Optimal Size of Outflow Patch in Total Correction of Tetralogy of Fallot

Akira FURUSE, M.D., Akira Mizuno, M.D., Goki SHINDO, M.D., Takaji YAMAGUCHI, M.D., and Masahiro SAIGUSA, M.D.

SUMMARY

Hemodynamic and angiocardiographic studies were performed in postoperative patients with tetralogy of Fallot. Pressure gradient between the right ventricle and pulmonary artery was correlated with the narrowest area in the pulmonary arterial pathway. Regurgitant fraction was also correlated with regurgitant area which was determined by preoperative area of the pulmonic annulus and width of the outflow patch. Follow-up study of postoperative patients with tetralogy indicated that those with pressure gradient less than 20mmHg and regurgitant fraction less than 15% could be considered ideally corrected. A table was constructed for determining the most appropriate width of the outflow patch for the ideal correction.

Additional Indexing Words:
Pulmonary regurgitation    Residual pulmonary stenosis

ALTHOUGH great improvement has been accomplished in early surgical results of total correction of tetralogy of Fallot, late hemodynamic studies have disclosed that a number of patients are surviving the operation with various residua, sequelae, or complications.1)–3)

Reconstruction of the outflow tract is the most important part of this operation. It is mandatory to place a patch across the pulmonary valvular annulus in cases with hypoplastic valvular ring. However, decision concerning use of the outflow patch or determination of size of the patch to be used has been made by relatively simple way. Some use the index finger for adult patients or small finger for infants as a measure to determine whether or not a patch should be placed across the valvular annulus.4) Even if this is a proper criterion, this does not tell the size of the patch to be utilized. Pressure measurement after closure of the right ventriculotomy will tell whether an outflow patch is necessary or not.3) This try-and-error method might increase postoperative morbidity by prolongation of perfusion time. Again the

From the Department of Thoracic Surgery, Faculty of Medicine, University of Tokyo, 7-3-1, Bunkyo-ku, Hongo, Tokyo 113, Japan.
Received for publication February 17, 1977.

629
size of the outflow patch to be inserted cannot be determined by this method.

Late hemodynamic and angiocardiographic studies on postoperative patients with tetralogy of Fallot offer data concerning relationship between size of the pulmonary arterial pathway and severities of residual pulmonary stenosis or regurgitation. In the previous paper we documented a method of quantifying pulmonary regurgitation.5) The first part of this paper deals with residual stenosis. Combining these 2 factors together, one can derive the most appropriate size of patch to be implanted for a given patient. This paper describes a practical method of determining the size of the patch.

**Methods**

I. Evaluation of residual pulmonary stenosis

Twenty-six patients with tetralogy of Fallot who underwent corrective surgery average 2.6 years previously were studied with right heart catheterization and right ventriculography. Those with residual inter-ventricular shunt were excluded from the current study. Lateral right ventriculograms were used to measure the smallest diameter of the pulmonary arterial pathway at end-diastole. Difference of the systolic pressures between the right ventricle and pulmonary artery was used to assess the hemodynamic severity of the residual obstruction.

II. Estimation of proper size of outflow patch

The following criteria were utilized to determine the most appropriate width of the outflow patch.

1. Pressure gradient between the right ventricle and pulmonary artery ($\Delta P$) should be less than 20 mmHg.
2. Regurgitant fraction (RF) should be less than 15%.

Calculations were made using a Canola SX-100 electronic programmable calculator.

**Results**

Smallest areas in the pulmonary arterial pathway corrected by body surface area ($A$) were plotted against systolic pressure gradients between the right ventricle and pulmonary artery ($\Delta P$) in Fig. 1. Logarithms of both parameters held linear regression correlation:

$$\log \Delta P = -2.19 \log A + 1.79 \quad (r = -0.87, \ p<0.001)$$

Therefore:

$$\Delta P = 62.0 A^{-2.19} \quad (1)$$

A curve showing this formula (PS curve) was also depicted in Fig. 1.
In the previous paper it was described that regurgitant fraction (RF) could be determined by regurgitant area corrected by body surface area (RA):

\[ RF = 6.94 RA^{1.09} \]

Since RA = A1 - A2, it was converted to:

\[ RF = 6.94(A_2 - A_1)^{1.09} \]  

where A1 and A2 were preoperative and postoperative annulus area respectively. Different curves showing relationship between postoperative annulus area and regurgitant fraction (PI curves) were obtained according to preoperative annulus area as illustrated in the previous paper.

Both PS curve and PI curves were put together in Fig. 2. Scales of 2 ordinates were adjusted so that maximum acceptable values of ΔP and RF lay on the same scale. Then proper size of the outflow patch was expressed as an optimal range for a given patient. This optimal range was shown in Fig. 2 as thick portion on the PI curve. The minimum limit of the range was determined by an intersection of the PS curve with a horizontal line indicating ΔP 20 mmHg. The minimum limit of the postoperative annulus area thus obtained was approximately 1.8 cm²/M² body surface area, independent of preoperative annulus area. The maximum limit of the optimal range was determined by intersections of the PI curves with a horizontal line indicating RF 15%. Since each patient had different PI curve according to his preoperative annulus area, the maximum limit of the range was also individualized. It is interesting to note that the smaller is preoperative...
Fig. 2. PS curve and PI curves. Scales of the ordinate were adjusted as described in the text. To determine proper size of the outflow patch, select a PI curve according to preoperative annulus size. Thick portion of the PI curve indicates acceptable range of postoperative annulus size. Patch width may be calculated using formula (4) in Appendix I.

Table I. Determination of Width of Outflow Patch (cm)

<table>
<thead>
<tr>
<th>Body surface area (M²)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
<th>1.1</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
<th>1.5</th>
<th>1.6</th>
<th>1.7</th>
<th>1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>0.8</td>
<td>1.1</td>
<td>1.3</td>
<td>1.6</td>
<td>1.8</td>
<td>2.0</td>
<td>2.2</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
<td>3.2</td>
<td>3.3</td>
<td>3.5</td>
</tr>
<tr>
<td>1.1</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>0.9</td>
<td>1.1</td>
<td>1.3</td>
<td>1.6</td>
<td>1.8</td>
<td>2.0</td>
<td>2.2</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
<td>3.2</td>
<td>3.3</td>
<td>3.5</td>
</tr>
<tr>
<td>1.2</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>0.9</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
<td>1.8</td>
<td>2.0</td>
<td>2.2</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
<td>3.2</td>
<td>3.3</td>
</tr>
<tr>
<td>1.3</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.0</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
<td>1.7</td>
<td>1.9</td>
<td>2.1</td>
<td>2.3</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>1.4</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.0</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
<td>1.7</td>
<td>1.9</td>
<td>2.1</td>
<td>2.3</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>1.5</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.0</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
<td>1.7</td>
<td>1.9</td>
<td>2.1</td>
<td>2.3</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>1.6</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.2</td>
<td>1.3</td>
<td>1.5</td>
<td>1.7</td>
<td>1.9</td>
<td>2.1</td>
<td>2.3</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
<td>3.2</td>
</tr>
<tr>
<td>1.7</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.2</td>
<td>1.3</td>
<td>1.5</td>
<td>1.7</td>
<td>1.9</td>
<td>2.1</td>
<td>2.3</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
<td>3.2</td>
</tr>
<tr>
<td>1.8</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.3</td>
<td>1.4</td>
<td>1.6</td>
<td>1.7</td>
<td>1.9</td>
<td>2.1</td>
<td>2.3</td>
</tr>
<tr>
<td>1.9</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.3</td>
<td>1.4</td>
<td>1.6</td>
<td>1.7</td>
<td>1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>2.0</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.3</td>
<td>1.4</td>
<td>1.6</td>
<td>1.7</td>
<td>1.9</td>
</tr>
<tr>
<td>2.1</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.3</td>
<td>1.4</td>
<td>1.6</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Asterisk indicates that outflow patch is not required.
annulus area, the narrower is the range.

When one chooses any size of postoperative annulus within this range, one can expect that the patient will have ΔP less than 20 mmHg and RF less than 15%. The selection of size within range seems to be personal preference of surgeons. Some may place a small patch permitting ΔP approximately 20 mmHg. Others may use a large patch leaving reasonable degree of pulmonary regurgitation. Final answer to this selection could be obtained if one knew relative contributions of pulmonary stenosis and regurgitation on the right ventricular function.

Meantime, as a practical choice, one can take an intersection of the PS curve with the PI curve for a given patient. Table I was computed based on this idea as described in Appendix I. When one knows the preoperative diameter of the annulus and body surface area of the patient, one can determine the width of the outflow patch to be placed across the annulus. Asterisks in the Table indicate that the patient does not require an outflow patch, because the preoperative annulus area of the patient exceeds the minimum limit of 1.8 cm²/M².

**DISCUSSION**

Main purpose of this communication is to describe how we can determine the most appropriate size of the outflow patch in total correction of tetralogy of Fallot. In the first place we should establish maximal acceptable limits in terms of residual pressure gradient and regurgitant fraction. Late follow-up study of postoperative patients with tetralogy of Fallot performed in our Department as well as others demonstrated that patients with residual pressure gradient between the right ventricle and pulmonary artery less than 50 mmHg were leading normal life without symptom. However, ideally the gradient should be less than 20 mmHg, since it has been known that exercise increases the pressure gradient considerably. Regarding regurgitant fraction, most patients have tolerated even severe pulmonary regurgitation without exercise intolerance. However, those with greater regurgitant fraction have larger right ventricular end-diastolic volume and smaller ejection fraction. While long-term prognosis of those with severe pulmonary regurgitation has not been determined, it is reasonable to make every effort to lessen the regurgitant fraction. As a tentative maximum limit of regurgitation we took regurgitant fraction of 15% as stated in the previous paper.

Reservation must be made as to the absolute accuracy of figures appearing in Table I due to several reasons described below. Firstly angiocardio-
condly interactions between residual pulmonary stenosis and regurgitation have been completely neglected. Presence of regurgitation apparently increases pressure gradient by increased right ventricular stroke volume. Simple calculations shown in Appendix II indicate that mean systolic pressure gradient across the stenosis will increase by 23, 56, or 104% when associated with regurgitant fraction of 10, 20, or 30%, respectively. Presence of residual stenosis also affects the amount of regurgitant volume. Calculations with several assumption as described in Appendix III indicate that residual stenosis in the vicinity of the annulus will reduce the regurgitant volume (Fig. 3). Even slight residual obstruction in this location that does not cause any measurable pressure gradient could reduce regurgitation considerably. Diffuse obstruction of the pulmonary arterioles requires special considerations in this regard. In this situation there is a reservoir which contains relatively large amount of blood as compared to usual regurgitant volume. Pulmonary arteriolar obstructions will not work as resistors to the regurgitant flow as considered in those with residual stenosis adjacent to the pulmonary valvular annulus. On the contrary, it will aggravate the regurgitation by elevating mean diastolic pressure difference between the pulmonary artery and right ventricle.

Table I was made using data collected from heterogenous patients with or without residual pressure gradient less than 20 mmHg, those with or without pulmonary regurgitation, and those with or without pulmonary hypertension. Therefore results shown in Table I must be considered as average values in these heterogenous patients. For clinical purpose, Table I should be used cautiously just as a guide. We have started a prospective study using
this Table. In a few patients so far operated according to this Table, results are satisfactory.

APPENDIX I

At the intersection of the PS curve with the PI curve in Fig. 2, relationship between $\Delta P$ and RF may be expressed:

$$\frac{\Delta P}{20} = \frac{RF}{15}$$

Since $\Delta P$ and RF in this equation can be obtained from empirical formulae (1) and (2) as:

$$\Delta P = 62.0A_2^{-2.19}$$
$$RF = 6.94(A_2-A_1)^{1.09}$$

where $A_1$ and $A_2$ are pre- and postoperative annulus area respectively, the above equation is converted to:

$$\frac{62.0A_2^{-2.19}}{20} = \frac{6.94(A_2-A_1)^{1.09}}{15}$$

This can be simplified as:

$$A_2^2 - A_1A_2 - 5.72 = 0$$

(3)

$A_1$ is obtained from preoperative diameter of the annulus ($D_1$) and body surface area ($B$) using an equation:

$$A_1 = \frac{\pi D_1^2}{4B}$$

Therefore $A_2$ can be computed from the equation (3). Then width of the patch to be implanted is:

$$\text{Patch width} = 2\sqrt{\pi B\left(\sqrt{A_2} - \sqrt{A_1}\right)}$$

(4)

APPENDIX II

Gorlin's formula\(^8\) may be expressed:

$$\sqrt{\Delta P} = \frac{HR}{k \cdot A} \cdot RVSV$$

where $\Delta P$=mean systolic pressure gradient across the stenosis, $k$=constant, $t$=systolic ejection time per minute, $A$=area at the stenosis, $HR$=heart rate, and $RVSV$=right ventricular stroke volume. Regurgitant fraction may be expressed:

$$RF = 100\left(1 - \frac{LVSV}{RVSV}\right)$$
where LVSV = left ventricular stroke volume. Therefore:

\[ \sqrt{JP} = \frac{HR}{k \times t \times A} \times \frac{100}{100 - RF} \]

When pulmonary regurgitation does not exist (RF = 0):

\[ \sqrt{JP_0} = \frac{HR}{k \times t \times A} \times LVSV \]

Therefore the following formula is obtained:

\[ \frac{JP}{JP_0} = \left( \frac{100}{100 - RF} \right)^2 \] (5)

**APPENDIX III**

Suppose residual obstruction is present in the main pulmonary artery and pulmonary regurgitation is also present due to a patch across the valvular annulus. Mean diastolic pressures in the pulmonary artery distal to the obstruction, proximal to the obstruction, and in the right ventricle are designated as \( P_1, P_2, \) and \( P_3 \) respectively. Diastolic area at the stenosis and regurgitant area at the annulus are designated as \( SA \) and \( RA \) respectively. Regurgitant volume (\( Q \)) flows from the pulmonary artery to the right ventricle during diastolic interval (\( t \)).

Thus the following 3 equations are obtained from Gorlin's formula:9)

\[ SA = \frac{Q}{kt \times \sqrt{P_1 - P_2}} \]

\[ RA = \frac{Q}{kt \times \sqrt{P_2 - P_3}} \]

\[ TRA = \frac{Q}{kt \times \sqrt{P_1 - P_3}} \]

where \( TRA \) is total regurgitant area of the system and \( k \) is a constant. From these 3 equations, the following formula may be derived:

\[ \frac{1}{TRA^2} = \frac{1}{SA^2} + \frac{1}{RA^2} \] (6)

In previous study concerning pulmonary regurgitation,5) regurgitant fraction has been correlated with regurgitant area:

\[ \text{Regurgitant Fraction} = \frac{100Q}{CI + Q} = 6.94RA^{1.09} + 7RA \]

where CI is cardiac index. Assuming that cardiac index is 4 L/min/M², this may be converted to:

\[ Q = \frac{0.28}{\frac{1}{RA} - 0.07} \]
Since this is considered to be a special solution of general regurgitant formula in cases with the normal-sized pulmonary artery (SA=3.5 cm²/M² in the equation (6)), RA may be expressed:

\[
\frac{1}{RA^2} = \frac{1}{TRA^2} - \frac{1}{3.5^2}
\]

Therefore the general regurgitant formula is:

\[
Q = \frac{0.28}{\sqrt{\frac{1}{SA^2} + \frac{1}{RA^2} - \frac{1}{3.5^2} - 0.07}}
\]

\( Q \) Reference