Studies on Stenosis and Jet Contraction in Cardiac Surgery

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HEMODYNAMIC consideration is necessary in the surgical treatment of cardiac patients. In addition, hydrodynamic consideration concerning with stenosis, where jet contractions occur, is important in the successful treatments of patients with cardiac lesions such as tetralogy of Fallot, valvular stenosis and so forth. Surgical treatment in connection with stenosis could be divided into following three groups.

- (1) eliminating (valvular stenosis, tetralogy of Fallot)
- (2) constructing (pulmonary artery banding)
- (3) concomitance (aorto-pulmonary anastomosis, etc.)

Theoretical consideration from hydrodynamic viewpoint as well as clinical and experimental results in each group is discussed in the following.

Fig.1. (a) Pressure curves in PA and RV outflow tract
(b) LV and aortic pressure curves, and aortic flow curve
Prsm: Preoperative systolic mean RV pressure
Pp : Pulmonary artery pressure
Plsm: Systolic mean LV pressure
Pa : Aortic mean pressure
Fssm: Systolic mean systemic blood flow

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Fig.2. Hemodynamic states before and after operation in tetralogy of Fallot

Prms: Preoperative systolic mean right ventricular pressure
 Plms: Preoperative systolic mean left ventricular pressure
 P'rms: Postoperative systolic right ventricular pressure
 P'lms: Postoperative systolic mean left ventricular pressure
 Ro: Preoperative right ventricular outflow resistance
 R'o: Postoperative right ventricular outflow resistance
 Rs: Systemic vascular resistance
 Rp: Preoperative pulmonary vascular resistance
 R'p: Postoperative pulmonary vascular resistance
 Fs: Systemic blood flow
 Fp: Preoperative pulmonary blood flow
 Fpsm: Preoperative systolic mean pulmonary blood flow

(1) Tetralogy of Fallot

(a) Theoretical Consideration

Radical operation consists of closure of VSD and relief of RV outflow obstruction. Two conditions are necessary in achieving a successful operation. One is to decrease RV pressure so as to minimize pressure loading to RV after operation.¹⁾ The other is to preserve as much RV function as possible to overcome postoperative pressure loading.

Preoperatively, systemic and pulmonary blood flow ratio is determined by output resistance of both ventricles, since VSD offer no impedance to blood flow in tetralogy of Fallot. As shown in Fig. 1 (a), where there is stenosis, blood flow is rather steady than pulsatile beyond it. Pulmonary artery pressure (P_p) is pulmonary blood flow (F_p) times pulmonary vascular resistance (R_p), so the following equation is obtained,

$$P_p = F_p \times R_p$$

Let P_{rms} , R_o and F_{psm} be systolic mean RV pressure, RV outflow resistance and systolic

Fig.3. Postoperative RV/LV pressure ratio (α , α')
 α : Calculated value from theoretical formula
 α' : Actual value obtained by pressure measurement

Fig.4. Graphical analysis of relationship between degree of PA constriction and pulmonary blood flow.

A1: constricted area, A2: unconstricted area of PA.

mean flow ejected to the pulmonary artery. Then, we have the following equation,

$$Prsm - Pp = Prsm - Fp \times Rp = Fpsm \times Ro$$

If ratio of systolic period to cardiac cycle is μ , Fp would be $\mu Fpsm$. Therefore,

$$Prsm - \mu Fpsm \times Rp = Fpsm \times Ro$$

Whence

$$Prsm / Fpsm = Ro + \mu Rp$$

As for systolic mean systemic resistance, it is LV systolic mean pressure ($Plsm$) divided by systolic mean systemic blood flow ($Fssm$) as shown, in Fig. 1 (b). Generally, there is little difference between mean aortic pressure (Pa) and $Plsm$. Therefore,

$$Rssm = Plsm / Fssm = Pa / Fssm = \mu Pa / Fs = \mu Rs$$

This means that vascular resistance might be considered to decrease to μ -fold during systole.

In the first place, it is studied as to what extent the resistance of RV outflow tract should be decreased, in order to lower RV/LV pressure ratio below a certain value (α) after operation? It is assumed that, to maintain identical systemic blood pressure before and after operation, systemic blood flow is unchanged. Thus, post-

operative pulmonary blood flow should be the same with preoperative systemic blood flow. As postoperative RV systolic mean pressure ($P'rsm$) is systolic pulmonary blood flow times the sum of residual RV outflow resistance ($R'o$) and postoperative pulmonary vascular resistance ($\mu R'p$), the following equation can be written

$$P'rsm = fssm (R'o + \mu R'p) = (Plsm / \mu Rs) (R'o + \mu R'p)$$

As it is assumed that systemic blood flow does not change before and after operation, pre-operative and postoperative systemic blood pressure should be the same. So, we find the following relationship,

$$\alpha = \frac{P'rsm}{P'lsm} = \frac{P'rsm}{Plsm} = \frac{R'o + \mu R'p}{\mu Rs} \quad (1)$$

Preoperative systemic and pulmonary blood flow ratio (γ) is inversely proportional to resistance ratio of systemic and pulmonary circulation. Therefore,

$$\gamma = \frac{Fs}{Fp} = \frac{Fssm}{Fpsm} = \frac{Ro + \mu Rp}{\mu Rs} \quad (2)$$

From equation (1) and (2), we have the following theoretical formula,

$$\frac{R_o'}{R_o} = \frac{\alpha\epsilon - R_p/R_p}{\gamma\epsilon - 1} = \frac{\alpha\epsilon - 1}{\gamma\epsilon - 1} \quad (3)$$

which predict postoperative to preoperative RV outflow resistance ratio for obtaining a certain value of α . Here, ϵ is preoperative systemic and pulmonary vascular resistance ratio (R_s/R_p), which is obtained from catheterization data.

Next, for the theoretical formula to be practical in use during surgery, resistance ratio (R_o'/R_o) should be transformed to easily measurable variable during operation. Gorlin's formula³ might be applicable in certain circumstances, when obstruction is localized. Therefore, attempt was made to find out relationship between resistance ratio and orifice area ratio.

When A , F and P are taken as orifice area, flow rate and pressure difference across the orifice, Gorlin's formula is expressed as follows,

$$A = \frac{F}{k\sqrt{P}}$$

Thus, orifice resistance is transformed in the following way,

$$R = \frac{P}{F} = \frac{F}{k^2 A^2}$$

Let A and A' be the smallest orifice area of RV outflow tract before and after operation, we have the following formula from equation (3).

$$\frac{A^2}{A'^2} = \frac{\gamma\epsilon - 1}{\gamma(\gamma\epsilon - 1)} \quad (4)$$

The above equation is the transformed formula for practical use.

(b) Clinical Results

To ascertain correctness of the theoretical and the transformed formula, clinical data of thirteen cases operated on were applied to the formulas and α were calculated from each formula. These values were compared with actual values obtained by postoperative RV/LV pressure measurement. R_o/R_o was obtained in the following way,

Fig.5. Relationship between circumference constriction and pulmonary flow
 C1: constricted PA circumference
 C2: unconstricted PA circumference
 T/C: thickness to circumference ratio of pulmonary artery

$$\frac{Ro'}{Ro} = \frac{Po'}{\gamma Po}$$

where Po and P_o represented preoperative and postoperative pressure difference across RV outflow tract. A/A' was obtained by measuring the most stenotic area of RV tract by a scale.

As shown in Fig. 3, the values of α calculated from the theoretical formula correlated well to the actual values with a coefficient of correlation of 0.87 ($p < 0.01$). On the other hand, close correlation could not be found between the values from the transformed formula and the actual values. This might be due to difficulties in measuring precisely stenotic area during operation, some discrepancy of the stenotic area in the stilled heart and the beating heart.

(2) Pulmonary Artery Banding

(a) Theoretical Consideration

Surgical constriction of the pulmonary artery offers a method of decreasing pulmonary blood flow in patients with large left to right shunt such as in VSD. Relationship between degree of constriction and pulmonary flow can be obtained graphically in the following method.⁴ As shown in Fig. 4, pressure difference-flow curves at constricted area for different degree of constriction, is obtained from Gorlin's formula.

Next, the following equation is applied across the banding.

$$P = P_p - P_d$$

where P , P_p and P_d represents pressure difference, RV pressure proximally and pulmonary artery pressure distally of the banding. Pulmonary blood flow (F) is pulmonary artery pressure divided by pulmonary resistance (R). Therefore,

$$F = \frac{P_d}{R} = \frac{P_p}{R} - \frac{P}{R} \quad (5)$$

Before constriction ($P = 0$), F equals P_p/R , which is called initial flow. When constriction is complete ($F = 0$), P equals P_p , which does not change greatly even after complete constriction, because of large VSD. Therefore, equation (5) represents roughly a straight line, crossing the ordinate at P_p/R and the abscissa at P_p , when R is constant. Note that the line is displaced up or down by changes in pulmonary resistance. Relationship between degree of constriction in terms of area ratio and pulmonary blood flow are obtained by plotting crossing points of the group

of curves and the straight line, as shown in Fig. 4. Pulmonary blood flow changes little up to the point $A1/A2$ is 0.2 or so, and then afterwards it decreases abruptly. This point can be called critical stenosis.⁵

(b) Experimental Results

Experiment were carried out by using a pulsatile pressure clamped pump, the chamber of which was connected to the pulmonary artery of a dog. A tape was placed around the pulmonary artery and constricted gradually. Pulmonary flow was measured at different degree of constriction. As shown in Fig. 5, critical stenosis was attained at circumference ratio (C/C') of 4.5/9 to 2.5/9. Critical stenosis was reached at the smaller degree of constriction, when the thickness to circumference ratio of the pulmonary artery was great.

(3) Aorto-Pulmonary Anastomosis

(a) Theoretical Consideration

Complications of increased pulmonary flow, such as heart failure and pulmonary hypertension, can occur after side-side anastomosis (Potts or Waterston), although they occur rarely after end-side anastomosis (Blalock). This might be due to proper length and orifice size which present proper resistance, not allowing too much blood delivered to the lung through the anastomosis.

It can be considered that total resistance of the anastomosis (R) consists of resistance of a narrowed orifice (R_g) and that of a narrowed segment (R_p). The former can be obtained from Gorlin's formula, the latter from Poiseuille's law. As a consequence,

$$R = R_g + R_p = \frac{kF + k'L}{\gamma^4}$$

Here, r is radius of a narrowed orifice, and L is length of a narrowed segment. By applying actual values into the above equation, it become evident that R_p is negligibly small compared to R_g .

(b) Experimental Results

Flow was compared between Blalock and Waterston anastomosis of the same orifice size made in a dog. Flow through Waterston anastomosis was about twice as much as flow through Blalock anastomosis at the identical aortic pressure. This was not concordant with results derived from the above equation.

SUMMARY

1. A theoretical and a transformed formula was derived as to what extent RV outflow tract

stenosis should be relieved to lower RV/LV pressure ratio below a certain value post-operatively in corrective surgery of tetralogy of Fallot. Values obtained from the theoretical formula correlated well with actual values in thirteen cases operated on.

2. Relationship between degree of constriction and pulmonary flow was analyzed graphically. Experiments showed that critical stenosis was reached at the smaller degree of circumference constriction at greater thickness to circumference ratio of the pulmonary artery.
3. Theoretical and experimental results were not concordant as to flow through Blalock and Waterston anastomosis. Further study should be required.

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