Hemodynamic Determinants of Pulmonary Valve Motion During Systole in Experimental Pulmonary Hypertension

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SUMMARY To clarify the determinants of pulmonary valve (PV) motion in pulmonary hypertension, we examined the correlations among PV echo patterns, the pulmonary artery (PA) flow curve just above the PA orifice and the pulmonary artery–right ventricle (PA–RV) pressure gradient. By constricting the PA, we could produce a variety of PV echo patterns, including mid-systolic semiclosure in open-chest dogs. Throughout the experiments, the PV echo pattern and PA flow curve were similar in pattern and timing. When the PV echo showed mid-systolic semiclosure with reopening, the PA flow curve showed a transient decrease followed by a transient increase during mid-systole. The PA–RV pressure gradient became transiently positive (PA pressure > RV pressure) and then negative in mid-systole only when the PV echo showed mid-systolic semiclosure with reopening. In conclusion, PV motion during systole may be instantaneously determined by PA flow change and the PA–RV pressure gradient during the cardiac cycle in experimental pulmonary hypertension.

ABNORMAL ECHO PATTERNS of the pulmonary valve (PV), including a small or absent “a” dip, decreased or negative diastolic slope, rapid opening slope, prolonged pre-ejection period and mid-systolic semiclosure, have been reported to be useful in assessing pulmonary hypertension. However, the sensitivity and specificity of these echocardiographic findings are controversial. Acquatella et al. reported a lack of correlation between PV echo patterns and the pulmonary artery (PA) pressure. The determinants of PV motion must be known to evaluate PV echograms in patients with pulmonary hypertension. This study was undertaken to clarify the hemodynamic determinants of PV motion during systole in experimental pulmonary hypertension.

Materials and Methods

Fourteen mongrel dogs that weighed 19–33 kg were anesthetized with i.v. pentobarbital, 30 mg/kg, and ventilated with room air. The heart was exposed through a midternal thoracotomy. The echocardiographic examination of the PV was performed with a commercially available Sonocardiograph SSL 51U using a 0.5-cm-diameter, 3-MHz transducer. The PA blood flow curve was recorded by an electromagnetic flowmeter (Nihon-Kohden Co., model MF-27) with a probe attached to the PA about 1 cm above the PA orifice. Two catheter-tipped Millar micromanometers were introduced into the PA trunk, one through the right ventricular (RV) apex and the other through a...
branch of the left PA (fig. 1). After micromanometric pressures were made equisensitive, one micromanometer introduced through the RV apex was withdrawn and was positioned in the right ventricle. The PV echogram was recorded from the pericardial surface of the RV outflow tract, simultaneously with PA pressure, RV pressure, PA flow, pulmonary artery-to-right ventricle (PA-RV) pressure gradient and ECG. The transducer was attached to a rigid bar and positioned on the pericardial surface of the outflow tract of the right ventricle. It was fixed lightly to the pericardial surface, taking care to minimize the

![Diagram](https://example.com/diagram.png)

**Figure 1.** The experimental method. UCG = ultrasonicocardiogram; PA = pulmonary artery; RV = right ventricle.

**Figure 2.** Designation of each point on the pulmonary valve echo (PVE), pulmonary artery flow (PAF) curve and pulmonary artery-right ventricle (PA-RV) pressure gradient (PG) curve. Points $P_1$, $P_2$, $P_3$, and $P_4$ are those at which the PA-RV pressure gradient curve crosses the zero line.

In the preliminary experiment, we observed no changes in PV echograms or hemodynamic measurements when one branch or two branches of the left PA were completely constricted. With constriction of the right main branch of the PA, typical midsystolic semiclosure or a severe degree of pulmonary hypertension was not observed. Therefore, after complete constriction of one branch or two branches of the left PA, we partially constricted the right main branch of the PA using a vascular occluder (in vivo Metric Systems). The extent of the constriction was varied in each experiment. After control data were obtained, recordings were repeatedly made during the constriction of the right main branch of the PA.

To compare the PV echo pattern, PA flow curve and pressure gradient curve to each other, we labeled each point (fig. 2). In the experiment in which the chest was opened, the hemodynamic state was not influenced by respiration, as shown by the absence of apparent changes in PA pressure and RV pressure during one respiratory cycle. In addition, the purpose of this study was to correlate the PV echo pattern and any hemodynamic changes induced by various degrees of pulmonary hypertension. Therefore, we made measurements without considering the phase of respiration.

**Results**

In the control state, the systolic pressure of the PA ranged from 19-34 mm Hg (table 1). The peak systolic pressures made by the constriction of the PA

<table>
<thead>
<tr>
<th>Dog</th>
<th>BW (kg)</th>
<th>Midystolic semiclosure of pulmonary valve</th>
<th>Control</th>
<th>Peak</th>
<th>Range of pressure during which MSSC appeared</th>
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<tbody>
<tr>
<td>1</td>
<td>33</td>
<td>Appeared</td>
<td>23</td>
<td>62</td>
<td>32-48</td>
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<tr>
<td>2</td>
<td>19</td>
<td>Appeared</td>
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<td>64</td>
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<td>23</td>
<td>Appeared</td>
<td>30</td>
<td>73</td>
<td>55-67</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>Appeared</td>
<td>19</td>
<td>47</td>
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<td>22</td>
<td>55</td>
<td>29-37</td>
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<tr>
<td>6</td>
<td>25</td>
<td>Appeared</td>
<td>20</td>
<td>65</td>
<td>34-44</td>
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<tr>
<td>7</td>
<td>19</td>
<td>Not appeared</td>
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<td>54</td>
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<tr>
<td>8</td>
<td>26</td>
<td>Not appeared</td>
<td>34</td>
<td>82</td>
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<tr>
<td>9</td>
<td>22</td>
<td>Not appeared</td>
<td>32</td>
<td>57</td>
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<td>21</td>
<td>54</td>
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Abbreviations: BW = body weight; PA = pulmonary artery; MSSC = midsystolic semiclosure of the pulmonary valve.
ranged from 47–82 mm Hg. A variety of PV echo patterns, including midsystolic semiclosure with or without reopening, occurred when varying degrees of pulmonary hypertension were produced by constriction. Typical midsystolic semiclosure was produced in dogs 1–6, but dogs 7–14 had only an indistinct semiclosure. The range of the systolic pressure of the PA was varied in each dog (table 1).

Figure 3 shows the representative data from dog 1.

As the constriction of the PA was increased, the PV echo pattern, the PA flow curve and the PA–RV pressure gradient curve changed their shapes.

In the control state, the echogram of the PV showed rapid and full opening in early systole, stayed widely open during mid systole and closed in end systole (fig. 4). Similarly, the PA flow curve showed a rapid increase in early systole (B–C), a gradual decrease during midsystole (C–D) and a steep decrease in end-systole (D–E).

FIGURE 3. Simultaneous recording of the pulmonary valve echogram, pulmonary artery flow (PAF) curve, pulmonary artery–right ventricle pressure-gradient (PG) curve, pulmonary artery pressure (PAP) curve and right ventricular pressure (RVP) curve in dog 1. The PAP curve was increased progressively by the constriction of pulmonary arteries. The peak systolic pressure of the pulmonary artery elevated from 34 mm Hg (the first beat) to 50 mm Hg (the last beat). Lower panel shows the traced curves. With increasing degrees of pulmonary artery pressure, the pulmonary valve echo, pulmonary artery flow and PA–RV pressure gradient curves changed their patterns.

FIGURE 4. Original data and traced representation in the control state (before constriction) in dog 1. The peak systolic pressure of the pulmonary artery (PAP) was 23 mm Hg. The pulmonary valve opened fully (b–c), stayed open (c–d) and closed (d–e). No midsystolic semiclosure was observed. The pulmonary artery flow (PAF) showed a rapid rise in early systole (B–C), a slow decline (C–D) in midsystole and a rapid decrease (D–E) in late systole. The pulmonary artery–right ventricular pressure gradient (PG) was negative (the right ventricular pressure was greater than the pulmonary artery pressure) in early systole (P1P2), almost zero in midsystole (P2P3) and positive (the right ventricular pressure (RVP) was lower than the pulmonary artery pressure) in late systole (after point P3).
systole (D-E). The PA–RV pressure gradient was negative and showed a decrescent and crescent curve in early systole \((P_1P_2)\). At the time of point \(c\) on PV echo, the PA–RV pressure gradient was almost zero (point \(P_3\)). Then, the pressure gradient was around zero until point \(P_4\) \((P_2P_3)\). After point \(P_5\), the pressure gradient curve became positive. These findings were consistent for all 14 dogs.

With a mild degree of PA constriction (the systolic pressure of the PA was increased by approximately 32–83\% of the control level), the PV echogram showed a slight but distinct mid-systolic semiclosure (fig. 5). In mid-systole, the PV moved anteriorly (c-n) to close partially and then moved posteriorly (n-o) to open again. The PA flow curve showed a sharp decline between points C and N. At point N, the flow curve changed its direction to form a slight notching. The pressure gradient curve showed four crossing points \((P_3P_4)\). During points c and n on the PV echo, the PA pressure became greater than the RV pressure, resulting in a positive PA–RV pressure gradient. The RV pressure curve showed a decrease in the rate of rise between points \(P_2\) and \(P_3\).

In the advanced degree of PA constriction (the systolic pressure of the PA was increased by 68–130\% of the control level), the PV echogram showed a typical pattern of mid-systolic semiclosure with reopening (fig. 6). After rapid opening, closure of the PV followed by reopening was clearly noted to occur. The PA flow curve showed a relatively steep downward slope between points C and N and reversed its direction at point N to make a shallow dip. The PA–RV

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**Figure 5.** Original data and traced representation of the first heart beat shown in figure 1 (dog 1). The peak systolic pressure of the pulmonary artery (PAP) was 34 mm Hg. The pulmonary valve echo showed mid-systolic semiclosure (c-n) with reopening (n-o). Pulmonary artery flow (PAF) showed a rapid increase (B-C) in early systole, a rapid decrease (C-N) with a slight decrease (N-O) in mid-systole and a slow decrease (O-D), followed by a rapid decrease (D-E) in late systole. The pulmonary artery–right ventricular (PA–RV) pressure gradient (PG) was negative \((P_3P_4)\) in early systole, positive \((P_2P_3\) dotted area) and then negative \((P_3P_4)\) in mid-systole and positive again (after point \(P_5\)) in end-systole. The reversal of the PA–RV pressure gradient (the right ventricular pressure [RVP] became less than the PAP) in mid-systole resulted from a transient decrease in the rate of rise of RVP (dotted area between the pulmonary artery and RVP curves).

**Figure 6.** Original data and traced representation of the third heart beat shown in figure 1. The peak systolic pressure of the pulmonary artery (PAP) was 37 mm Hg. The pulmonary valve echogram showed a typical mid-systolic semiclosure (c-n) with reopening (n-d). The pulmonary artery flow (PAF) showed a rapid increase (B-C) in early systole, a rapid decrease (C-N) with a slight re-increase (N-O) in mid-systole and a slow decrease (O-D), followed by a rapid decrease (D-E) in late systole. The pulmonary artery–right ventricular pressure gradient (PG) was negative \((P_3P_4)\) in early systole, positive \((P_2P_3\) dotted area) and then negative \((P_3P_4)\) in mid-systole and positive again (after point \(P_5\)) in late systole. There was a decrease in the rate of rise of the right ventricular pressure (RVP) between points \(P_2\) and \(P_3\) (dotted area).
pressure gradient became positive between points P2 and P3 because a decrease in the rate of rise of the RV pressure occurred in this period.

With a more advanced degree of PA constriction (the systolic pressure of the PA was increased up to nearly peak pressure in table 1), the PV echo showed gradual opening in early systole and a slow closure in mid- and end-systole (fig. 7). The amplitude of the PV echogram was decreased. The PA flow curve showed a slow increase, followed by a slow decrease, and it decreased markedly in its amplitude. The pressure-gradient curve crossed the zero line at two points (points P1 and P2). After point P2, the pressure gradient was positive and small in amplitude.

A similar relationship between PV echo patterns and hemodynamic changes occurred in dogs 2–6.

The temporal relations between the PV echo pattern and PA flow pattern or PA–RV pressure gradient curve were examined in these six dogs. The times from the Q wave of ECG to each point were measured and compared with each other. Figure 8 shows the results in dog 1. The respective times of the PV echogram and the PA–RV pressure gradient correlated well (y = 1.06x – 7.3, r = 0.98, p < 0.001). The respective times of the PV echogram and the PA flow curve also correlated well (y = 1.03x – 14.5, r = 0.99, p < 0.001). However, the respective times of the PA flow curve were longer than those of the PV echogram by about 10 msec. The other five dogs had similar results. To summarize the results of the six dogs, the times of pressure gradient curves were almost equal, or were shorter by 5 msec or less, to those on the echocardiograms. The respective times of PA flow curves were longer than those of echocardiograms by 8–12 msec.

Figure 9 shows the representative data from dog 7. Despite the high PA pressure up to about 60 mm Hg, midsystolic semiclosure of the PV, a transient decrease in PA flow or transient reversal of the PA–RV pressure gradient was not observed during increasing degrees of PA constriction. However, the echo patterns and the PA flow curves appeared to be similar in pattern and timing. Similar relations were shown in dogs 8–14 as well.

**Figure 7.** Original data and traced representation of the last beat in figure 1. The peak systolic pressure of the pulmonary artery (PAP) was 50 mm Hg. The pulmonary valve echo showed a slow opening (b-c) in early systole and a gradual closure (c-e) in mid- to late systole. Pulmonary artery flow (PAF) showed a slow increase (B-C) in early systole and then a gradual decrease (C-E) in mid- to late systole. The amplitude of pulmonary artery flow curve was markedly decreased. The pulmonary artery–right ventricular pressure gradient (PG) was slightly negative (P1, P2) in early systole and was positive (after point P3) in mid- and late systole. RVP = right ventricular pressure.

**Figure 8.** Temporal relationship between pulmonary valve echogram (PVE) and pulmonary artery flow (PAF) curve or the pulmonary artery–right ventricle (PA–RV) pressure-gradient (PG) curve. A line showing y = x is drawn in the figure. Q-b~o = time intervals from the beginning of Q waves of ECG to points b~o on echogram; Q-P1~4 = time intervals from the beginning of Q waves to points P1~4 on the PA–RV pressure-gradient curve; Q-B~O = time intervals from the Q waves to points B~O on the pulmonary artery flow curve. The regression equations obtained were as follows: y = 1.06x – 7.3, r = 0.98, p < 0.001 (PG vs PVE); y = 1.03x – 14.5, r = 0.99, p < 0.001 (PAF vs PVE).
FIGURE 9. Simultaneous recording of the pulmonary valve (PV) echogram, pulmonary artery flow (PAF) curve, pulmonary artery-right ventricular (PA-RV) pressure-gradient (PG) curve, pulmonary artery pressure (PAP) curve and right ventricular pressure (RVP) curve in dog 7. The peak systolic pressure of the pulmonary artery increased from 33 mm Hg to 54 mm Hg. No mid-systolic semiclosure was observed in any beat. PAF increased and then gradually decreased without a midsystolic dip. The amplitude of the PAF curve decreased gradually as the PAP increased. The PA-RV pressure gradient was around zero during systole.

Discussion

In the present study, the PV echo was shown to correlate well with PA flow, clearly shown in mid-systolic semiclosure of the PV. In this condition, semiclosure with reopening of the PV and a transient decrease followed by an increase in PA flow occurred simultaneously in midsystole. Points B, C, N and O on the PA flow curve occurred about 10 msec after respective points b, c, n and o on the echogram of the PV. When a flow probe was attached to the right main branch of the PA about 5 cm distal to the PA orifice in two dogs, the delay time was about 60 msec. This may explain the delay time of PA flow (about 10 msec) that was measured by a flow probe attached to the PA about 1 cm distal to the PA orifice.

This experiment also shows that the PV echo patterns showed a good correlation with changes in the PA-RV pressure gradient curve. When the PA-RV pressure gradient became negative (P1P2 and P2P3 in figs. 5 and 6), the PA flow increased and the PV opened. When the pressure gradient became positive (P1P3 and after point P3 in figs. 5 and 6), the PA flow decreased and the PV closed. The points at which the pressure gradient curve crossed the zero line almost coincided with the respective points of PV echo (fig. 8). From these observations, we conclude that the PV may move to open when the PA blood flow increases and the PA-RV pressure gradient becomes negative. When the PA blood flow decreases and the PA-RV pressure gradient becomes positive, the PV may move to close.

The transient reversal of the PA-RV pressure gradient in midsystole resulted mainly from a transient decrease in the rate of rise of RV pressure. The transient decrease may be caused by various factors, including tricuspid regurgitation and altered RV function which are caused by an increased afterload of the RV. Because we did not record tricuspid flow curve or hemodynamic measurements that reflect RV function in this experiment, we cannot comment on this point.

The results of the present study suggest that we can predict the PA flow pattern and the pressure gradient change from the PV echo pattern during systole. Therefore, the PV echo may provide an important clue for understanding the hemodynamic events in the right side of the heart in patients with pulmonary hypertension. Mid-systolic semiclosure of the PV occurred only in six of 14 dogs examined in the wide range of PA pressure. This observation seems to be consistent with those in patients with pulmonary hypertension. We do not know why the mid-systolic semiclosure and transient reversal of the PA-RV pressure gradient were not observed in eight dogs. Contractility of the RV may vary in each animal.

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