RECONSTRUCTION OF PULMONARY ARTERY WITH SUBSTITUTE VALVE
— With Special Reference to Size of Conduit and Valve —

HIDETAKA OKU, M.D., HITOSHI SHIROTANI, M.D., TATSUO YOKOYAMA, M.D.
JUN KAWAI, M.D., TAKAZUMI NISHIoka, M.D., HIROSHI OKA, M.D.
OSAMU KATAYAMA, M.D., TOSHIHIKO SAGA, M.D.
and NOBUO WAKAKI, M.D.

Operative risk factors and postoperative late results were evaluated in 26 patients undergoing pulmonary artery reconstruction with a substitute valve. Seventeen extracardiac conduits bearing a valve were used in 16 patients and an in situ pulmonary valve insertion was carried out in the other 10. The surgical results were influenced by complexity of the underlying cardiac lesions and pulmonary vascular status, with a high mortality rate in patients with several cardiac defects including single ventricle, asplenia syndrome, complete atrioventricular canal etc. The mortality rate was 6% in patients with an immediate postrepair Ppv/sv of less than 0.75 and 77.8% in those with a Ppv/sv over 0.75. Postoperative Ppv/sv was mainly regulated by valve area index and a close correlation was obtained for the regression equation Ppv/sv = 0.41/(Val)² + 0.36 (r = −0.61, p < 0.05). To obtain excellent hemodynamics with a Ppv/sv of less than 0.50, valve area index should be over 1.7 cm²/M², and to eliminate re-implantation of the conduit after reaching adulthood, the diameter of the conduit should be 18 mm or more and the valve size 23 A, or more when a SJM valve is used.

EXTRACARDIAC conduit has been used mainly for patients with a decreased pulmonary blood flow and a discontinuity between the pulmonary ventricle and artery. Recently, this procedure has also been employed for patients with pulmonary hypertension involving transposition and ventricular septal defect, and Taussig-Bing malformation as well as truncus arteriosus. However, there are unresolved problems regarding the quality of the valves and conduits, and long-term complications. On the other hand, when continuity is preserved between the right ventricle and pulmonary artery, an in situ valve insertion is a preferable procedure for reconstruction of the pulmonary artery. To our knowledge, there has been no report on the relationship between the surgical and late results and the size of conduit and valve.

The present study deals with the surgical risk factors and the postoperative hemodynamic results, with special reference to the size of the conduit and valve, in patients undergoing reconstruction of the pulmonary artery with these substitute valves.

**Key Words:**
- PA reconstruction
- Substitute valve
- Ppv/sv and valve area index

**MATERIALS AND METHODS**
From June 1975 to August 1983, 26 patients

(Received October 23, 1983; accepted May 1, 1984)
Department of Cardiovascular Surgery, Kinki University School of Medicine, Osaka, Japan
Mailing address: Hidetaka Oku, M.D., Department of Cardiovascular Surgery, Kinki University School of Medicine, 380 Nishiyama, Sayama-cho, Minamikawachi-gun, Osaka 589, Japan

1074 Japanese Circulation Journal Vol. 48, October 1984
underwent 27 reconstructions of the pulmonary artery with an extracardiac conduit and an in situ valve insertion. These 26 were classified into six different diagnostic categories as follows; six patients had a single ventricle, another six had pulmonary atresia with ventricular septal defect (VSD), three had complete transposition of the great arteries (TGA), four had tetralogy of Fallot, two had absent pulmonary valve syndrome and the remaining five were classified as miscellaneous. In the six patients with single ventricle, four had double outlet right ventricle and two had TGA. Pulmonary stenosis (PS) was present in five and pulmonary hypertension in one. Three were of asplenia syndrome with complete atrioventricular canal, single atrium and other defects. Out of the three patients with TGA and VSD, two had pulmonary stenosis and one severe pulmonary hypertension. Absent pulmonary valve syndrome was seen in the patients with Fallot's tetralogy and two-chambered right ventricle. In the total 26 patients, 19 had PS and five severe pulmonary hypertension. As a prior operation, Blalock-Taussig shunt had been performed in 10 patients, Brock's operation, palliative Rastelli operation and pulmonary artery banding had each been performed in one, and correction of tetralogy of Fallot in two.

The average age at operation was 13.3 years with a range from 9 months to 54 years. Valved conduits were used in 17 operations including one reoperation, and in situ valve insertions were performed in the other 10. The extracardiac conduit was placed from the morphologic right ventricle to the pulmonary artery in 11 cases and from a septated univentricular heart to the pulmonary artery in six. In an extracardiac conduit repair, when the main pulmonary artery was present, it was divided and the proximal stump oversewn. A conduit was then interposed between the pulmonary ventricle and distal stump of the pulmonary artery. In placing the in situ valve insertions, a transannular incision was made from the pulmonary ventricular outflow tract to the main pulmonary artery in order to implant a substitute valve at the valve ring or in the pulmonary artery wall above the ring. The defect of the anterior wall of the pulmonary artery and ventricular outflow tract was covered with a knitted Dacron patch.

Deep hypothermia with cardiopulmonary bypass was employed in two cases and routine moderate hypothermic cardiopulmonary bypass

Table 1: Effective Orifice Area of Substitute Valves

<table>
<thead>
<tr>
<th>Substitute valve</th>
<th>Effective orifice area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S J M - 31</td>
<td>4.33</td>
</tr>
<tr>
<td>L K - 20</td>
<td>2.89</td>
</tr>
<tr>
<td>S J M - 23</td>
<td>2.55</td>
</tr>
<tr>
<td>S J M - 21</td>
<td>2.06</td>
</tr>
<tr>
<td>B S - 21</td>
<td>1.55</td>
</tr>
<tr>
<td>B S - 19</td>
<td>1.16</td>
</tr>
<tr>
<td>H X - 27</td>
<td>2.10</td>
</tr>
<tr>
<td>H X - 25</td>
<td>1.75</td>
</tr>
<tr>
<td>H G - 23</td>
<td>4.15</td>
</tr>
<tr>
<td>H X - 23</td>
<td>1.46</td>
</tr>
<tr>
<td>C E - 21</td>
<td>1.35</td>
</tr>
<tr>
<td>H X - 21</td>
<td>1.15</td>
</tr>
<tr>
<td>C E - 19</td>
<td>1.06</td>
</tr>
<tr>
<td>H X - 19</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Table 2: Surgical Results According to Diagnostic Category and Procedure

<table>
<thead>
<tr>
<th>Diagnostic category</th>
<th>ISVI</th>
<th>EC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV</td>
<td>0</td>
<td>6 (4)</td>
<td>6 (4)</td>
</tr>
<tr>
<td>PA + VSD</td>
<td>1 (1)</td>
<td>5 (1)</td>
<td>6 (2)</td>
</tr>
<tr>
<td>TGA</td>
<td>0</td>
<td>3 (1)</td>
<td>3 (1)</td>
</tr>
<tr>
<td>TF</td>
<td>4 (0)</td>
<td>0</td>
<td>4 (0)</td>
</tr>
<tr>
<td>APVS</td>
<td>2 (0)</td>
<td>0</td>
<td>2 (0)</td>
</tr>
<tr>
<td>Others</td>
<td>3 (0)</td>
<td>2 (1)</td>
<td>5 (1)</td>
</tr>
<tr>
<td>Total</td>
<td>10(1)</td>
<td>16 (7)</td>
<td>26 (8)</td>
</tr>
</tbody>
</table>

Abbreviations:
ISVI = in situ valve insertion;
EC = extracardiac conduit
( ) = No. of deaths

in the remainders. For 13 patients, cold blood cardioplegia was intermittently infused. Sixteen mechanical valves were used in 15 patients, a porcine valve in 10 and an aortic homograft in one.

Intraoperative pressure measurement was done on all just before closure of the thorax. Cardiac catheterization and angiography were performed in all survivors one to three times postoperatively. The effective orifice areas

Japanese Circulation Journal Vol. 48, October 1984
(EOA) of the substitute valves were taken from the literature\textsuperscript{1–4} (Table I). The values of HX-19 and CE-19 were obtained from the intraconduit pressure gradient across the valve and the cardiac output at operation.

**SURGICAL RESULTS**

(1) Surgical Outcome According to Diagnostic Categories and Procedures

Surgical results according to the type of disorder are shown in Table II. The mortality rate was highest (66.6%) in the patients with single ventricle. It was 33.3% in the patients with pulmonary atresia and VSD and in the TGA patients, and 20% in the miscellaneous category. There was no incidence of death among the patients with Fallot’s tetralogy and those with absent pulmonary valve syndrome. Three out of the four deaths in the patients with the single ventricle were due to low cardiac output syndrome and one to advanced pulmonary vascular obstructive disease. The two deaths among the pulmonary atresia patients were due to pulmonary vascular obstructive disease and obstruction of the distal anastomosis. The TGA patient’s death was related to disseminated intravascular coagulation and deterioration of proliferative nephritis which was present preoperatively. One patient with truncus arteriosus died of hypoxia due to a reverse shunt through the residual atrial septal defect.

Out of 17 operations involving extracardiac conduit repair, seven patients died, giving a mortality rate of 41.2%. Only one of the 10 with an in situ valve insertion succumbed, resulting in a much lower mortality rate of 10%.

(2) Surgical Results and Effective Orifice Area of the Substitute Valves

Figure 1 shows the surgical results and EOAs of the substitute valves. A solid line indicates the average value of the EOA and body surface area (BSA). Of the 12 patients with relatively large substitute valve, plotted above the line, only one died, giving mortality rate of 8.3%. Of the 15 patients plotted below the line, two out of seven with a BSA exceeding 0.95 M\textsuperscript{2} died, whereas five of the eight patients with BSAs of less than 0.95 M\textsuperscript{2} (shadow area in Fig. 1) died. Thus, in the case of children with a BSA of less than 0.95 M\textsuperscript{2}, it is preferable to choose a valve which can be plotted above the regression line.

(3) Surgical Results and Postrepair Pulmonary to Systemic Systolic Pressure Ratio

Figure 2 shows the surgical results according to the valve area index (EOA/BSA) and postre-
pair systolic pressure ratio of the pulmonary to systemic ventricles (Ppv/sv) obtained just before closure of the thorax. Seven out of 9 patients with a Ppv/sv over 0.75 died, whereas only one out of 18 succumbed when this ratio was less than 0.75. Turning to valve area index (VAI), five out of eight patients with an index of less than 1.5 cm²/m² died, compared with only three deaths in the 19 patients with an index over 1.5 cm²/m². These three deaths in the latter group did not relate to this ratio but were the result of proliferative nephritis, hypoxia due to a reverse

shunt through the residual atrial septal defect and low cardiac output syndrome caused by long-term perfusion. Thus, the use of a substitute valve with a VAI over 1.5 cm²/m² is one factor related to the decrease in mortality.

**LATE RESULTS**

Late death occurred in two patients. One death was due to obstruction of left ventricular outflow tract and the other due to mediastinitis. Figure 3 shows the relationship between the postoperative pulmonary to systemic systolic pressure ratio (Ppv/sv) and the VAI one month to 8 years after surgery in the long-term survivors, except for the two late deaths. A close correlation expressed by the regression equation \( Y = 0.41/X^2 + 0.36 \) \((r = -0.61, \ p < 0.05)\) was obtained between the postoperative Ppv/sv and VAI in 15 data of 10 postoperative patients, except for 3 patients with residual defects shown by asterisks 1 to 3 in Fig. 3. Thus, the postoperative Ppv/sv was mainly regulated by VAI. To obtain excellent hemodynamics with a Ppv/sv of less than 0.50, the VAI should be 1.70 cm²/M² or more. To avoid re-placement of the conduit and to maintain excellent hemodynamics, even after reaching adulthood, the diameter of the extracardiac conduit should be 18 mm at least and the valve size 23A or more when a SJM mechanical valve is used.

The residual defects detected in three patients were branch stenosis of the pulmonary artery (asterisk 2) and residual shunt (asterisks 1, 3). In another two patients (asterisks 4, 5) with BS-19 valve, the Ppv/sv had been increased in accordance with physical development, as predicted. In one of these patients, re-placement of the conduit was carried out with a composite graft consisting of 18 mm, 24 mm Dacron grafts and a SJM 23A valve, eight years after the initial surgery because the Ppv/sv was 1.13. Cardiac catheterization two months after the second surgery showed the Ppv/sv being 0.40. A fibrous peel was present within the excised conduit and thickness of the peel was 4 to 6 mm in the prevallular conduit.

In one patient (asterisk 6) with a BS-21 valve, the Ppv/sv decreased with growth, contrary to expectation, and was 0.40 seven years after surgery despite the calculated VAI being 1.00 cm²/m². The Ppv/sv increased to 0.80, when the heart rate was increased from 80/min to 120/min with the administration of isoproterenol. Con-

*Japanese Circulation Journal* Vol. 48, October 1984
siderable right ventricular hypertrophy was also demonstrated on electrocardiograms and the right ventriculogram showed a remarkable stenosis at the substitute valve. Thus, the BS-21A valve does not seem to be sufficiently large, even when the Ppv/sv is 0.40 at rest.

**DISCUSSION**

The factors affecting operative results include complexity of intracardiac structure, pulmonary vascular resistance, size of the conduit and valve, obstruction of the anastomosis, duration of perfusion and myocardial protection. In this series, surgical results were poor in patients with single ventricle, particularly in those with asplenia syndrome and complex cardiac lesions including complete atrioventricular canal etc. At the Mayo clinic, surgical and late results were poor in septation repair for single ventricle, and the Fontan operation is now available for patients with normal pulmonary vascular resistance.

In cases of pulmonary atresia with VSD, surgical results have recently improved and mortality rates are now less than 10%. Our two who died were both initial patients and advanced pulmonary vascular obstructive disease and obstruction of the distal anastomosis were present. Recently, a detailed evaluation of the pulmonary vascular resistance and use of a technical device have decreased the mortality rates considerably. Since it was reported from the Mayo clinic that surgical correction is indicated for patients with pulmonary vascular resistance of less than 10 unit.m² and this criterion has been widely applied. However, our evaluation of pulmonary vascular resistance in the TGA patients with severe pulmonary hypertension revealed that corrective surgery is indicated when the resistance is less than 15 unit.m². In patients with low pulmonary blood flow, we often find that the pulmonary artery pressure cannot be measured and have to use (RPA + LPA)/desc Ao and maximum left atrial volume instead. At present, we consider that corrective surgery is indicated when the former is over 1.2 and the latter is over 50% of the predicted normal value.

As a technical device, we often interpose a Ryyg tube or a pericardial tube between the post-valvular conduit and the distal pulmonary artery when bifurcation of the pulmonary artery is stenotic, and main or right and left pulmonary arteries are hypoplastic. Obstruction of the anastomosis can thus be avoided.

Recently, the mortality following Rastelli operation for TGA patients with VSD and PS has decreased considerably. In TGA patients with VSD, successful corrections by means of Rastelli operation and Damus-Kaye-Stansel operation have been reported. We successfully carried out repair in a TGA patient with VSD and PDA, who underwent Rastelli operation at the age of 18 months. Postoperative care presented few difficulties compared with that required after Mustard operation, and postoperative hemodynamics and systemic ventricular function were satisfactory. In TGA patients with VSD and PS, surgical correction is generally considered to be indicated when the child is 5 year-old or over. In TGA patients with VSD, left and right ventricular volumes are enlarged and right ventricular end-diastolic volume is about 200% of normal. This means that the right ventricular volume is still quite large even after the insertion of an internal conduit between VSD and the aortic orifice. As left ventricular end-diastolic volume should be at least 60–65% of normal to support systemic circulation, the lower limit of right ventricular end-diastolic volume necessary to maintain pulmonary circulation is considered to be 60–65% of normal, as well. Thus, extracardiac conduit repair can be done on infants. Yokota and Makino stated from their experience of successful Stansel operation on infants, that the pre-valvular conduit to right ventricular volume ratio is related to postoperative right ventricular failure, and that a conduit with a diameter of 20 mm is probably too large for infants. An acceptable ratio has to be established.

The surgical results in the patients undergoing in situ valve insertions were better than those of the patients who had extracardiac conduit repairs. This was due to differences in the complexity of the anatomic structure rather than the procedures, but an in situ pulmonary valve insertion does have many advantages. It allows for insertion of a larger valve, and eliminates the possibility of compression, obstruction at the proximal and distal anastomosis and obstruction due to fibrous peel. Furthermore, it is indicated for patients with a small right ventricular volume because it results in less dead space.

Generally, Ppv/sv has served as useful parameter for postoperative hemodynamics. In the present study, the mortality rate was high in the
patients with a Ppv/sv over 0.75 just before closing the thorax and low in the patients with a Ppv/sv of less than 0.75. Therefore, ensuring that the Ppv/sv (which is regulated by the resistances from the right ventricle to the peripheral pulmonary arteries) is less than 0.75 is a major factor in improving the surgical result.

Pulmonary vascular resistance should be 15 unit.m² or less, as already mentioned. Length and size of the conduit can also influence the pulmonary circulation, however the resistance of the conduit is insignificant, compared with that of the valve contained within it. Hence, the EOA of the substitute valve should be given. Provided that the pulmonary vascular resistance is normal and stenosis is not present at the anastomosis, the VAI should be 1.0 cm²/M² or more, in order to obtain a Ppv/sv of less than 0.75. In practice, the VAI should be 1.5 cm²/M² or more, because there is resistance in areas other than the valve.

Late Ppv/sv is a useful parameter in estimating the postoperative long-term prognosis. This is provided by the systemic vascular resistance and the pulmonary ventricular afterload including total resistance from the ventricle to the peripheral pulmonary arteries. In the present study, a close correlation was obtained between Ppv/sv (Y) and VAI (X), which is expressed in the regression equation Y = 0.41/X² + 0.36. This is very similar to the equation y = 0.42/x² + 0.36 which was obtained between the right ventricular to aortic systolic pressure ratio (y) and cross-sectional area index (x) in the postoperative Fallot's patients. In the late postoperative period, the resistances of the pulmonary vascular bed, conduit and the anastomosis are significantly small, compared with that of the valve, and Ppv/sv is mainly regulated by VAI. This regression equation is very useful for evaluating the late postoperative Ppv/sv and in choosing the substitute valve. According to the equation, VAI should be 1.7 cm²/M² or more to obtain excellent hemodynamics with a Ppv/sv of less than 0.50. In the adult patients, the diameter of the conduit should be 18 mm at least and the valve size over 23A, or more in the SJM valve which has a relatively large EOA.

McGoon et al. mentioned that postrepair Ppv/sv, together with age, was a principal prognostic indicator of late survival. In our study also, late hemodynamic results were excellent in all patients with a Ppv/sv of less than 0.70, whereas in all patients with a Ppv/sv over 0.70, residual lesions were detected. In one of these patients, conduit re-implantation was carried out. The fundamental cause of conduit obstruction was in the BS-19 valve itself and fibrous peel within the preavalval conduit was a major factor leading to an increase in pressure in the pulmonary ventricle. The incidence of conduit obstruction due to fibrous peel is strikingly small, compared with that of stenosis in the aortic homograft. Agarwal et al. stated that reoperation for obstruction due to fibrous peel was required in eight of 308 patients with conduit bearing a porcine valve. The etiology of peel formation is unknown, however thrombosis and infection may play some role.

Acknowledgment

We thank M. Ohara (Kyushu University) for critical readings of the manuscript.

REFERENCES

10. CIARAVELLA JM Jr., MCGOON DC, DANIIELSON

Japanese Circulation Journal Vol. 48, October 1984


