motion was analyzed in the parasternal short-axis view of the left ventricle at the level of the papillary muscles, chordae tendineae, or tips of the mitral leaflets.\(^\text{11, 12}\)

Septal motion was interpreted as normal if the septum maintained a convex configuration toward the right ventricle and the left ventricle remained spherical in both systole and diastole. Abnormal diastolic interventricular septal motion was defined as flattening of the septum at end-diastole and return to a normal spherical configuration in systole (paradoxic septal motion); abnormal systolic septal motion was characterized by flattening of the septum at end-diastole and further indentation of the septum towards the left ventricle in systole. Tricuspid regurgitation was detected as a holosystolic turbulent signal and graded as I + 4+ by pulsed Doppler flow mapping of the donor right atrium.\(^\text{13}\)

**Statistical methods.** The results are presented as mean ± 1 SD. Means were compared by two-tailed Student’s t tests of paired sample groups; statistical significance was defined as a p value < .05. Inferences regarding proportions (percentages) were based on the McNemar test and the serial frequency of tricuspid regurgitation was analyzed by the Wilcoxon signed-rank test. Correlations between measurements were determined by linear regression with the method of least squares.

Results

**Preoperative hemodynamics.** The 24 transplant recipients underwent diagnostic cardiac catheterization 8 ±
Before the transplant procedure, PAM elevated over 1 year (>20%) and remained ± Hg, RVS 49 ± 13 mm Hg, RVD 16 ± 6 mm Hg, PAS 50 ± 12 mm Hg, PAD 30 ± 7 mm Hg, PCWP 30 ± 8 mm Hg, CO 3.5 ± 1.1 liters/min, PVR 213 ± 113 dynes·sec·cm⁻². Preoperative PAM was <50 mm Hg in all patients.

Postoperative hemodynamics. Serial posttransplant hemodynamics are tabulated in table 1. After transplantation, right and left heart filling pressures declined in parallel; they reached a nadir at 2 weeks after surgery and remained unchanged except for minor fluctuations over 1 year of follow-up (figure 3). RAP (mm Hg) declined from 15 ± 5 preoperatively to 9 ± 4 at 2 weeks (p < .01) and was 7 ± 4 at 1 year (p < .001 vs preoperative value, p > .10 vs 2 weeks) after the transplantation procedure. At 1 year, only four of 16 patients had an RAP greater than 8 mm Hg. PAM (mm Hg) decreased from 38 ± 9 preoperatively to 22 ± 5 at 2 weeks (p < .001) and was 19 ± 5 at 1 year (p < .001 vs preoperative value, p > .10 vs 2 weeks) after surgery. At 1 year after the transplantation procedure, only five of 16 patients (31%) had a PAM greater than 20 mm Hg (range 23 to 28). Similarly, PCWP (mm Hg) decreased from a preoperative value of 30 ± 8 to 14 ± 5 at 2 weeks (p < .001) and to 12 ± 4 at 1 year (p < .001 vs preoperative value, p > .10 vs 2 weeks) after the transplantation.

At 1 year after the transplant procedure, in the 15 patients for whom follow-up data were available, PVR had decreased from 202 ± 89 dynes·sec·cm⁻² preoperatively to 99 ± 36 dynes·sec·cm⁻² (p < .001; figure 4), with only three of 15 patients having a mild persistent elevation in PVR (range 132 to 176). Over the same period, CO increased from 3.7 ± 1.2 to 6.3 ± 1.5 liters/min (range 4.2 to 9.8, p < .001; figure 5). The percent decrease in PVR ranged from 10% to 84%, with the greatest change occurring in patients with the highest preoperative values.

We assessed the relationship between right and left heart hemodynamics before and after transplantation by regression analysis. Before the transplantation procedure, PAM (38 ± 9 mm Hg) correlated closely with PCWP (30 ± 8 mm Hg; r = .87, PAM = 9.1 + 0.97 PCWP), but there was a poor correlation between RAP (15 ± 5 mm Hg) and PCWP (r = .31, PCWP = 22.8 ± 0.45 RAP). In contrast, postoperatively there was a close correlation between PAM and PCWP and between PCWP and RAP in an analysis of 356 data.

### TABLE 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preop</th>
<th>1 week</th>
<th>2 weeks</th>
<th>3 weeks</th>
<th>1 month</th>
<th>3 months</th>
<th>6 months</th>
<th>1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP</td>
<td>15 ± 5</td>
<td>14 ± 5</td>
<td>9 ± 4</td>
<td>9 ± 5</td>
<td>9 ± 6</td>
<td>8 ± 4</td>
<td>7 ± 4</td>
<td>7 ± 4</td>
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<tr>
<td>RVS</td>
<td>49 ± 13</td>
<td>44 ± 10</td>
<td>36 ± 8</td>
<td>35 ± 7</td>
<td>34 ± 7</td>
<td>31 ± 9</td>
<td>30 ± 5</td>
<td>28 ± 6</td>
</tr>
<tr>
<td>RVD</td>
<td>16 ± 6</td>
<td>16 ± 5</td>
<td>11 ± 5</td>
<td>11 ± 6</td>
<td>10 ± 6</td>
<td>9 ± 5</td>
<td>8 ± 4</td>
<td>8 ± 4</td>
</tr>
<tr>
<td>PAS</td>
<td>50 ± 12</td>
<td>41 ± 8</td>
<td>32 ± 8</td>
<td>33 ± 9</td>
<td>32 ± 7</td>
<td>30 ± 9</td>
<td>29 ± 5</td>
<td>28 ± 6</td>
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<td>PAD</td>
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<td>16 ± 5</td>
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<td>16 ± 6</td>
<td>16 ± 6</td>
<td>16 ± 4</td>
<td>15 ± 4</td>
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<tr>
<td>PAM</td>
<td>38 ± 9</td>
<td>27 ± 6</td>
<td>22 ± 5</td>
<td>22 ± 6</td>
<td>21 ± 6</td>
<td>21 ± 7</td>
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<td>PCWP</td>
<td>30 ± 8</td>
<td>18 ± 5</td>
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<td>12 ± 4</td>
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<tr>
<td>PAM-PCWP</td>
<td>8 ± 4</td>
<td>9 ± 4</td>
<td>8 ± 3</td>
<td>8 ± 4</td>
<td>8 ± 2</td>
<td>8 ± 3</td>
<td>9 ± 3</td>
<td>7 ± 2</td>
</tr>
<tr>
<td>CO</td>
<td>3.5 ± 1.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.3 ± 1.5</td>
</tr>
<tr>
<td>PVR</td>
<td>213 ± 113</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>99 ± 36</td>
</tr>
</tbody>
</table>

Pressures are in mm Hg, CO in 1/min, and PVR in dynes·sec·cm⁻².

**FIGURE 3.** Serial hemodynamics after cardiac transplantation compared with preoperative measurements. Depicted are group means ± 1 SD for RAP, PAM, and PCWP (in mm Hg).
FIGURE 4. In the 15 patients for whom complete data sets were available, PVR (dyne·sec·cm⁻²) decreased from 202 ± 89 preoperatively to 99 ± 36 at 1 year after the transplantation procedure (p < .001).

points (figure 6): PAM = 8.9 + 0.90 PCWP, r = 1.0; PCWP = 5.7 + 0.87 RAP, r = .81. Preoperatively, the difference between PAM and PCWP (transpulmonary gradient) was 8 ± 4 mm Hg and remained unchanged (7 ± 2) at 1 year follow-up.

Postoperative echocardiography. The echocardiographic dimensions obtained in 10 normal subjects were: RVEDA, 14.46 ± 2.58 cm²; RVEDD, 2.74 ± 0.39 cm; RVWT, 0.51 ± 0.07 cm. RVEDA (cm²) after cardiac transplantation (table 2 and figure 7) was significantly greater than normal on the first postoperative day (21.68 ± 3.73, p < .001); this increased further at 1 month (25.29 ± 5.08, p < .001 vs normal, p < .05 vs day 1) and by 1 year had returned to immediate postoperative values (20.98 ± 3.59, p < .001 vs normal, p > .10 vs day 1). RVEDDD showed a similar trend at day 1 (3.29 ± 0.29 cm, p < .05 vs normal), 1 month (3.68 ± 0.58, p < .01 vs normal, p < .05 vs day 1) and at 1 year (3.29 ± 0.45, p < .05 vs normal, p > .10 vs day 1) after transplantation. By contrast, RVWT tended to increase with duration of follow-up, but the difference from normal was not statistically significant.

Assessment of interventricular septal motion revealed end-diastolic flattening in 100% of patients on the first day after transplantation (table 2). This proportion decreased to 88% at 1 week (p > .10 vs day 1), 75% at 1 month (p < .05 vs day 1), and 42% at 1 year (p < .05 vs day 1). Abnormal systolic septal motion was detected in 12% of patients on the first postoperative day, in 6% at 1 week, and in 0% thereafter. None of the normal subjects had abnormal systolic or diastolic interventricular septal motion. Concomitantly tricuspid regurgitation of grade 1 + 3 + by Doppler tricuspid regurgitation was present in 67% on day 1, 64% at 1 week (p > .10 vs day 1) 73% at 1 month (p > .10 vs day 1), and in only 36% at 1 year (p > .10 vs day 1) after the transplantation procedure. In contrast, none of the 10 normal subjects had a holosystolic signal of tricuspid regurgitation. The grade of tricuspid regurgitation was similar at the follow-up intervals (2.0 ± 0.6 at day 1 vs 1.8 ± 1.0 at 1 year). Subgrouping patients into those with none/mild (0–1 +) tricuspid regurgitation and those with moderate (2 + 3 +) tricuspid regurgitation revealed a higher preoperative PAM in patients with moderate tricuspid regurgitation (39.7 ± 12.2 vs 34.8 ± 10.3 mm Hg, p > .05).

Discussion

The majority of patients with chronic left ventricular failure referred for cardiac transplantation have secondary PHT. PHT (PVR > 480 dyne·sec·cm⁻² or 6 Wood units) is currently the principle hemodynamic contraindication to orthotopic cardiac transplantation. Patients with marked PHT (PVR > 640 dyne·sec·cm⁻² or 8 Wood units) are usually regarded as candidates for heterotopic cardiac or heart and lung transplantation. This contraindication is based on reports of acute right ventricular decompensation in the
donor heart when it is exposed to the elevated pulmonary arterial pressures (right ventricular afterload) in the recipient. However, no serial systematic analysis of pulmonary hemodynamics and right ventricular adaptation during the immediate postoperative period has been performed.

Preoperative catheterization in our patients revealed elevated right and left ventricular filling pressures, depressed CO, and increased PVR. Twenty-three of the 24 transplant recipients had moderate preoperative PHT (PAM < 50 mm Hg). Isoproterenol was administered to all patients immediately after the transplantation procedure and none had symptomatic deterioration of right ventricular function. Serial hemodynamic studies revealed a consistent pattern of circulatory adjustment. Right and left heart filling pressures decreased by 1 week after transplantation and reached a nadir in the upper normal range at 2 weeks, with parallel decreases in RAP, PAM, and PCWP. The filling pressures showed a tendency to decrease further over the ensuing year to within the normal range. At 1 year, while mean RAP (7 ± 4 mm Hg) and RVD (8 ± 4 mm Hg) were in the upper range of normal, mean PCWP was still mildly elevated at 12 ± 4 mm Hg. The abnormal PCWP may be due to decreased left ventricular compliance, possibly resulting from cyclosporine-induced systolic and diastolic hypertension.

Several previous studies of cardiac transplant recipients performed between 1 month and 1 year postoperatively have also demonstrated normalization of right and left ventricular filling pressures at rest. However, many of the reports do not describe preoperative hemodynamics for quantitative comparison and all but one did not perform serial studies to assess the time course of normalization of intracardiac filling pres-

FIGURE 6. The relationship between RAP and PCWP (both mm Hg) heart hemodynamics before and after the transplantation procedure as assessed by regression analysis.

FIGURE 7. Serial right ventricular echocardiographic measurements after transplantation (± 1 SD) are compared with control values (n = 10). Shown are RVEDA (cm²), RVEDD (cm), and RVWT (cm).
sures. The only serial study of pulmonary arterial pressures after transplantation was performed in a small number of patients before the introduction of cyclosporine for immunosuppression and demonstrated that pulmonary arterial pressures declined but were still above normal at 1 week after transplantation.\textsuperscript{15} The results in our patients, all of whom received cyclosporine, are similar in that PAM and right ventricular and left ventricular filling pressures declined at 1 week after surgery and reached a nadir in the upper normal range at 2 weeks after the transplantation procedure. Although there were several episodes of mild-to-severe rejection, these were not associated with any consistent change in intracardiac hemodynamics.

By 1 year after the transplantation procedure, PVR had returned to normal in 80\% of our patients, with only mild elevations persistent in three recipients. The percent decline in PVR ranged from 10\% to 84\%, with patients with the highest preoperative values having the largest reduction. Although CO at 1 year after transplantation has previously been reported to remain subnormal, our study demonstrates that CO was in the normal range at the 1 year follow-up period. The sustained improvement in CO in our patients may reflect the use of cyclosporine for immunosuppression and is similar to the experience of Thompson et al.\textsuperscript{16} Although cyclosporine may produce systolic and diastolic hypertension and maintain elevated systemic vascular resistance, its greater effectiveness in suppressing rejection may account for the preservation of normal left ventricular performance.\textsuperscript{16}

Possible causes for the patients’ preoperative PHT may include (1) passive transmission of elevated left atrial pressures to the pulmonary vasculature, (2) inappropriate pulmonary vasoconstriction, and (3) secondary organic pulmonary vascular disease. The transpulmonary gradient or pressure drop (PAM-PCWP) across the pulmonary circuit was normal, i.e., less than 10 to 12 mm Hg preoperatively, and remained so after transplantation. This suggests that the passive increase in PAM secondary to pulmonary venous hypertension is the major mechanism responsible for the preoperative PHT. Postoperatively the pressure drop did not change by 2 mm Hg or more, implying that the postoperative decline in PCWP can account entirely for the decrease in PAM.\textsuperscript{17} The time course of resolution of PHT in the immediate postoperative period may be due to transient depression of left ventricular systolic performance that could lead to the persistent mild elevation of PCWP and secondary elevation in PAM.\textsuperscript{15, 18}

The preoperative PHT in transplant recipients may also have been the result of inappropriate pulmonary vasoconstriction similar to the abnormal vasomotion documented in patients with mitral stenosis.\textsuperscript{17, 19} Patients undergoing mitral valve replacement show a pattern of decrease in PVR that is similar to that seen in the transplant recipients in that patients with the higher preoperative values have the greatest percent decrease in postoperative PVR.\textsuperscript{17} The decrease in PVR seen postoperatively in our patients, despite the increase in CO, suggests a change in pulmonary vasoreactivity.\textsuperscript{20} However, the preoperative regression analysis of PAM vs PCWP yielded a slope very similar to that for normal subjects reported in the literature, suggesting a lack of inappropriate pulmonary vasoconstriction that, unlike passive PHT, would be expected to alter the slope of this relationship.\textsuperscript{19}

The response of the donor right ventricle to the abnormal pulmonary hemodynamics in the recipients was assessed by serial echocardiography. On the first day after the transplantation procedure the right ventricle increased in size and dilated further at 1 month and subsequently declined to immediate postoperative dimensions at 1 year after surgery. The right ventricular

---

### TABLE 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Normal</th>
<th>1 day</th>
<th>1 week</th>
<th>1 month</th>
<th>1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVEDA</td>
<td>14.46 ± 2.58</td>
<td>21.68 ± 3.73</td>
<td>22.68 ± 5.08</td>
<td>25.29 ± 5.08</td>
<td>20.98 ± 3.59</td>
</tr>
<tr>
<td>RVEDD</td>
<td>2.74 ± 0.39</td>
<td>3.29 ± 0.29</td>
<td>3.40 ± 0.45</td>
<td>3.68 ± 0.58</td>
<td>3.29 ± 0.45</td>
</tr>
<tr>
<td>RVWT</td>
<td>0.51 ± 0.07</td>
<td>0.58 ± 0.08</td>
<td>0.62 ± 0.11</td>
<td>0.65 ± 0.15</td>
<td>0.65 ± 0.11</td>
</tr>
<tr>
<td>TR (frequency; %)</td>
<td>0</td>
<td>67</td>
<td>64</td>
<td>73</td>
<td>36</td>
</tr>
<tr>
<td>TR (grade)</td>
<td>---</td>
<td>2.0 ± 0.6</td>
<td>1.7 ± 1.0</td>
<td>1.3 ± 0.5</td>
<td>1.8 ± 1.0</td>
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<tr>
<td>SM-D (%)</td>
<td>0</td>
<td>100</td>
<td>88</td>
<td>75</td>
<td>42</td>
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<tr>
<td>SM-S (%)</td>
<td>0</td>
<td>12</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

TR = tricuspid regurgitation; SM-D = abnormal diastolic interventricular septal motion; SM-S = abnormal systolic interventricular septal motion.
size at 1 year was significantly enlarged over that in control subjects. The RVWT tended to increase during follow-up but was not statistically different from normal. Abnormal diastolic interventricular septal motion was present in all patients immediately postoperatively. This decreased to a 42% incidence at 1 year. Concurrently, tricuspid regurgitation was detected in 67% of the patients on day 1 after the transplant procedure and this incidence decreased to 36% at 1 year.

The high incidence of tricuspid regurgitation early after transplantation with persistence during follow-up in our study is similar to that reported in two preliminary series. The presence of moderate-to-severe tricuspid regurgitation has previously been correlated with higher preoperative levels of PAS. Our study shows a similar trend in that patients with grades 2+ to 3+ tricuspid regurgitation had higher preoperative PAM values than patients with grades 0 to 1+ tricuspid regurgitation. Although abnormal diastolic interventricular septal motion was present in all our patients early after transplantation, the pattern of abnormal systolic septal motion was very uncommon, probably because PAM decreases significantly immediately after transplantation. Although abnormalities of interventricular septal motion have commonly been reported after intracardiac surgery, the concomitant decrease in the frequency of abnormal right ventricular diastolic septal motion and tricuspid regurgitation suggests a pathophysiologic correlation between tricuspid regurgitation and the enlarged right ventricular dimensions due to volume overload. The donor right ventricle thus responds to transplantation by increasing its dimensions and tending to thicken with follow-up. However, unlike the increased left ventricular mass seen after the transplant procedure, we did not detect a significant increase in RVWT. The explanation for this discrepancy may lie in the persistence of increased left ventricular afterload (systolic and diastolic hypertension, elevated systemic vascular resistance) after transplantation while right ventricular afterload (PVR, PAM) declines to normal levels.

Tricuspid regurgitation of a mild to moderate degree is thus common after transplantation and may be responsible for producing and maintaining enlarged right ventricular dimensions. Potential causes for the development of tricuspid regurgitation include (1) early postsurgical right ventricular dysfunction due to increased afterload, (2) prolonged donor right ventricular ischemic time in transit, and (3) disruption of the chordal supporting apparatus of the tricuspid valve due to mechanical trauma or ischemia/infarction. However, prior studies have shown no relationship between donor heart cold storage (ischemic) time and the development of tricuspid regurgitation and flail tricuspid valve leaflets or torn tricuspid chordae was not detected in any of our patients. Right ventricular systolic dysfunction has been observed in the immediate postoperative period but this improves with follow-up. Thus, tricuspid regurgitation early after transplantation due to afterload mismatch may be the basis for right ventricular dilatation by volume overload that can subsequently maintain tricuspid regurgitation remote from transplantation by dilatation of the tricuspid anulus. This could explain the persistence of tricuspid regurgitation with follow-up, despite the presence of near normal right ventricular afterload (PAM) beyond 2 weeks after surgery. However, it is important to emphasize that none of the patients in our series had symptoms related to chronic right ventricular volume overload and right-sided pressures were relatively normal at the end of 1 year. Thus, tricuspid regurgitation after transplantation is well tolerated and is rarely of clinical significance, as noted in the report of Lewen et al. Our report details the pattern of right ventricular modeling to moderate preoperative PHT. The response of the donor right ventricle to severe preoperative PHT, currently a principal contraindication to orthotopic cardiac transplantation, deserves serial study to allow revision of current criteria for transplantation based on PAM and PVR.

Preoperatively there was a poor correlation between right and left heart filling pressures (RAP vs PCWP, r = .31); however, after transplantation, RAP and PCWP showed an excellent correlation (PCWP = 5.7 + 0.87 RAP, r = .81). Although the postoperative correlations may be fortuitous because of the relative normality of the filling pressures, decreased ventricular compliance, restrictive cardiomyopathy, or subclinical postoperative pericardial constriction producing approximation of diastolic filling pressures cannot be excluded.

In conclusion, we have serially studied 24 recipients of orthotopic cardiac transplants with invasive hemodynamic measurements and echocardiography. Moderate preoperative PHT (PAM < 50 mm Hg) resolved rapidly in the postoperative period and PAM approached normal values at 2 weeks after surgery. Patients with the highest preoperative PVR had the greatest percentage decrease after the transplant procedure. The donor right ventricle remodels in response to recipient perioperative PHT with the development of dilatation and tricuspid regurgitation that persists at 1 year of follow-up despite resolution of PHT. Thus, at 1 year follow-up, while resting hemodynamics are nor-
mal, the donor right ventricle remains enlarged and slightly thickened, probably as an adaptation to chronic volume overload.

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