Relationship Between the Pulmonary Artery Index and Physiological Properties of the Pulmonary Vascular Bed

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Background: To clarify the physiological significance of the pulmonary artery index (PAI), we examined the relationship between PAI and physiological properties of the pulmonary vascular bed. We also examined the limitations of PAI in practical use.

Methods and Results: We examined the relationships between PAI and pulmonary vascular resistance (Rp), pulmonary arterial compliance (Cp), and the time constant (RC) of pulmonary circulation in 50 patients with congenital heart disease with decreased pulmonary blood flow. PAI was significantly related to Cp and RC (r=0.67, r=0.63, respectively). These correlations became more significant when we excluded patients in whom the central pulmonary arteries were disproportionately dilated in contrast to the peripheral pulmonary arteries (r=0.80, r=0.70, respectively).

Conclusions: PAI reflects the state of the pulmonary vascular bed, especially when the peripheral arteries develop in proportion to the central pulmonary artery. (Jpn Circ J 1996; 60: 334—340)

The pulmonary artery index (PAI; cross-sectional area of the right and left pulmonary arteries just proximal to the origin of the first lobe branch/body surface area) has been considered to represent the size and development of the pulmonary artery, and has been used as a criterion in the surgical treatment of congenital heart disease with decreased pulmonary blood flow. Thus, PAI is believed to reflect the physiological properties of the pulmonary vascular bed and to influence postoperative hemodynamics. However, in practice, we sometimes experience patients in whom the central pulmonary arteries are disproportionately dilated in contrast to their peripheral pulmonary arteries. Therefore, several investigators have suggested that PAI, which is derived only from the size of the proximal pulmonary artery, does not always reflect the size and development of peripheral pulmonary arteries, and that PAI is insufficient as a surgical criterion.

In this paper, to clarify the physiological significance of PAI, we examined the relationship between PAI and physiological properties of the pulmonary vascular bed. We also evaluated the limitations of PAI in practical use.

MATERIALS AND METHODS
Fifty consecutive patients (ages 5 months to 15 years, mean 7 years) with congenital heart disease and decreased pulmonary blood flow were selected for this study. The patients’ characteristics are given in Table I.
Some of the patients had increased pulmonary blood flow secondary to palliative surgery.

Using anteroposterior pulmonary arterial angiography (Siemens) PAI was measured according to the method proposed by Nakata et al. The cross-section of the pulmonary artery was assumed to be a circle. To clarify the physiological significance of PAI, we examined the relationships of PAI to pulmonary vascular resistance (Rp) and pulmonary arterial compliance (Cp), which are the physiological properties of the pulmonary artery. To eliminate factors that may produce a discrepancy between the central pulmonary artery and the peripheral pulmonary arteries, we examined the relationships between PAI and either Rp or Cp by excluding 14 patients in whom the central pulmonary arteries were disproportionately dilated in contrast to the peripheral pulmonary arteries, and 8 patients in whom the pulmonary to systemic flow ratio (Qp/Qs) was more than 2. We defined disproportionately dilated central pulmonary arteries as those in which the cross-sectional area of the pulmonary artery just proximal to the origin of the first lobe branch was larger than the sum of the cross-sectional areas of the pulmonary artery 2nd branches, since this ratio is less than 1 in normal pulmonary vasculature.

Hemodynamic data were obtained by routine right heart catheterization. Pulmonary arterial pressure was measured with a 6-Fr high-fidelity pressure transducer (Millar

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**TABLE 1 PATIENT CHARACTERISTICS**

<table>
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<th>Diagnosis</th>
<th>Palliation</th>
<th>Number</th>
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<td>PA, VSD, PDA</td>
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**Fig 1.** Scheme of the theory for calculating pulmonary vascular compliance. (A) analogy of the pulmonary circulation to an RC electric circuit. (B) a theoretical pulmonary artery pressure pulse with mean left atrial pressure. (C) summarized equations for calculating pulmonary vascular compliance. R: resistance, C: capacitor (compliance), mPA: main pulmonary artery, mLAP: mean left atrial pressure, PAP: pulmonary artery pressure.

**Fig 2.** Relationship between the pulmonary artery index (PAI) and pulmonary vascular resistance (Rp).
Fig 3. Relationship between the pulmonary artery index (PAI) and pulmonary vascular resistance (Rp) when we excluded patients in whom the central pulmonary arteries were disproportionately dilated in contrast to the peripheral pulmonary arteries. Closed squares represent patients with a proportional central pulmonary artery.

Fig 4. Relationship between the pulmonary artery index (PAI) and pulmonary vascular resistance (Rp) when we excluded patients in whom Qp/Qs was more than 2. Closed squares represent patients in whom Qp/Qs was less than 2.

Fig 5. Relationship between the pulmonary artery index (PAI) and pulmonary vascular compliance (Cp)

Fig 6. Relationship between the pulmonary artery index (PAI) and pulmonary vascular compliance (Cp) when we excluded patients in whom the central pulmonary arteries were disproportionately dilated in contrast to the peripheral pulmonary arteries. Closed squares represent patients with a proportional central pulmonary artery.

Houston Instruments, Inc), and was monitored using an RMC-1100 (Nihon Kohden). Pulmonary blood flow was determined by the Fick method for oxygen saturation. Rp was calculated in accordance with Ohm’s law by using mean pulmonary artery pressure,
mean pulmonary venous atrial pressure and pulmonary blood flow. Pulmonary artery wedge pressure was used to approximate mean pulmonary venous atrial pressure when it could not be measured. C\textsubscript{p} was obtained by assuming a simple RC circuit (Fig 1). In this analogy, the voltage discharge from the capacitor is an exponential function of time. The difference in diastolic pressure between the main pulmonary artery and the pulmonary venous atrium also shows exponential decay, which is related to the

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**Fig 7.** Relationship between the pulmonary artery index (PAI) and pulmonary vascular compliance (C\textsubscript{p}) when we excluded patients in whom Qp/Qs was more than 2. Closed squares represent patients in whom Qp/Qs was less than 2.

\[ y = 0.41117 + 0.0024362 \times x \\
\hat{r} = 0.68, p = 0.0001 \]

**Fig 9.** Relationship between the pulmonary artery index (PAI) and the time constant (RC) when we excluded patients in whom the central pulmonary arteries were disproportionately dilated in contrast to the peripheral pulmonary arteries. Closed squares represent patients with a proportional central pulmonary artery.

\[ y = 0.000840 + 0.00052082 \times x \\
\hat{r} = 0.70, p = 0.0001 \]

**Fig 8.** Relationship between the pulmonary artery index (PAI) and the time constant (RC)

\[ y = 0.059506 + 0.00098181 \times x \\
\hat{r} = 0.63, p = 0.0001 \]

**Fig 10.** Relationship between the pulmonary artery index (PAI) and the time constant (RC) when we excluded patients in whom Qp/Qs was more than 2. Closed squares represent patients in whom Qp/Qs was less than 2.

\[ y = 0.073622 + 0.0009754 \times x \\
\hat{r} = 0.87, p = 0.0001 \]
time constant (RC) of this circuit. Cp can be obtained by replacing R in the formula in Fig 1 by the calculated Rp. To evaluate the relevance of this analogy, the instantaneous difference in diastolic pressure between the main pulmonary artery and the pulmonary venous atrium was plotted on semi-logarithmic sectioned paper, and the existence of a linear correlation between the pressure difference and the diastolic time interval was determined. The correlation coefficients in all cases were greater than 0.95. The relationship between PAI and RC was also examined, since RC is a good physiological indicator of pulmonary circulation.\textsuperscript{7–9}

STATISTICAL ANALYSIS

Associations between variables were determined by linear regression analysis, and correlation coefficients were calculated. A value of $p<0.05$ was considered statistically significant.

RESULTS

As shown in Fig 2, there was no statistically significant correlation between PAI and Rp, although there was a trend toward low resistance in patients with larger PAI. Fig 3 shows the relationship between PAI and Rp when we excluded 14 patients in whom the central pulmonary arteries were disproportionately dilated in contrast to the peripheral pulmonary arteries, and Fig 4 shows the relationship when we excluded 8 patients in whom $Q_p/Q_s$ was more than 2. No significant correlation was observed even with these limitations.

On the other hand, a significant positive correlation ($r=0.67$, $p=0.0001$) was found between PAI and Cp (Fig 5). As noted in Fig 6, the correlation between PAI and Cp became more significant ($r=0.80$, $p=0.0001$) when we excluded the 14 patients in whom the central pulmonary arteries were disproportionately dilated in contrast to the peripheral pulmonary arteries. As shown in Fig 7, high pulmonary blood flow did not seem to have a significant effect on this relationship ($r=0.68$, $p=0.0001$).

As noted in Fig 8, RC had a significant positive correlation with PAI ($r=0.63$, $p=0.0001$). This relationship became slightly more significant ($r=0.70$, $p=0.0001$) when we excluded the 14 patients in whom the central pulmonary arteries were disproportionately dilated in contrast to the periph-
eral pulmonary arteries (Fig 9), but did not change remarkably when we excluded the 8 patients in whom Qp/Qs was more than 2 (Fig 10).

DISCUSSION

If we assume blood flow to be Newtonian, the resistance of the vessel can be expressed approximately as \(8 \kappa L/\pi r^4 \) (L: length of vessel, r: radius of vessel, k: viscosity of blood) according to the law of Poiseuille. Based on this equation, Rp should be inversely proportional to (PAI). However, as shown in Fig 11, there was no significant correlation between Rp and 1/(PAI); even though factors which may have produced a discrepancy between the central and the peripheral pulmonary arteries were eliminated. This indicates that the difference in the radius of proximal arteries does not reflect the difference in the radius of vessels which determine the total resistance of the pulmonary artery, i.e., "resistance vessels".

Regarding Cp, compliance of the vessel can be expressed as \(3\pi r^2L(r/h+1)^2/E (2r/h +1) \) (L: length of vessel, r: radius of vessel, k: viscosity of blood, E: Young's modulus of the vessel wall, h: wall thickness of vessel). This equation indicates that vascular compliance is determined by the vascular size and the distensibility of the vascular wall, and is proportional to the vascular size. In addition, in the actual pulmonary artery, Cp is almost proportional to the vascular size represented by PAI (Figs 5-7), and Cp increases with the size of the pulmonary artery. As noted in Fig 6, if we select patients in whom the central pulmonary arteries are not disproportionately dilated in contrast to the peripheral pulmonary arteries, we can estimate Cp from PAI more accurately. In the disproportionately dilated central pulmonary artery, Cp seems to be lower than that which is expected when the peripheral pulmonary arteries develop in proportion to the central pulmonary artery. Thus, the size of the central pulmonary artery represented by PAI does not accurately reflect the state of the total pulmonary vascular bed when the central pulmonary artery is disproportionately dilated in contrast to the peripheral pulmonary arteries. When pulmonary blood flow increases, Cp tends to decrease slightly, probably due to pulmonary vascular constriction. However, as noted in Fig 7, high pulmonary blood flow does not seem to have a significant effect on the relationship between PAI and Cp.

A significant positive correlation was found between the time constant (RC) and PAI. RC reflects how long the blood entering the pulmonary vascular bed takes to reach the left atrium, and is maintained at a certain level (0.18±0.03 sec) in a normal pulmonary circulation. Thus, we can use RC as a good physiological indicator of the state of the pulmonary vascular bed. Since PAI is significantly related to RC, PAI can reflect the change in pulmonary circulation which accompanies the development of the pulmonary vascular bed. With the development of the pulmonary artery, RC approaches the normal value. PAI represents the state of the pulmonary circulation more accurately if we remove factors that may produce a discrepancy between the central pulmonary artery and peripheral pulmonary arteries.

Elevated pulmonary artery pressure may also cause a discrepancy between the central pulmonary artery and the peripheral pulmonary arteries. However, since only a few patients in the present study showed pulmonary hypertension, further study in this regard is needed.

CONCLUSION

The present results indicate that PAI is significantly related to Cp as a physiological property of the pulmonary vascular bed, and to RC as a physiological indicator of pulmonary circulation. However, when the central pulmonary artery is disproportionately dilated in contrast to the peripheral pulmonary arteries, PAI does not accurately reflect the true state of the pulmonary vascular bed. Therefore, when we evaluate the development of the pulmonary artery using PAI, we should confirm the proportion of the sizes of the central and peripheral pulmonary arteries. When the central pulmonary artery is disproportionately dilated in contrast to the peripheral pulmonary arteries, we should consider that PAI may overestimate the development of the pulmonary artery.
REFERENCES


