New Criteria for the Radical Repair of Congenital Heart Disease with Pulmonary Hypertension

In Order to Avoid Postoperative Residual Pulmonary Hypertension

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SUMMARY

In congenital heart disease (CHD) with pulmonary hypertension (PH) resulting from high pulmonary flow, we sometimes experience patients whose PH continues even after the normalization of flow following surgery. Preoperative identification of these patients is difficult even using direct hemodynamic measurements at cardiac catheterization. The purpose of this study is to interpret the state of the pulmonary vascular bed more precisely using a new theoretical approach and to present the criteria available for avoiding residual PH.

During preoperative routine catheter examination in CHD patients with PH we applied the Windkessel model to the pulmonary circulation and calculated the diastolic time constant (Td) of the pulmonary circulation. Td of Group 1 (0.50 ± 0.03 sec), 6 patients who manifested residual PH after surgery, was higher than that of group 2 (0.23 ± 0.14 sec), 42 patients with normalized pulmonary artery pressure after surgery. Furthermore, the relationships between Td and pulmonary blood flow (Qp) or pulmonary to systemic flow ratio (Qp/Qs) were very sensitive for distinguishing between these two groups. Group 1 was located in the left-upper quadrant of the graph of Td vs Qp or Td vs Qp/Qs relationships, whereas group 2 was located in the right-lower quadrant.

The relationships between Td and Qp or Qp/Qs were considered to reflect the pathological change in the pulmonary vasculature more precisely. As a consequence, they would be very useful in understanding the state of the pulmonary vascular bed and avoiding residual PH. (*Jpn Heart J* **36**: 49–59, 1995)

Key words: Windkessel model diastolic time constant pulmonary vascular compliance pulmonary vascular obstructive disease

IN treating patients with congenital heart disease (CHD) with pulmonary hypertension (PH) due to an increased pulmonary blood flow, it is very

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important that the degree of the pathological change in the pulmonary vascular bed be evaluated for evidence of pulmonary vascular obstructive disease (PVO) prior to surgery. Pulmonary vascular resistance (R_p) has been mainly used as a physiologic indicator of the pathological state of the pulmonary vascular bed.¹⁾

Yet among some CHD patients with PH who have been surgically treated, PH persists and progresses postoperatively although the results of preoperative evaluation by R_p were acceptable for surgery.²⁻¹²⁾ Such patients inevitably continue to suffer postoperatively from progressive right heart failure and die sooner than they would have if they had not undergone surgery.

Therefore, the true state of the pulmonary vascular bed cannot be accurately evaluated only by R_p . Because R_p is a measure of the opposition to non-pulsatile blood flow (mean-steady flow), while the blood flow is pulsatile and the vessel is viscoelastic, R_p does not sufficiently indicate the pathological changes that may have occurred in the pulmonary vascular bed.¹³⁻¹⁷⁾ To evaluate the true picture of the entire vascular bed, it is not sufficient to investigate only the resistance; compliance must also be considered.

In this study, to avoid residual PH, we examined the time constant of the pulmonary circulation (T_d) by using the Windkessel model which includes compliance as well as resistance, and clarified the true pathological state of the pulmonary vascular bed of CHD patients with PH.

MATERIALS AND METHODS

Forty-eight consecutive CHD patients with PH who had undergone surgery between 1988 and 1991 in our hospital were studied retrospectively. Their ages ranged from 4 months to 13 years at the time of surgery. Forty-five patients had a simple ventricular septal defect (VSD), 2 patients had an atrial septal defect (ASD), 2 patients had both ASD and VSD, and 3 patients had a coarctation or an interruption of the aorta with VSD. All patients showed some degree of PH at the preoperative catheter examination, with systolic pulmonary to systemic pressure ratios from 0.48 to 1.0.

Based on the results of their postoperative catheter examinations, they were divided into two groups; Group 1, 6 patients who manifested residual PH after surgery; and Group 2, 42 patients with normalized pulmonary artery pressure after surgery. The results of postoperative catheterizations in Group 1 patients were of those performed more than 1 year after surgery. Hemodynamic data of the Group 1 patients are summarized in the Table.

To reevaluate the true state of the pulmonary vascular bed, we examined the preoperative T_d values of all patients, and compared the two groups. T_d was also examined in four Eisenmenger patients for comparison. Further, to distin-

Table. Pre and Post-operative Catheterization Data for Group 1

	Age	Sex	Qp/Qs	Rp/Rs	Pp/Ps	Rp	O ₂ test	T-test	Td	Age (p.o.)	Pp (p.o.)	Pp/Ps (p.o.)
VSD (Down)	4 mo	M	1.52	0.56	0.91	10.5	+		0.480	3y3mo	102/64	1.00
VSD	4 mo	M	1.48	0.59	0.81	11.5	+		0.550	2y2mo	98/50	1.00
CoA	2y1m	F	1.84	0.96	1.00	17.4		+	0.500	4y6mo	96/46	0.95
VSD	2y	F	1.63	0.85	0.98	9.3	+		0.489	5y	108/62	0.96
VSD (Down)	1y10m	M	1.30	0.76	1.00	8.2	+	+	0.500	3y7mo	120/78	1.10
CoA	1y11m	F	1.42	0.60	0.92	9.2	+		0.495	5y2mo	112/72	1.15

VSD = ventricular septal defect; Down = Down syndrome; CoA = coarctation complex; Qp/Qs = pulmonary to systemic flow ratio; Rp/Rs = pulmonary to systemic resistance ratio; Pp/Ps = pulmonary to systemic systolic pressure ratio; Rp = pulmonary vascular resistance; Td = diastolic time constant; Pp = pulmonary artery pressure. Plus (+) under O₂ test and trazolin test (T-test) indicates that there was a reduction of Rp by testing. The tests were not performed in free space. p.o. = postoperative.

guish more clearly Group 1 from Group 2, we examined Td in relation to pulmonary blood flow (Qp) and pulmonary to systemic flow ratio (Qp/Qs). Pulmonary artery pressure was measured with a high-fidelity pressure transducer (Miller Instruments, Inc). Qp was determined by the Fick method for oxygen saturation. Oxygen consumption was determined by collecting expired air with a Douglas bag for 5 minutes and measuring oxygen content using the Scholander technique. When a patient was too small to measure the oxygen consumption, the thermo-dilution technique was used. Oxygen saturation of the pulmonary vein was directly measured when the patient had a foramen ovale or ASD. In other patients, excluding the Eisenmenger patients, it was estimated by the oxygen saturation of the aorta. In the Eisenmenger patients, oxygen saturation of the pulmonary vein could be measured directly. Rp was calculated according to the following formula:

$$Rp = (mPAP - mLAP) / Qp$$

where mPAP is the mean pulmonary artery pressure and mLAP is the mean left atrial pressure.

Td was obtained by the method shown in Figure 1 by applying the concept of a parallel circuit consisting of the resistance (R) and the compliance (C) to the pulmonary circulation. In the RC circuit in Figure 1, the voltage discharge from the capacitor is an exponential function of time. Accordingly, the diastolic pressure difference between the main pulmonary artery and the left atrium also shows an exponential decay, which is related to the time constant (Td) of this circuit. To evaluate the relevance of such an analogy, the instantaneous diastolic pressure difference between the main pulmonary artery and the left atrium was plotted on semi logarithmic sectioned paper, and the existence of the linear correlation between the pressure difference and the diastolic time interval was determined. In all cases there was a linear correlation (on regression analysis, the

Figure 1. Scheme of the theory for the calculation of time constant of the pulmonary circulation (Td). A in the figure shows the RC electric circuit analogy of the pulmonary circulation. B shows a theoretical pulmonary artery pressure pulse with mean left atrial pressure. C shows the formula which represents the summarized equations for the calculation of Td. R = resistance, C = capacitor (compliance), mPA = main pulmonary artery, mLAP = mean left atrial pressure; PAP = pulmonary artery pressure.

correlation coefficient was above 0.95). We were then able to obtain Td as a linear gradient.

Statistical Analysis: All values are expressed as mean $\pm$ SD, and comparisons were made by the unpaired t test. A value of $p < 0.05$ was considered to be statistically significant.

RESULTS

Td values of the three groups are; Group 1, 0.50 ± 0.03 sec; Group 2, 0.23 ± 0.14 sec; and the Eisenmenger group, 0.56 ± 0.04 sec. As seen in Figure 2, Td of Group 1 was much greater than that of group 2 ($p < 0.05$), and was not significantly different from that of the Eisenmenger Group. We can almost differentiate Group 1 from Group 2 by the Td value, although in a few patients there

Figure 2. Comparison of diastolic time constant (Td) among the patients of Group 1, Group 2, and Eisenmenger Group. The mean value and standard deviation of each group was 0.50 ± 0.03 sec of Group 1, 0.23 ± 0.14 sec of Group 2 and 0.56 ± 0.04 sec of Eisenmenger Group. Td of Group 1 was significantly higher than that of Group 2 ($p < 0.05$). There was no significant difference in Td between Group 1 and the Eisenmenger Group.

Figure 3. Relationship between diastolic time constant (Td) and pulmonary blood flow (Qp). Hatched area represents marginal area. Closed circle = Group 1, open circle = Group 2, open triangle = Eisenmenger Group.

was an overlapping of these two groups.

Differences between the two groups can be more clearly distinguished by examining the relationship between Td and Qp or Qp/Qs. Figure 3 shows the relationship between Td and Qp, and Figure 4 shows the relationship between

Figure 4. Relationship between diastolic time constant (Td) and pulmonary to systemic flow ratio (Q_p/Q_s). Hatched area represents marginal area. Closed circle = Group 1, open circle = Group 2, open triangle = Eisenmenger Group.

Td and Q_p/Q_s , with the closed circles representing Group 1 patients and the open circles Group 2 patients, respectively. For comparison, the Eisenmenger Group patients, represented by open triangles, are also plotted.

Group 1 and Eisenmenger Group values are located in the left-upper quadrant of the graph, which can be compared to Group 2 values in the right lower quadrant.

DISCUSSION

The Windkessel model is based on the concept of elasticity, and the electric circuitry is shown in part A of Figure 1. This model was first applied to study the systemic circulation by Frank in 1899,¹⁸⁾ and since then, many investigators have used it mainly to study the characteristics of the systemic circulation.¹⁹⁻²¹⁾ We have now used this model to study the pulmonary circulatory system in CHD patients with PH.

In the pulmonary circulation, a portion of the systolic blood flow coming into the pulmonary artery is temporarily pooled in a reservoir and then is pushed out as diastolic blood flow by the elastic recoil of this reservoir. This mechanism is reproduced by the Windkessel model, wherein resistance (R) and compliance (C) duplicate the physiological action of the pulmonary vasculature.

Td value represents the length of time it takes the blood entering the pulmonary vascular bed to reach the left atrium. It is kept within a certain level (0.18 ± 0.03 sec) in the normal pulmonary circulation.²²⁾ A high Td value would

Figure 5. Expected change in the relationship between diastolic time constant (T_d) and pulmonary blood flow (Q_p) according to the change in hemodynamics and pathology of pulmonary vascular bed. Curve 1 represents the normal pulmonary vascular bed, curve 2 represents reversible changes in pulmonary vascular bed and curve 3 represents irreversible changes in pulmonary vascular bed, respectively. The area surrounded by dotted lines represents normal values of T_d and Q_p . See text concerning A, A', A'', B, B', and C.

indicate that the systolic blood flow entering the pulmonary vascular bed requires a long time to reach the left atrium. This indicates that the blood does not go through the pulmonary vascular bed smoothly. As noted in Figure 2, T_d values are very high in Eisenmenger patients and Group 1 patients.

Thus, we can use T_d as a good physiological indicator of the ease of blood flow through the pulmonary vascular bed.

Figure 5 shows the expected change in the relationship between T_d and Q_p in association with the progression of PVO.

In the normal pulmonary artery, the relationship between T_d and Q_p will be represented by curve 1. A large volume of blood can go through the pulmonary vascular bed without stagnation (within normal T_d). In the pulmonary artery which has some degree of pathological change, the curve will shift to the left upper quadrant and will be represented by curve 2. This curve indicates that blood flow is becoming more stagnant. In other words, blood flow is not going smoothly through the pulmonary vascular bed. However, this curve represents a potentially reversible pathological condition because T_d becomes normal when the pulmonary blood flow is within the normal range. T_d values of patients in Group 2 must be on such a curve. In the pulmonary artery where PVO is further advanced, the curve will shift further to the left and will be represented by curve 3. The blood always stagnates and only a small volume of blood can go through

Figure 6. Comparison of pulmonary vascular resistance (R_p) among the three groups.

Figure 7. Comparison of pulmonary to systemic vascular resistance ratio (R_p/R_s) among the three groups.

the pulmonary vascular bed. On this curve, Td does not normalize even though the pulmonary blood flow becomes normal. It is easy to assume that Td values of Group 1 patients fall upon such a curve.

From the viewpoint of the time course, A on curve 1 (a patient with ex-

Figure 8. Comparison of pulmonary to systemic pressure ratio among the three groups.

tremely high pulmonary blood flow) will move to A' and further to A'', as PVO progresses over time. B on curve 1 (a patient with moderately high pulmonary blood flow) will move to B' which has no irreversible pathological change. C on curve 1 (a patient with almost normal pulmonary blood flow) will not move very much even as time goes by. In some patients, for example in patients with Down syndrome, the starting points may be on curve 2. In this way, in accordance with the progress of pathological change the curve will shift to the left upper quadrant of the graph as a result of difficulties in maintaining a smooth pulmonary circulation. Where then is the cut-off line that represents the pathologic condition reversible by radical operation?

Comparing the preoperative Td and Qp relationship among the patients who had PH before surgery, we can find the cut-off line below which Td can normalize after surgery and pathological changes in the pulmonary vasculature will be reversible. Group 1 patients as well as Eisenmenger Group patients show markedly higher Td against Qp (Figure 3), or against Qp/Qs (Figure 4) than Group 2 patients. Thus, we can set the cut-off line around the hatched area. This reflects well the logical speculation presented in Figure 5.

Based on the preoperative hemodynamic data presented in the Table, Group 1 patients underwent surgery, but suffered from residual PH after surgery. Every Group 1 patient died due to right heart failure within 3 years after surgery. Figures 6, 7 and 8 show the comparisons of the preoperative hemodynamic data among the three groups. We found that no indicators enabled us to completely

distinguish Group 1 patients from Group 2 patients preoperatively. In many patients, there is an overlapping of the two groups. However, by examining the relationships between Td and Qp or Qp/Qs, we can clearly distinguish these two groups.

It can be concluded that patients whose Td values are plotted in the left-upper quadrant above the cut-off line on Td vs Qp or Qp/Qs relationships have a high probability for residual PH even after radical surgical repair. In contrast, patients whose Td values are plotted in the right-lower quadrant have little risk of residual PH. Patients whose Td values fall upon the hatched area should be considered as marginal cases.

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