Analysis of Pulmonary Arterial Pressure Patterns

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Since Beutner\(^1\) first recorded mean pulmonary arterial pressure, various attempts to analyze the hemodynamics of pulmonary arterial system have been done referring to its blood pressure. But the most reliable information for clinicians obtained by the right heart catheterization is mean pulmonary arterial pressure even at present stage. So far as the pressure pattern is concerned, observation is still limited to the empirical and qualitative one.

On the other hand, efforts have been made by physiologists to find out the meaning of pressure pattern from the hemodynamic point of view. Wezler\(^9\), Brömser\(^5\) and Ranke suggested the formulae for calculation of cardiac output, total vascular resistance and vascular compliance on the foundation of Windkesseltheorie\(^6\) and applied them in pulmonary circulation. Mc Donald\(^6\), Taylor\(^6\) and Fry\(^7\) used Fourier analysis and approached quantitatively to the pressure pattern. The pressure pattern as arbitrary function was expressed in the form of equation for further hemodynamic analysis. Recently, mathematical model of pulmonary artery was made by Attinger\(^9\)\(^10\). He devised the pulmonary artery into several segments for geometrical consideration. And analysis including Fourier analysis was done in each segment. These series of fundamental investigations indicate that a great deal of important informations is obtained from the pressure pattern. Caro\(^11\)\(^12\) obtained arterial pressure pattern at two different points of the pulmonary artery during the performance of open chest operation.

In this paper, the data obtained by cardiac catheterization were compared with quantitatively analyzed arterial pressure pattern. The pulmonary\(^10\) arterial system was isolated as transfer element of control system, though there might be a little controversy to do so. Using the following two parameters, gain margin\(^11\)\(^15\) and phase margin, the speculation was made on pulmonary arterial system.

In the cases of mitral stenosis, cardiac failure is not frequently encountered even though pulmonary arterial pressure is high enough, while in the cases of chronic pulmonary emphysema, cardiac failure easily takes place\(^10\)\(^17\)\(^14\)\(^10\)\(^29\) in comparatively low mean pulmonary arterial pressure. This fact suggests that mean pulmonary arterial pressure alone is not a decisive factor for the mechanism of producing the right heart failure. Influence of the stability of the pulmonary arterial system on the right heart was studied here.

For this purpose, the first derivatives\(^2\)\(^2\)\(^2\)\(^3\)\(^4\) of the pulmonary arterial pressure pattern were calculated. The peak value of systolic ejection of the first derivative curve was calculated.

METHODS

Right heart catheterization was performed on fourteen patients with chronic pulmonary emphysema, fourteen patients with mitral stenosis and four patients with atrial septal defect. Their age was ranged from six to seventy-eight. Pulmonary arterial pressure was recorded when the catheter tip was placed in the main pulmonary artery.

Wedge pressure, right ventricular pressure and right atrial pressure were respectively recorded. Several routine examinations such as measurement of pulmonary blood flow, stroke volume and arterial oxygen saturation were performed.

Then, total pulmonary vascular resistance and pulmonary vascular compliance were calculated. Total pulmonary vascular resistance was calculated by Wezler-Böger's formula.

\[ \frac{s/W^p}{(P_m-P_v)} = \frac{60}{V_m} \]  
\[ \frac{d E^p}{p} = \frac{(P_m-P_v) - (P_s-P_d) \cdot 60}{P \cdot D \cdot V_m} \]

W^p : total pulmonary vascular resistance.

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E'p : pulmonary vascular compliance.
V_m : cardiac output.
P_m : mean pulmonary arterial pressure.
P_s : systolic pulmonary arterial pressure.
P_d : diastolic pulmonary arterial pressure.
D : diastolic time.

Pulmonary vascular compliance was calculated by KNEBEL's^{280} formula, in which wedge pressure was used in place of P_v after SAITO's^{280} suggestion.

Pressure recording was done by Statham P 23Db pressure transducer connected with COURNAND 8F catheter.

Recorded pulmonary arterial pressure patterns were normalized and FOURIER coefficients were calculated by NEAC P25 analog computer, using following block diagram shown in Fig. 1.

![Block diagram of harmonic analysis for analog computer.](image)

Fig. 1. Block diagram of harmonic analysis for analog computer. FOURIER coefficient "a" is obtained from R_3 and "b" is obtained from R_4.

\[
(II) \quad a = \frac{1}{T} \int_{0}^{T} f(t) \cdot \sin \omega t \, dt \quad \text{.................(3)}
\]

\[
b = \frac{1}{T} \int_{0}^{T} f(t) \cdot \cos \omega t \, dt \quad \text{.................(4)}
\]

These results were expressed in the Bode diagram. Gain margin and phase margin were obtained from the Bode diagram.

First derivatives of pulmonary arterial pressure pattern (PA dp/dt) and that of right ventricular pressure pattern (RV dp/dt) were given by the same computers and the peak value of systolic ejection was measured.

RESULTS

Fig. 2 shows schematic expression of the Bode diagram of the three groups of chronic pulmonary emphysema, mitral stenosis and atrial septal defect. Four break points were observed, denoted by A, B, C and D indicating the band around 8 rad/sec, the band around 25 rad/sec, the band around 50 rad/sec and the band around 80 rad/sec, respectively. In the cases of chronic pulmonary emphysema, break points were observed at the point A, B, and D. The point C observed in the cases of mitral stenosis and atrial septal defect was shifted to the point D in the cases of chronic pulmonary emphysema. This implies that the high energy distribution can be found among the higher frequency in the latter group compared with the other two groups.

Gain margin and phase margin were then compared with mean pulmonary arterial pressure. As shown in the Fig. 3a., gain margin and phase margin of chronic pulmonary emphysema were smaller than those of the other two groups. This implies that the stability of the pulmonary

![Fig. 3a. Mean pulmonary arterial pressure is compared with gain margin. No relationship can be found between them. In the cases of chronic pulmonary emphysema, there are many which have small gain margin, while the other two groups have large gain margin.](image)

Japanese Circulation Journal Vol. 29, November 1965
PULMONARY ARTERIAL PRESSURE PATTERNS

Fig. 3b. Mean pulmonary arterial pressure is compared with phase margin. Same tendency as shown in Fig. 3a. can be seen.

The arterial system of chronic pulmonary emphysema was poorer than that of the other two groups. This figure also shows that there was no relationship between the stability and mean arterial pressure.

There was no relationship between age and heart rate, and gain margin and phase margin. No effect of arterial oxygen saturation upon stability could be found. Anoxia test was performed on four cases, and no change in the stability could be found before and after the performance. There was no intimate relationship between the calculated total vascular resistance and the stability. As shown in Fig. 4., there was the inverse relationship between pulmonary vascular compliance and the stability.

In order to know the influence of the stability on the method of ejection of the blood from the right ventricle, the rate of rise in pulmonary arterial pressure pattern and right ventricular pressure pattern were respectively compared with gain margin and phase margin. As shown in Fig. 5., the cases which had small gain margin have large peak value of PA dp/dt, but the cases which had large peak value of PA dp/dt had not always small gain margin. The peak value of PA dp/dt was large in the cases of chronic pulmonary emphysema in comparison

Fig. 5. The peak value of PA dp/dt is compared with gain margin. In the cases of chronic pulmonary emphysema, there are many which have large peak value of PA dp/dt, while other two groups have small peak value of PA dp/dt. Relationships between them are discussed in this paper.

Fig. 6. The peak value of RV dp/dt is compared with PA dp/dt. Relationships between them are discussed in this paper.

*Japanese Circulation Journal* Vol. 29, November 1965
with the other two groups. Fig. 6. showed that RV dp/dt was large when PA dp/dt was large. but PA dp/dt was not always large when RV dp/dt was large. No relationship could be found between RV dp/dt and right ventricular end-diastolic pressure. No close dependance of PA dp/dt and RV dp/dt on heart rate, age and mean pulmonary arterial pressure were found.

DISCUSSION

That the mean pulmonary arterial pressure still plays an important role in the clinical field chiefly depends upon the availability of the pressure recording system. The frequency-amplitude characteristics of manometer conventionally used are satisfactory, but this fidelity is decreased when catheter is connected. Furthermore, the frequency-amplitude characteristics are considered to be unstable in vivo. Therefore, this facts should be taken into consideration when oscillating pressure is investigated and observation as well as speculation should be made within the range where frequency-amplitude characteristics are in flat curve. In this paper, the results were obtained within the range where the frequency-amplitude characteristics of Statham P 23Db connected with Cournand 8F catheter were flat. For further investigation of higher frequency, the catheter tip manometer should be used.

In order to obtained the accurate information of pulmonary arterial system, it might be necessary to make adequate models. Attinger devided pulmonary arterial system into several system into several segments. Hatakeyma performed transfusion of the sine wave as an input of the system. Two hypotheses should be taken into consideration because of clinical restriction. One was that pulmonary arterial system was treated as one isolated transfer element of control system, and the other was that results obtained by Fourier analysis was estimated as frequency response of the system. Therefore, gain margin and phase margin in this paper have not always been true in the strict meaning, though they were convenient parameters to make speculation. Staffin et al. suggested the method to distinguish aortic valvular disease from normal by similar way of thinking. There are two kinds of stability of pressure of pulmonary arterial system: ability to maintain the mean pressure stable, and stability of oscillating pressure. Stability in this paper means the latter.

Ruling factors of the hemodynamics of the artery is considered to be compliance, resistance and length according to Windkesseltheorie. Recently Noordergraaf and Attinger suggested respectively that it should be devided into several segments for making electrical analog circuits. These three factors may play an important role when the pulmonary arterial system is investigated as a whole. It should be taken into consideration that the pulmonary arterial system is shorter than systemic arterial system and easily influenced by mechanical force of the surrounding tissue. The pulmonary arterial wall is more distensible arterial wall and no sphincter arterioles can be found. The fact that pulmonary vascular compliance is related to the stability agrees with foregoing properties of the pulmonary arterial wall and implies that the essential difference between chronic pulmonary emphysema and other two groups might depend upon the stability determined chiefly by the distensibility. There is still much controversy when the length of the system is considered. The system should includes the pulmonary vein and the left atrium, if the concept of precapillary and post capillary hypertension is included. Investigation of the left atrial function and the wedge pressure of the pulmonary vein should be necessary.

When blood is ejected out into rigid and distensible tubes from the same pump, the rate of rise in blood pressure in the rigid tube might be larger than that in the distensible tube. The same result may happen when we considered the reason why the peak value of the PA dp/dt in chronic pulmonary emphysema is larger than that in the other two groups. However, if the mode of ejection from the pump varies, this phenomenon might also be changed. That is to say, if the condition of the heart changes, for example, as in cardiac failure, it is rather dangerous to observe it only from the peak value of PA dp/dt. The cases which have large peak value of PA dp/dt have large peak value of
RV dp/dt, but the cases which have large peak value of RV dp/dt have not always large peak value of PA dp/dt. These facts indicate that the stability of the pulmonary arterial system gives influence in part upon the contractility of the right ventricle. However, this is not the main factor to determine the contractility of the right ventricle. There is no relationship between the peak value of RV dp/dt and the right ventricular end-diastolic pressure. As stated before, from the clinical experience, it is known that in cases of chronic pulmonary emphysema, cardiac failure easily takes place in comparatively lower mean pulmonary arterial pressure than that of mitral stenosis. There may be some relationship between the stability of the pulmonary arterial system and the producing mechanism of the right heart failure, though the clear-cut reason still remains obscure from the results obtained in this paper.

SUMMARY

Quantitative observations on the pulmonary arterial pressure pattern were made by approaching mathematically using the method of FOUER analysis and the first derivatives. Concept that the pulmonary arterial system was a transfer element of the control system made it possible to make analysis of its stability by utilizing the results of Fourier analysis. Right heart catheterization was performed of thirty-two patients with mitral stenosis, atrial septal defect and chronic pulmonary emphysema. The Bode diagram revealed that the high energy distribution in the higher frequency was seen in cases with chronic pulmonary emphysema than in mitral stenosis or atrial septal defect. Gain margin and phase margin were smaller in chronic pulmonary emphysema than in the other two groups. Pulmonary vascular compliance was nearly inversely proportional to gain margin and phase margin. Positive relationships were found between PA dp/dt and gain margin and phase margin. Positive relationship were also found between PA dp/dt and RV dp/dt.

The stability of the pulmonary arterial system was chiefly determined by the distensibility of the pulmonary artery. And this distensibility effects the systolic ejection and possibly the contractility of the heart muscle.

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