The development of mitral and aortic prostheses has allowed surgery for patients with pathology of multiple valves not otherwise correctable. Experience with this type of surgery culminated in replacement of the tricuspid, mitral, and aortic valves during one operation in certain patients with severe rheumatic heart disease. The present report will describe the hemodynamic findings in eight of these patients during the first year after triple valve replacement. We are not aware of previous reports describing the hemodynamic results of tricuspid valve replacement, and therefore, catheterization data from two other persons who had combined tricuspid and mitral valve replacement are included also.

Preoperative Cardiac Catheterizations

Preoperative catheterization results were available in nine of the 10 patients (table 1). The highest cardiac index was 1.90 L/min/m² and the average was 1.70. Mean right atrial pressure was elevated in eight patients with values up to 22 mm Hg. Severe pulmonary hypertension was present in four of the cases with right ventricular systolic pressures between 75 and 118 mm Hg. Left atrial or pulmonary arterial wedge pressures were elevated in all but one person in whom they were measured.

Severe aortic stenosis was not present in any of the patients; modest systolic gradients across the aortic valve were found in four. The eight patients who had triple valve replacement had aortic insufficiency. Mitral valve disease was present in all 10 patients with stenosis and insufficiency in various combinations. Definite tricuspid stenosis was diagnosed in four patients, and all 10 had tricuspid insufficiency.

Methods

Eight patients had replacement of the tricuspid, mitral, and aortic valves, and two others had replacement of the tricuspid and mitral valves. Starr-Edwards ball-valve prostheses were used and the mitral type was employed in the tricuspid orifice (fig. 1). The clinical experience with tricuspid replacement in our hospital has been reviewed recently.

Patient 1 had two operations. He was the first of the group to have tricuspid, mitral, and aortic valve replacement. He failed to obtain optimal improvement postoperatively, and a second procedure was performed 9 months after the first, when leaks around the mitral and tricuspid prostheses were repaired.

The postoperative studies were performed 4 to 10 months after the operations. The patients received pentobarbital, 100 mg, and came to the laboratory in the morning after an overnight fast. The left brachial artery was cannulated percutaneously with 15 cm of polyethylene tubing (PE160). A transseptal catheter was introduced into the right femoral vein percutaneously and was advanced until its tip was in the right atrium. From a venous cutdown in the right arm a no. 5 or 6 F Lehman catheter was also advanced to the right atrium. This catheter was then introduced into the right ventricle through the tricuspid prosthesis. Simultaneous right atrial and right ventricular pressures were recorded; then right atrial pressure was continuously recorded through
## Results in All Patients

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age at operation (yr)</th>
<th>Months before or after operation</th>
<th>Pre- or post-operative State</th>
<th>Rhythm</th>
<th>Heart rate</th>
<th>Oxygen consumption (ml/min/m²)</th>
<th>Cardiac index (L/min/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>1</td>
<td>Preop</td>
<td>Rest</td>
<td>AF</td>
<td>74</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9 after 30 yrs</td>
<td>Postop 1</td>
<td>Rest</td>
<td>AF</td>
<td>82</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop 2</td>
<td>Rest</td>
<td>AF</td>
<td>76</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>6</td>
<td>Preop</td>
<td>Rest</td>
<td>AF</td>
<td>84</td>
<td>141</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop 2</td>
<td>Exer.</td>
<td>AF</td>
<td>84</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>2</td>
<td>Preop</td>
<td>Rest</td>
<td>NSR</td>
<td>65</td>
<td>134</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>Postop</td>
<td>Rest</td>
<td>NSR</td>
<td>88</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Exer.</td>
<td>NSR</td>
<td>103</td>
<td>431</td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>10</td>
<td>Preop</td>
<td>Rest</td>
<td>NSR</td>
<td>94</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Exer.</td>
<td>NSR</td>
<td>96</td>
<td>260</td>
</tr>
<tr>
<td>5</td>
<td>29</td>
<td>2½</td>
<td>Preop</td>
<td>Rest</td>
<td>NSR</td>
<td>84</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Rest</td>
<td>NSR</td>
<td>74</td>
<td>133</td>
</tr>
<tr>
<td>6</td>
<td>44</td>
<td>2½</td>
<td>Preop</td>
<td>Rest</td>
<td>AF</td>
<td>60</td>
<td>138</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Rest</td>
<td>AF</td>
<td>70</td>
<td>133</td>
</tr>
<tr>
<td>7</td>
<td>47</td>
<td>5½</td>
<td>Preop</td>
<td>Rest</td>
<td>AF</td>
<td>68</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Preop</td>
<td>Exer.</td>
<td>AF</td>
<td>94</td>
<td>261</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Exer.</td>
<td>AF</td>
<td>58</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Exer.</td>
<td>AF</td>
<td>92</td>
<td>347</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>5½</td>
<td>Postop</td>
<td>Rest</td>
<td>NSR</td>
<td>98</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Exer.</td>
<td>NSR</td>
<td>126</td>
<td>—</td>
</tr>
<tr>
<td>9</td>
<td>47</td>
<td>4</td>
<td>Preop</td>
<td>Rest</td>
<td>NSR</td>
<td>120</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Rest</td>
<td>NSR</td>
<td>122</td>
<td>154</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Exer.</td>
<td>NSR</td>
<td>132</td>
<td>253</td>
</tr>
<tr>
<td>10</td>
<td>39</td>
<td>1½</td>
<td>Preop</td>
<td>Rest</td>
<td>NSR</td>
<td>96</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Rest</td>
<td>NSR</td>
<td>65</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Exer.</td>
<td>NSR</td>
<td>81</td>
<td>267</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>Preop</td>
<td>Rest</td>
<td>—</td>
<td>83</td>
<td>136</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Postop</td>
<td>Rest</td>
<td>—</td>
<td>79</td>
<td>132</td>
</tr>
</tbody>
</table>

Patients 1 to 8 had the tricuspid, mitral, and aortic valves replaced. Patients 9 and 10 had tricuspid and mitral valves replaced.

Abbreviations: RA = right atrium, RV = right ventricle, LA = left atrium, LV = left ventricle, BA = brachial artery, AF = atrial fibrillation, NSR = sinus rhythm.

*Pulmonary artery wedge pressure.
†Diastolic pressure only.

The atrial catheter while the right ventricular catheter was withdrawn to the right atrium. In patients 1 and 2, right ventricular pressure was measured instead after anterior percutaneous puncture of the right ventricle. Right ventricular cineangiography was performed in patient 2 by injection through the percutaneous needle.

Atrial septal puncture was performed, and the transseptal catheter was placed with its tip in the middle of the left atrium, well away from the mitral ring. Expired air was then collected in a Tissot spirometer during a steady state at rest and during the fourth through sixth minutes of exercise. Exercise was performed by pedaling an electrically braked bicycle ergometer at a low-work setting with the left leg. The cardiac output was measured during the collections of expired air by the indocyanine green-dilution method. A 5 mg bolus of dye was flushed into the left atrium (or occasionally the right atrium) by 10 ml of normal saline during continuous withdrawal of systemic arterial blood through a cuvette densitometer (Waters X300).
TRIPLE VALVE REPLACEMENT

A period of rest followed the exercise study. Then the left ventricle was punctured by the apical transthoracic route with a 18 or 19-gauge thin-walled cannula with a pointed stylet. Simultaneous left atrial and left ventricular pressures were recorded. In five of the patients (patients 2, 4, 6, 7, and 8), left ventricular cineangiography was then performed with power injection of 80% sodium iothalamate through the ventricular needle. The two patients with only mitral and tricuspid prostheses had retrograde arterial catheterization of the left ventricle rather than puncture.

Oxygen consumption was determined by analysis of expired air by the Scholander method. Indocyanine green-dilution curves were calibrated by drawing arterial blood without dye added and with three known concentrations of dye through the densitometer at the same flow rate as employed during inscription of the original dilution curves. Blood pressures were recorded by Statham P23Gb and P23Db strain gauges and a Sanborn photographic recorder.

Results

The complete results are presented in table 1 and figure 2. The cardiac output at rest was higher postoperatively in each case. The average for the group was 2.69 L/min/m² and was in the normal range (above 2.5 L/min/m²). The average change was almost 1 L/min/m² and thus represented a substantial increase over the preoperative level. Representative dye-dilution curves from which the cardiac

---

Circulation, Volume XXXIV, September 1966
outputs were calculated are shown in figure 3. The change in blood flow postoperatively was due almost entirely to an increase in stroke volume since the heart rates were little different at the two times; the average stroke volume increased 64%. Despite the rise in cardiac output in all patients, four remained below the lower normal limit.

Figure 1
Posteroanterior chest roentgenograms from patient 5 before and after replacement of the aortic, mitral, and tricuspid valves. The tricuspid prosthesis is in the midline over the spine.

Figure 2
Right heart pressure and cardiac output results from the nine patients who had catheterizations before and after tricuspid valve replacement. Abbreviations: RA = right atrial; RV = right ventricular; RVEDP = right ventricular end-diastolic pressure; - - - = average.
TRIPLE VALVE REPLACEMENT

A. 10 sec

LA - BA

after before

B. 10 sec

LA-BA

LV-BA

after before

Figure 3

Arterial indocyanine green-dilution curves obtained during cardiac catheterization before and after valve replacement. (A) Patient 1, who had triple replacement. Left atrial injection; brachial arterial sampling. (B) Patient 10, who had mitral and tricuspid replacement. Indicator was injected into the left ventricle preoperatively and into the left atrium postoperatively. The effects of correction of valvular insufficiency on the configuration of the dilution curves in these patients are shown by the more rapid downslopes and by the development of distinct recirculation curves.

The mean right atrial pressure (MRAP) decreased in seven of the nine patients in whom preoperative values were available for comparison, and the average MRAP was less than half the preoperative level for the group. Some patients showed marked changes (patients 3, 4, 9, and 10). The average at rest for the group remained slightly abnormal, however, and only three persons had a MRAP within the normal range (5 mm Hg or less). Diastolic pressure gradients across the tricuspid prosthesis were demonstrable in each case and examples are shown in figure 4. The mean tricuspid diastolic gradients averaged slightly less than 5 mm Hg, and the average calculated effective tricuspid orifice area was 2.1 cm².

The presence of the right ventricular catheter through the ball-valve prosthesis did not seem to have an important effect upon its function, as judged by comparison of right atrial pressure records during and immediately after the right ventricular catheter was in place (fig. 5).

Pulmonary arterial pressure was evaluated indirectly in these studies from measurements of right ventricular systolic pressure. The average systolic pressure in the lesser circuit decreased from 68 before surgery to 34 mm postoperatively and all but one patient had a decrease. Four persons had values persistently above normal, ranging from 34 to 51 mm Hg. Four patients had remarkable diminution in right ventricular systolic pressure (patients 4, 6, 9, and 10). The greatest change was from 118 mm Hg before surgery to 30 mm Hg afterward. Improvement in right ventricular function and relief of right ventricular overload appeared significant in several patients in whom right ventricular end-diastolic pressure decreased.

Left atrial pressure (or pulmonary arterial wedge pressure) was measured both before and after operation in six persons and was found to decrease in each. In two patients in the group abnormal mean left atrial pressure at rest persisted postoperatively (fig. 6). Mean diastolic pressure gradients across the mitral prosthesis were of the same order of magnitude as those across the tricuspid prosthesis; the average for the group was 5.6 mm Hg. There was no pressure gradient between the left ventricle and brachial artery (or aorta).
Simultaneous postoperative right atrial and ventricular pressure records. Right ventricular pressure was obtained by a small catheter traversing the tricuspid prosthesis. (A) Patient 9 who has normal right atrial pressure. (B) Patient 4 whose mean right atrial pressure is above the normal range. The diastolic pressure gradients across the tricuspid prosthesis are indicated by the black areas. It is evident that the right atrial a wave precedes right ventricular systole by abnormal period, due to delayed onset of right ventricular contraction.

Pressures in patient 9, as a catheter was pulled back from the right ventricle to the right atrium while a second catheter continuously recorded right atrial pressure. This maneuver did not show gross changes in right atrial pressure-pulse configuration or in the level of mean right atrial pressure due to the catheter traversing the tricuspid prosthesis.
in four patients. Others had peak systolic gradients between 5 and 35 mm Hg, as shown in figure 7.

The stress of exercise was assessed in seven patients. Right ventricular or pulmonary arterial pressures were not obtained because of the tricuspid prosthesis, and observations were limited to right and left atrial and systemic arterial pressures, oxygen consumption, and cardiac output. Right atrial pressure rose with exercise in all; the average MRAP at rest of 6 mm Hg increased to 10 with exercise. Left atrial pressure rose in the persons in whom it could be measured during exercise, and values from 8 to 25 mm Hg were found. Records from a patient whose right and left atrial pressures remained within the normal range during exercise are shown in figure 8. The relationship between changes in oxygen consumption and cardiac output with exertion could be appraised only incompletely. In five individuals the average increase in cardiac output for each 100-ml increase in oxygen consumption was 510 ml, a subnormal value. In individual patients varied widely in their ability to increase cardiac output with exercise. Patient 1 had no change while patient 10 had a large, normal increase.

Left ventricular cineangiograms were obtained in five patients. There was no discernible mitral regurgitation in two persons, and two others had faint traces of contrast agent appear transiently in the left atrium, not considered indicative of a leak around the mitral prosthesis. One patient (no. 7) had more mitral regurgitation than usually was seen after ball-valve replacement of the mitral valve, and a moderate leak around the prosthetic ring is believed present.

Discussion

Previous studies have demonstrated the hemodynamic characteristics of the Starr-Edwards mitral valve prosthesis. Although it was known from those investigations that a small diastolic pressure gradient exists across the prosthesis when used in the mitral orifice, the level of MRAP which would result after replacement of the tricuspid valve was not known. The present observations suggest that tricuspid valve replacement will result in a MRAP which is at or slightly above the upper

Figure 6

Simultaneous left atrial and ventricular pressures. (A) Patient 9, who has normal left atrial pressure at rest, despite tachycardia of approximately 110 per minute. The top of the left ventricular pressure record is cut off due to high amplification. (B) Patient 4 whose mean left atrial pressure at rest is abnormal. The diastolic pressure gradients across the mitral prosthesis are indicated by the black areas.
Simultaneous left atrial, left ventricular, and systemic arterial pressures in two patients who had tricuspid, mitral, and aortic valve replacement. (A) Patient 3 who has no systolic pressure gradient between the left ventricle and brachial artery. (B) Patient 5 who has a systolic pressure gradient larger than that usually found after aortic valve replacement. Though recorded at low amplification here, the small diastolic pressure gradients across the mitral prosthesis are evident.

In addition to the characteristics of the prosthesis itself, two factors seem important in determining the level of the MRAP. Right ventricular diastolic pressure is one of these determinants, since any pressure gradient across the prosthesis is superimposed above this level. Thus it was found, as expected, that those persons with the lowest right ventricular end-diastolic pressures tended to have lower MRAP. The second additional factor is the cardiac rhythm. The average MRAP for four patients with atrial fibrillation was almost 9 mm Hg, whereas it was slightly above 4 mm Hg in those six persons with normal sinus rhythm. These small groups do not allow statistically valid generalization and uncertainty concerning cause and effect remains. Nonetheless, it is suggested that organized atrial contraction resulting from sinus rhythm is important in producing a lower MRAP in the presence of a tricuspid ball-valve prosthesis than would be present with atrial fibrillation. Previous observations by Braunwald and Frahm upon left atrial function in man seem analogous in this regard.12 These workers demonstrated the importance of left atrial contraction in keeping mean left atrial pressure at a low level when inflow into the ventricle was impeded by left ventricular hypertrophy.

The passage of a small cardiac catheter through the tricuspid prosthesis had no adverse effects, judging from the configuration of the right atrial pressure records before and after the right ventricular catheter was in place. Despite these observations related to the tricuspid prosthesis, we have not put
catheters through aortic or mitral ball-valve prostheses and remain reluctant to do so.

A marked decrease in right ventricular systolic pressure in association with a higher cardiac output after operation suggests an important fall in pulmonary vascular resistance in several patients. This was most apparent in the four persons who had preoperative right ventricular systolic pressures of 75 to 119 mm Hg, whose postoperative values were from 29 to 46 mm Hg. In our experience, marked elevation of pulmonary arterial pressure after mitral valve replacement has been associated with persistently abnormal left atrial pressure and has been relatively uncommon. Increasing evidence indicates reversibility of the anatomic or physiological changes in the pulmonary vascular bed associated with pulmonary hypertension due to chronic mitral valve disease. Recently, Braunwald and his associates \(^\text{13}\) reviewed their experience after mitral valve replacement in patients who had important pulmonary hypertension preoperatively. They concluded that a significant decrease in pulmonary vascular resistance is the usual postoperative finding. Using their own prosthesis, Beck and associates \(^\text{14}\) also found some gross decreases in pulmonary vascular resistance after mitral replacement. The results in some of our patients are similar and support the concept that severe pulmonary hypertension in mitral valve disease is not necessarily persistent after left atrial pressure is reduced.

The systolic pressure gradients across the aortic prosthesis were generally similar to those observed after isolated aortic replacement. \(^\text{15}\) An exception is patient 5, whose gradient was larger than that usually found. We believe that a region which produces a major contribution to the pressure gradient across the aortic prosthesis is between the ball and the aortic wall. This idea has been supported by observations at surgery and by the fact that transvalvular pressure gradients and valve size have not been consistently related.

The function of the ball-valve prosthesis in the mitral ring has been investigated by several workers. Although there is a diastolic pressure gradient between the left atrium and ventricle, most patients have mean left atrial pressure which is within the normal range. This is the case in six of the eight patients in this report in whom postoperative left atrial pressures were recorded. In the two patients with persistent left atrial hypertension, mitral regurgitation around the prosthesis has been excluded by cineangiography as a cause of the continuing abnormality.
Patient 2 is the only one of the group who has had no significant clinical improvement from his operation. His catheterization findings before operation did not seem different from those of others who have had a satisfactory result from surgery, and his outcome does not seem to have been predictable. His postoperative catheterizations revealed elevated right ventricular systolic and end-diastolic pressures as well as the highest resting MRAP in the entire group. Left ventricular end-diastolic pressure was just above the upper normal limit as well. Right ventricular and left ventricular angiography performed through a percutaneous needle did not demonstrate mitral or tricuspid regurgitation. His left atrial pressure has not been measured postoperatively, and it is conceivable, though not considered likely, that a left atrial thrombus is present and is impeding transvalvular diastolic flow. However, we have concluded, tentatively, that myocardial disease of unknown cause is responsible for his failure to improve after valve replacement.

The genesis and character of a myocardial "factor" producing impaired hemodynamic function postoperatively is not clear. The existence of primary muscle dysfunction in rheumatic heart disease was discussed as long as 10 years ago, and yet has not really become clarified. Such an influence could be related to the subnormal rise in cardiac output with exercise which some of our patients displayed in these studies during their first postoperative year. Overt postoperative myocardial insufficiency is less frequent than we believed a few years ago, but its importance, nonetheless, seems exemplified by patient 2, as described earlier. At present, we believe that an inadequate clinical or hemodynamic result after valve replacement can be blamed on a myocardial abnormality only after angiographic and other studies have excluded prosthetic leak or dysfunction. The basis for such presumed myocardial dysfunction is not yet established but might not necessarily be related to permanent histopathological findings such as myofibrosis.

Summary

Postoperative cardiac catheterizations were performed in eight patients within the first year following replacement of the tricuspid, mitral, and aortic valves with Starr-Edwards ball-valve prostheses. Two additional patients were studied who had mitral and tricuspid replacement. Before surgery the patients characteristically had distinct elevation of right and left atrial pressures, and markedly reduced cardiac outputs. Four individuals had marked pulmonary hypertension. At the postoperative catheterizations, consistent changes were an increase in cardiac output, a decrease in right and left atrial pressures, and a decrease in right ventricular systolic pressure. The last change was particularly notable in those individuals who had marked pulmonary hypertension before surgery.

Acknowledgment

We are grateful to the following physicians who supplied preoperative catheterization findings: Dr. A. M. Schmidt, University of Utah (patient 2); Dr. Phillip Wagner, U. S. Naval Hospital, San Diego, California, (patient 4); Dr. D. W. Sutherland, Portland, Oregon, (patient 6); and Dr. H. J. Semler, Portland, Oregon, (Patients 3 and 9). Dr. L. W. Ritzmann, Veteran's Hospital, Portland, Oregon, supplied preoperative and postoperative data for patient 2.

References

6. BRAUNWALD, E., FISCHER, A. P., AND COURAND, A.: Time relationship of dynamic events in the cardiac chambers, pulmonary artery and


Francis Bacon: Of Regiment of Health (Circa 1625)

Physicians are some of them so pleasing and conformable to the humour of the patient, as they press not the true cure of the disease; and some other are so regular in proceeding according to art for the disease, as they respect not sufficiently the condition of the patient. Take one of a middle temper; or if it may not be found in one man, combine two of either sort; and forget not to call as well the best acquainted with your body, as the best reputed of for his faculty.—Hugh G. Dick (Ed.) Selected Writings of Francis Bacon. In The Modern Library. New York, Random House, 1955, p. 86.
Cardiac Catheterization Studies after Combined Tricuspid, Mitral, and Aortic Valve Replacement

J. DAVID BRISTOW, FRANK E. KLOSTER, RODNEY HERR, ALBERT STARR, COLIN W. MCCORD and HERBERT E. GRISWOLD

*Circulation.* 1966;34:437-447
doi: 10.1161/01.CIR.34.3.437

*Circulation* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231

Copyright © 1966 American Heart Association, Inc. All rights reserved.

Print ISSN: 0009-7322. Online ISSN: 1524-4539

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/34/3/437

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/