Validation of Doppler-derived pulmonary arterial pressure in patients with ductus arteriosus under different hemodynamic states

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ABSTRACT  Twenty-nine patients with a patent ductus arteriosus (PDA) in isolation (n = 17) or in combination with other lesions (n = 12) underwent simultaneous hemodynamic assessment and evaluation of PDA flow velocity by the Doppler method. The accuracy with which Doppler velocity across the PDA predicted pulmonary arterial pressure and the influence of PDA size and shape on the Doppler velocity-pressure relationship were examined. Seventy percent had a cone-shaped PDA (narrowest at the pulmonary artery end), and the remainder were tubular. Narrowest PDA diameter ranged from 1.5 to 9 mm (mean 3.5 mm). Peak systolic and mean pulmonary arterial pressure ranged from 10 to 116 and 8 to 72 mm Hg, respectively. Twenty-one patients (group 1) had left-to-right shunting only. The following variables showed significant correlation in this group: peak instantaneous systolic aortic-to-main pulmonary arterial (MPA) pressure gradient and maximum Doppler velocity across the PDA (slope = 1.03, SEE = 13 mm Hg, r = .94, p < .001), mean aortic-to-MPA pressure gradient and mean Doppler velocity (slope = 1.06, SEE = 10 mm Hg, r = .95, p < .001), and end-diastolic aortic-to-MPA pressure gradient and minimum Doppler velocity (slope = 1.12, SEE = 8 mm Hg, r = .96, p < .001). Eight patients (group 2) had bidirectional shunting. In this group peak instantaneous aortic-to-MPA pressure gradient significantly correlated with maximum Doppler velocity measured from the left-to-right shunt (slope = .70, SEE = 2 mm Hg, r = .92, p < .002) and mean pressure gradient correlated with mean Doppler velocity (slope = .83, SEE = 3 mm Hg, r = .78, p < .003). Right-to-left Doppler velocities showed no correlation with pressures. In six patients with pulmonary hypertension Doppler velocity changes accurately predicted the effect of pulmonary vasodilation on pulmonary arterial pressure. Doppler velocity of PDA flow reliably predicts pulmonary arterial pressure over a wide range of pressures and PDA shapes and sizes.


ONE OF THE most common lesions encountered either in isolation or in association with other forms of congenital heart disease is the patent ductus arteriosus (PDA). By combined two-dimensional and Doppler echocardiography both direct imaging and blood flow evaluation are possible.1–5 Until recently, Doppler measurement of systolic pulmonary arterial pressure in the setting of a PDA has been accomplished by indirect assessment with the use of time intervals,6 which does not provide easily reproducible absolute values. Estimation of pulmonary arterial systolic pressure has been attempted in the clinical setting of an aorticopulmonary shunt including PDA,7 where Doppler and pressure measurements were not all simultaneous. More recently, in an experimental preparation of discrete ductal constriction in the fetal lamb,8 simultaneous systolic and diastolic pressure measurements showed good correlation with Doppler velocity measurements.

While it appears that peak systolic pressures correlate with Doppler velocities in the experimental setting, similar information is not available from a patient population incorporating a wide age range and variety of ductal sizes. Furthermore, previous studies have not provided information about mean pulmonary arterial pressure, which is necessary for assessment of alterations in pulmonary vascular resistance.

This study addresses the reliability of Doppler-de-
rived systolic, diastolic, and mean pulmonary arterial pressure measurements in the setting of PDA with a wide range of pulmonary arterial pressures and ductal dimensions. We also evaluated the usefulness of this technique in following the hemodynamic response to pulmonary vasodilators in a subgroup of patients with pulmonary hypertension.

Methods

Patient population. Twenty-nine patients (nine boys, 20 girls, mean age 2.7 ± 3.5 years, range 3 months to 13 years) with a PDA were studied by Doppler echocardiography during simultaneous cardiac catheterization between November 1984 and March 1987.

Fifteen patients with an isolated PDA were undergoing transcatheter occlusion with a Rashkind prosthesis. Twelve had an associated cardiac lesion and two had an isolated PDA with severe pulmonary hypertension (tables 1 and 2). Patients were consecutively studied during prearranged cardiac evaluation or intervention. Therefore, for the purposes of this study, no specific selection criteria were used. All patients underwent complete two-dimensional echocardiographic examinations before cardiac catheterization.

Cardiac catheterization. Patients not undergoing PDA closure were sedated with a mixture of meperidine, promethazine, and chlorpromazine one-half hour before catheterization. Continuous intravenous ketamine anesthesia was used during PDA occlusion. During catheterization, pullback pressures from the descending aorta to the main pulmonary artery were performed with a single fluid-filled catheter in 23 patients. Three others had simultaneous aortic and pulmonary arterial pressure measurements with two fluid-filled catheters, while in three other patients a double-lumen high-fidelity catheter was placed across the ductus. PDA dimensions were measured from lateral descending aorta angiograms with use of the catheter diameter as the reference scale. The diameter was measured at its narrowest point and at the aortic end, and the length was measured from the pulmonary arterial to the aortic insertion of the ductus.

Doppler ultrasound examination. Two-dimensional echocardiographic and Doppler examinations were carried out with an Ultrasound 8 mechanical sector scanner (Advanced Technology Laboratories Inc) or Hewlett-Packard ultrasound imaging system model 77020. Both systems were equipped with pulsed-wave and nonimaging continuous-wave Doppler probes. In all but one (No. 15, table 1) the PDA was visualized from the high left parasternal position, which ensured that the angle of incidence between the Doppler beam and maximum vector of PDA flow was less than 20 degrees (figure 1). Despite the inability to directly visualize the PDA in the one patient, adequate velocity profiles with a discrete envelope to instantaneous peak velocities were obtained in all patients. These were recorded on videotape for later analysis. Where a single catheter was used to measure pressures, Doppler examination of PDA flow velocity was performed immediately after pullback of the catheter into the main pulmonary artery. In this way, the possibility of heart rate variation was minimized such that pressure tracings could be superimposed for determination of peak instantaneous pres-

### Table 1

Data for patients with ductal left-to-right shunting only (group 1)

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age</th>
<th>Diagnosis</th>
<th>PDA orifice (mm)</th>
<th>Inst peak ΔP Ao-MPA (mm Hg)</th>
<th>Mean ΔP Ao-MPA (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cath</td>
<td>Doppler</td>
</tr>
<tr>
<td>1</td>
<td>18 mo</td>
<td>PDA</td>
<td>3</td>
<td>72</td>
<td>66</td>
</tr>
<tr>
<td>2</td>
<td>8.5 yr</td>
<td>PDA</td>
<td>2.5</td>
<td>83</td>
<td>78</td>
</tr>
<tr>
<td>3</td>
<td>9 yr</td>
<td>PDA</td>
<td>3</td>
<td>92</td>
<td>105</td>
</tr>
<tr>
<td>4</td>
<td>9 mo</td>
<td>PDA</td>
<td>3</td>
<td>46</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>3 mo</td>
<td>PDA, PVS</td>
<td>1.5</td>
<td>80</td>
<td>64</td>
</tr>
<tr>
<td>6</td>
<td>1 yr</td>
<td>PDA</td>
<td>2.5</td>
<td>84</td>
<td>96</td>
</tr>
<tr>
<td>7</td>
<td>16 mo</td>
<td>PDA</td>
<td>4</td>
<td>84</td>
<td>88</td>
</tr>
<tr>
<td>8</td>
<td>5.6 yr</td>
<td>PDA</td>
<td>—</td>
<td>92</td>
<td>103</td>
</tr>
<tr>
<td>9</td>
<td>3.5 yr</td>
<td>PDA</td>
<td>2.5</td>
<td>64</td>
<td>68</td>
</tr>
<tr>
<td>10</td>
<td>9 mo</td>
<td>VSD, PDA</td>
<td>1.5</td>
<td>27</td>
<td>26</td>
</tr>
<tr>
<td>11</td>
<td>3 mo</td>
<td>TGA, VSD, PDA</td>
<td>8</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>12</td>
<td>7 mo</td>
<td>PDA</td>
<td>3.5</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>13</td>
<td>1 yr</td>
<td>VSD, PDA</td>
<td>2</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>14</td>
<td>5.5 yr</td>
<td>PDA</td>
<td>3</td>
<td>125</td>
<td>90</td>
</tr>
<tr>
<td>15</td>
<td>13 yr</td>
<td>PDA</td>
<td>3</td>
<td>118</td>
<td>112</td>
</tr>
<tr>
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<td>93</td>
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<tr>
<td>17</td>
<td>8 mo</td>
<td>PDA</td>
<td>3</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td>18</td>
<td>6 mo</td>
<td>PDA</td>
<td>4</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>1 yr</td>
<td>PDA</td>
<td>3.5</td>
<td>53</td>
<td>54</td>
</tr>
<tr>
<td>20</td>
<td>6 mo</td>
<td>PDA, LPA sling</td>
<td>1.5</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>21</td>
<td>6 mo</td>
<td>PDA, VSD</td>
<td>6</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Mean</td>
<td>3.4</td>
<td>PDA, VSD</td>
<td>1.5</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>± SD</td>
<td>±3.8</td>
<td></td>
<td>±1.5</td>
<td>±35</td>
<td>±33</td>
</tr>
</tbody>
</table>

Ao = aorta; Cath = cardiac catheterization pressure; ΔP = pressure gradient; Inst = instantaneous; LPA sling = left pulmonary artery sling; MPA = main pulmonary artery; PDA = patent ductus arteriosus; PVS = pulmonary valve stenosis; VSD = ventricular septal defect; TGA = complete transposition of the great arteries.
sure gradients between the aorta and the main pulmonary artery. The continuous-wave Doppler technique was used in 23 patients. To assess the effect of sampling site within the ductus on Doppler velocity, a pulsed-wave Doppler method was used in seven patients with pulmonary hypertension. The range cell was sequentially placed at the pulmonary arterial and the aortic end, then in the middle of the ductus.

Echocardiographic measurement of the ductus was possible only in very small infants in whom the vessel walls could be clearly imaged. As this group was in the minority, no attempt was made to correlate PDA size with that obtained angiographically.

**Pressure and Doppler velocity measurements.** For purposes of analysis, patients were divided into two groups on the basis of the pattern of ductal shunting demonstrated by Doppler ultrasound. Group 1 (n = 21) had continuous left-to-right shunting throughout the cardiac cycle, and group 2 (n = 8) had bidirectional shunting. In group 1, peak instantaneous systolic, mean, and end-diastolic pressure gradients between the aorta and main pulmonary artery were determined for three to five consecutive cardiac cycles, and the average was taken. These values were then compared with the respective Doppler velocities, as detailed below. In group 2 the measured peak instantaneous pressure gradient invariably occurred in diastole. This value was used for comparison with the maximum Doppler velocity measured during the phase of left-to-right ductal flow. The mean pressure difference was similarly compared with mean Doppler velocity determined from the period of left-to-right shunting. Attempts were also made to correlate systolic right-to-left flow velocity with pressure gradients. Doppler measurements were performed by one observer without prior knowledge of catheterization data with a Sony Cardiologic Analysis system (Sony, Inc.). Three to five consecutive Doppler velocity spectral displays from selected stop frames were traced on a digitizing tablet attached to the computer. Maximum and minimum Doppler velocities were measured for each cardiac cycle by digitizing the Doppler spectral display between two consecutive R waves on the electrocardiogram. Computation of the mean velocity was accomplished by the computer with the formula: mean pressure = \(4 \Sigma (v_i^2 + v_2^2 + \ldots + v_n^2)/n\), where \(v_i\) is the peak velocity measured at predetermined intervals on the spectral display, and \(n\) is the number of velocity measurements performed.

The time from onset of the R wave to the point of maximum Doppler velocity was also measured and expressed as a percentage of the total duration of the cardiac cycle measured between two consecutive R waves in all patients.

**Statistical analysis.** Analysis of variance was used to compare catheterization data between groups 1 and 2, and Scheffé's F test was used to indicate variables with a significant difference at the level of \(p \leq .05\). Catheterization pressure gradients and Doppler flow velocities within groups were compared by standard linear regression analysis.

**Results**

**Patient data, ductal size, and hemodynamics.** Patient data are presented in tables 1 and 2. All patients in group 2 had trisomy 21 (Downs syndrome). Although there was no significant difference between the mean

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**TABLE 2**

Data from patients with bidirectional ductal shunting (group 2)

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>Age</th>
<th>Diagnosis</th>
<th>PDA orifice (mm)</th>
<th>Pressure grad. Ao-MPA (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cath</td>
</tr>
<tr>
<td>1</td>
<td>6 mo</td>
<td>AVSD, PDA, CoA</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>6 mo</td>
<td>AVSD, PDA</td>
<td>9</td>
<td>2 (14)</td>
</tr>
<tr>
<td>3*</td>
<td>10 mo</td>
<td>PDA</td>
<td>—</td>
<td>2 (2)</td>
</tr>
<tr>
<td>4</td>
<td>1 yr</td>
<td>AVSD, PDA</td>
<td>3</td>
<td>8 (4)</td>
</tr>
<tr>
<td>5</td>
<td>7 mo</td>
<td>AVSD, PDA</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>1 yr</td>
<td>AVSD, PDA</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>6 mo</td>
<td>AVSD, PDA</td>
<td>5</td>
<td>7 (10)</td>
</tr>
<tr>
<td>8*</td>
<td>14 mo</td>
<td>PDA</td>
<td>5</td>
<td>2 (3)</td>
</tr>
</tbody>
</table>

\(\text{AVSD} = \text{primum atrial septal defect; CoA} = \text{coarctation of the aorta; other abbreviations as in table 1.}\)

\(\text{*Trial of continuous intravenous infusion of vasodilators with no significant effect on pulmonary arterial pressures and no change in Doppler shunting pattern or velocity. Values in parentheses represent measurements in 100% oxygen.}\)

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**FIGURE 1.** Two-dimensional echocardiographic image of a PDA from the high left parasternal position showing a Doppler sampling angle of less than 20 degrees. \(\text{d ao} = \text{descending aorta; mpa} = \text{main pulmonary artery. Arrows indicate pulmonary arterial end of ductus.}\)**
TABLE 3
Comparison of data from groups 1 and 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group 1 (n = 21)</th>
<th>Group 2 (n = 8)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age (years)</td>
<td>3.4±3.8</td>
<td>0.8±0.2</td>
<td>NS</td>
</tr>
<tr>
<td>PDA orifice size (mm)</td>
<td>3.0±1.5</td>
<td>5.0±3.0</td>
<td>NS</td>
</tr>
<tr>
<td>Peak systolic PAP (mm Hg)</td>
<td>36.5±20</td>
<td>76±12</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Mean PAP (mm Hg)</td>
<td>25.5±12</td>
<td>49±12</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Mean pressure gradient (aorta-MPA) (mm Hg)</td>
<td>48±30</td>
<td>5±4</td>
<td>&lt;.003</td>
</tr>
<tr>
<td>Peak to peak systolic gradient (aorta-MPA (mm Hg))</td>
<td>62±34</td>
<td>3±9</td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

PAP = pulmonary arterial pressure (note use of peak to peak, not instantaneous, systolic pressure gradient in this comparison between group 1 and 2); other abbreviations as in tables 1 and 2.

Age of group 1 and group 2 patients, those in group 2 tended to be younger (table 3). No significant difference was observed in the diameter of the PDA at its narrowest point between the two groups. Ductal length varied from 5.5 to 13 mm (mean 8), and aortic orifice varied from 1.5 to 13 mm (mean 7.5). Pulmonary arterial pressures and aortic-to-pulmonary arterial pressure gradients were significantly different between the two groups (p < .001).

Figure 2 demonstrates the variation in shape of the PDA, from the cone shape encountered in 70% of patients (figure 2, A), to the tubular PDA seen in the remainder (figure 2, B). In the latter subgroup, a discrete point of narrowing was generally not evident. In one patient each the narrowest point was at the aortic end and in the middle of the PDA.

Effect of site of Doppler interrogation. The effect of sampling site on Doppler velocity was apparent in four group 2 patients in whom pulsed Doppler was used. The maximum velocities of both the right-to-left systolic and left-to-right diastolic flow were dependent on position of the Doppler range cell within the PDA. For right-to-left flow, maximum velocity increased by a small amount from the pulmonary arterial to the aortic end of the PDA. The opposite applied to left-to-right flow, where maximum velocity was highest immediately proximal to the pulmonary arterial end of the PDA, and lowest at the aortic end. Figure 3 depicts the change in maximum left-to-right velocity as the Doppler range cell was moved from one end of the PDA to the other. For comparison with pressure gradients, Doppler measurements were therefore taken at the position indicated in figure 3, A, when pulsed Doppler was used.

Doppler velocity-pressure relationship

Group 1. Doppler velocity profiles in this group showed a characteristic pattern of turbulent flow with a discrete envelope of peak velocities (figure 4). Maximum Doppler velocity ranged from 1.83 to 5.14 m/sec. Maximum, mean, and minimum Doppler velocities significantly correlated with peak instantaneous, mean, and end-diastolic aortic-to-main pulmonary arterial pressure gradients. The regression curves for these relationships are shown in figure 5, A, B, and C, respectively.

Four patients in this group (Nos. 11, 12, 13, and 21, table 1) with elevated pulmonary arterial pressures and a persistent left-to-right pressure gradient throughout the cardiac cycle had low-velocity continuous left-to-right flow across the PDA by Doppler ultrasound. Mean aortic-to-main pulmonary arterial pressure gradients in these four patients ranged from 2 to 10 mm Hg. The timing of maximum Doppler velocity from onset of the R wave occurred later in the cardiac cycle in these

![Figure 2](http://circ.ahajournals.org/doi/figure/10.1161/01.CIR.85.2.993)

**FIGURE 2.** Lateral aortic angiograms showing variation in shape of the PDA. A, The cone-shaped ductus, narrowest at main pulmonary arterial end (arrows), which was seen in 70% of patients. Scale = 1 cm. B, Long tubular PDA. Ductal shunting in both patients was left to right only. Scale = 1 cm. Abbreviations as in figure 1.
patients, shifting toward diastole with values of 56%, 69%, 85%, and 70% of RR duration, respectively. In the remainder with low pulmonary arterial pressures, maximum Doppler velocity occurred at a mean of 46% (range 42% to 53%) from onset of the R wave.

**Group 2.** No consistent relationship was found between peak systolic aortic-to-main pulmonary arterial pressure gradient and maximum Doppler velocity for the period of right-to-left shunting. Significant correlations were, however, found between peak instantaneous aortic-to-pulmonary arterial pressure gradient and mean Doppler velocity during the period of left-to-right flow (figure 6). The ratio of diastolic (left-to-right) flow time to the total cardiac cycle (RR interval) did not show a consistent relationship with either systolic or mean pressure gradients between the aorta and main pulmonary artery. Maximum Doppler velocity in this group occurred at a mean of 84% from onset of the R wave.

**Effect of pulmonary vasodilation.** Pressure and Doppler velocity measurements of ductal flow in room air and 100% oxygen were performed in five group 2 patients and one patient from group 1. In all cases, pressure gradient alterations were reflected by similar changes in Doppler flow velocities. Catheterization and Doppler data from patient 2 (group 2) is presented in figure 7. Three patients showed no alterations in pulmonary arterial pressures or Doppler flow velocities from room air to 100% oxygen. In two of these (patients 3 and 8, table 2), who had isolated hypertensive PDA, no changes in ductal pressure gradients or Doppler flow velocities occurred during intravenous infusion of vasodilator agents (albuterol, nifedipine, and hydralazine). Patient 3 subsequently died after an open lung biopsy to determine the stage of pulmonary vascular disease; results showed advanced Heath-Edwards grade 3 changes. Patient 8 had consistently suprasystemic systolic pulmonary arterial pressures, with diastolic and mean pressures less than 10 mm Hg below aortic pressure (figure 8). Doppler flow velocity in this patient differed from those in the rest of the group 2 patients only in the duration of systolic right-to-left flow, which occupied 55% of the cardiac cycle. In contrast, systolic right-to-left flow was very abbreviated in all other group 2 patients, occupying less than 20% of the cardiac cycle. Continuous right-to-left flow across the PDA was observed in two patients (Nos. 2 and 7, table 2), in one following sedation for routine precathe-
terization echocardiographic evaluation, and in the other a few hours after cardiac catheterization. The Doppler spectral display from one of these patients is shown in figure 7, C.

Discussion

This study demonstrates that Doppler flow velocity across the PDA can be used to accurately estimate systolic, mean, and diastolic pulmonary arterial pressure over a wide range of values. The important feature is the potential value in the ability to detect by the Doppler method small changes in the velocity and direction of ductal shunting, which reflect alterations in pulmonary arterial pressure under varying conditions.

PDA imaging and Doppler interrogation. While it would be ideal if the ductus could always be imaged in its entirety to ensure parallel Doppler interrogation of flow, this does not appear to be necessary to obtain an accurate assessment of pulmonary arterial pressure. Thus, provided a high left parasternal position is used imaging may not be essential. The limiting factor with this latter approach would be related to an unusual ductal position, or in the setting of reduced pulmonary blood flow where the ductus may be tortuous and form an acute angle with the descending aorta, making parallel interrogation difficult.

In the setting of bidirectional shunting, the magnitude of Doppler velocity was influenced by the position of sampling within the PDA when the pulsed Doppler method was used. Sampling in the middle of the ductus resulted in underestimation of both components of bidirectional flow, while sampling immediately proximal to the ductal orifice in the main pulmonary artery yielded the highest left-to-right Doppler velocities. This suggests that the PDA has a discrete point of

FIGURE 4. Characteristic Doppler velocity spectral display of PDA flow in patients with left-to-right shunting only. A, Restrictive PDA with high pressure gradients. The superimposed simultaneous pressure tracing (top panel) shows a continuous gradient from aorta to MPA. Peak Doppler velocity of 54 mm Hg corresponded to a peak instantaneous pressure gradient of 53 mm Hg. Minimum Doppler velocity (23 mm Hg) occurring at end-diastole corresponded to a minimum pressure gradient of 26 mm Hg. The mean Doppler velocity (41 mm Hg) corresponded to a mean pressure gradient of 40 mm Hg. B, Hypertensive PDA with low pressure gradients. Peak instantaneous systolic pressure gradient occurring in systole was 30 mm Hg, corresponding to a maximum Doppler velocity of 32 mm Hg. Mean pressure gradient was 14 mm Hg, with a mean Doppler velocity of 12 mm Hg. Flow below the zero line was simultaneously recorded from the descending aorta by the continuous-wave Doppler transducer. Ao = aorta; MPA = main pulmonary artery.
narrowing at the pulmonary arterial end even when it appears long and tubular on imaging. We can only speculate that the small increase in right-to-left Doppler velocity from the pulmonary arterial end of the ductus is due to the effect of ductal geometry on flow profile, since the ductus tends to widen toward its aortic end.

In the presence of pulmonary hypertension, where velocities may be sufficiently low to permit use of pulsed Doppler to assess PDA flow, the Doppler sample should therefore be placed immediately proximal to the pulmonary arterial end of the ductus to obtain the true maximum Doppler velocities for left-to-right flow, and at the aortic end for right-to-left flow. When a continuous-wave Doppler technique is used, the above effect is not apparent.

**PDA size.** A constant Doppler velocity-pressure drop relationship has been shown to hold for orifices with a minimum diameter ranging from 3.0 to 8 mm.\(^{10-12}\) In these studies, the major limitations in applying the modified Bernoulli equation to the Doppler velocity-pressure relationship have arisen from the inability to detect a jet across the orifice, due to departure from laminar flow at very small orifice dimensions.

Although it has been speculated\(^ {13}\) that the ratio of inlet orifice to outlet orifice size (main pulmonary arterial to PDA size in this case) rather than the absolute orifice size may be the limiting factor determining the point at which the Doppler velocity-pressure relationship deviates significantly from unity, this hypothesis has not been tested. In addition, viscous energy losses across small orifices may contribute significantly to underestimation of pressure drop from Doppler velocity.\(^ {12, 13}\)

In this study, the PDA orifice diameter, ranging from 1.5 to 9 mm (mean 3.5 mm) represents orifice areas much smaller than those encountered in valvular heart lesions. Despite this, the regression lines for the correlations between peak instantaneous systolic and mean pressure gradients and maximum and mean Doppler velocities were not significantly different from the lines.

**FIGURE 5.** A, Relationship between maximum Doppler velocity across the PDA and peak instantaneous pressure gradient from aorta to MPA in group 1 patients. Cath = catheterization; Inst = instantaneous. B, Relationship between mean Doppler velocity across the PDA and mean pressure gradient from aorta to MPA in group 1 patients. C, Relationship between minimum Doppler velocity across the PDA and end-diastolic pressure gradient from aorta to MPA. The regression line for the relationship is indicated by the heavy line. The other line represents the line of identity. Slight divergence is noted between these lines as pressure gradient increases.
of identity, thus showing no consistent tendency of the Doppler method to under- or overestimate pressure gradient. Minimum Doppler velocity, however, tended to underestimate the end-diastolic pressure gradient, as shown by the deviation of this regression line from the line of identity. It is not clear why this effect is confined to the end-diastolic Doppler-pressure relationship alone, but the magnitude of the underestimation does not appear to be of sufficient significance to limit the value of this technique in clinical practice.

PDA shape. Recent evidence from studies in vitro using rigid synthetic tubes suggests that Doppler ultra-

sound tends to underestimate pressure drop across tunnel-like obstructions at luminal diameters less than 3 mm, the degree of underestimation increasing significantly when the length of the tunnel exceeds 10 mm. The ductus might be expected to yield similar results.

However, the majority of ductuses in this study had a discrete narrow point at the pulmonary arterial end, and a much wider aortic end. In addition, all except three, which measured 13 mm each, were less than 10 mm in length, including those with a tubular appearance. A tunnel-like effect, which might result in consistent significant underestimation of a pressure drop by Doppler ultrasound, was not evident. One explanation may be the large number of cone-shaped ductus (70%) encountered. The effect on Doppler velocity of sampling position within the ductus also suggests that even when a discrete narrowing is not evident on imaging, the ductus behaves as though a discrete stenosis were present at its pulmonary arterial end.

Although the effects of PDA size and shape could not be independently examined in this clinical study, the results obtained confirm that within this group of patients, the Doppler velocity-pressure correlation across the PDA was not significantly limited by PDA size or shape.

Pattern of shunting. Spach et al. using high-speed cine-angiocardiographic techniques for the evaluation of the pressure-flow dynamics across the PDA under diverse hemodynamic states, demonstrated continuous left-to-right flow in some patients with peak systolic pulmonary arterial pressures elevated to within 6 to 10 mm Hg of aortic pressure, a range similar to that found in patients with bidirectional flow. These findings were noted in four of our patients with pure left-to-right shunting and systolic and mean pressure gradients similar to those in some group 2 patients. The reason that some patients with elevated pulmonary arterial pressure had bidirectional ductal shunting while others with similar hemodynamics shunted left to right only was not clear when pressures alone were examined. In their study, Spach et al. noted that when systolic pressures in the descending aorta and main pulmonary artery were equal, blood arrived at the pulmonary arterial end of the ductus before the aortic end due to the larger distance traversed from the aortic valve to the ductus around the aortic arch, thus explaining systolic right-to-left flow across the ductus when the time lag between onset of right and left ventricular ejection was so brief that it alone was not sufficient to explain this flow. Additionally, earlier right ventricular ejection in patients with pulmonary hypertension may result in the pulmonary arterial pressure rising higher than descend-
ing aortic pressure in early systole, possibly explaining early systolic right-to-left ductal flow.

The early systolic right-to-left shunting observed in group 2 patients was associated with a pulmonary arterial pressure that was always either equal to or slightly less than that in the aorta during all of systole. In no case did pulmonary arterial pressure rise so early compared with descending aortic pressure that a measurable gradient was evident to explain right-to-left flow, including those in which high fidelity catheters were used. Right-to-left flow also occupied a very small part of systole, and was of small magnitude.

Systolic right-to-left Doppler flow may therefore occur in the apparent absence of a transdudal right-to-left pressure gradient. In the patient with suprasystemic pulmonary arterial systolic pressure, a prolonged duration of right-to-left ductal flow was observed, consistent with the transdudal right-to-left pressure gradient. In this setting, the maximum systolic right-to-left Doppler velocity may well correlate with pulmonary arterial-to-aortic peak instantaneous systolic gradient. This could not be verified in this study because only one patient had suprasystolic pulmonary arterial pressure.

Provided the potential for error due to sampling site within the PDA is observed when the pulsed-wave Doppler method is used, Doppler velocity during left-to-right shunting can be used to predict pulmonary

**FIGURE 7.** Bidirectional flow across the PDA in a patient from group 2. Simultaneous pressure measurements (upper panels) and Doppler velocity spectral displays are shown. Flow toward the transducer (aorta to MPA) is above the zero line. Abbreviations are as in previous figures. Pressure and Doppler measurements obtained in room air. There was no pressure gradient between the aorta and MPA either in systole or diastole. Doppler image shows systolic right-to-left flow and very low-velocity variable left-to-right flow in diastole. The pulsed Doppler method was used for this measurement, with the range cell placed at the pulmonary arterial end of the ductus. B, In 100% oxygen, the MPA diastolic and mean pressures have decreased, and the Doppler velocity in diastole has correspondingly increased to reflect the higher pressure gradient between the aorta and MPA. Arrows indicate peak instantaneous pressure gradient between the aorta and the MPA (20 mm Hg), and maximum Doppler velocity, both in diastole (2.5 m/sec, equivalent to 25 mm Hg). The Doppler velocity of the right-to-left flow (1 m/sec, equivalent to 4 mm Hg) does not change between the two states. C, Doppler spectral display from the same patient obtained the day before cardiac catheterization. Shunting was all right to left. The patient was moderately heavily sedated, and became mildly cyanotic.
arterial pressure in the setting of bidirectional shunting. In this situation, the maximum Doppler velocity reflects the peak instantaneous aortic-to-main pulmonary arterial pressure gradient, which is invariably in diastole. The systolic pulmonary arterial pressure cannot therefore be obtained from this assessment. More importantly, however, the mean pressure gradient between the aorta and the main pulmonary artery can be predicted from the mean Doppler flow velocity computed from the left-to-right shunt component.

In patients with pulmonary hypertension and continuous left-to-right ductal shunting, the point in the cardiac cycle at which maximum Doppler velocity occurs is of importance. When this point occurs in systole, as in the patient depicted in figure 4, B, the maximum Doppler velocity can be used to obtain the peak systolic pulmonary arterial pressure by subtracting the maximum Doppler velocity from the systolic blood pressure. When it occurs in diastole, the same does not apply. The mean pulmonary arterial pressure, which is of more clinical value, can, however, always be obtained.

Recently, the new technique of Doppler color flow mapping has been used in the evaluation of PDA shunting and flow disturbances in the main pulmonary artery resulting from this shunting. It is possible that some of the velocities across the ductus demonstrated by pulsed and continuous-wave Doppler methods represent disturbed flow in the main pulmonary artery. However, conventional Doppler interrogation of shunt flow imaged by color flow mapping in an animal preparation of PDA with a wide range of pulmonary-systemic flow ratios has shown systolic and diastolic Doppler flow velocities with a close temporal relationship to measured transudtal pressure gradients. This suggests that the peak velocities demonstrated by the Doppler method are dependent on and reflect these pressure gradients, regardless of shunt magnitude and flow disturbances in the main pulmonary artery. These findings support the use of peak transudctal Doppler velocities to estimate pressure gradients.

Effect of vasodilators. Inhalation of 100% oxygen is frequently used in the evaluation of pulmonary hypertension resulting from left-to-right shunting in congenital heart disease. It alters pulmonary vascular resistance by its effect on pulmonary arteriolar smooth muscle tone. Doppler flow velocity across the PDA in five patients with pulmonary hypertension and bidirectional shunting closely reflected simultaneous changes in pressure gradient between the aorta and main pulmonary arterial during administration of 100% oxygen or intravenous vasodilators. The detection of continuous right-to-left ductal shunting in two patients, who on different occasions showed both bidirectional shunting and different responses to 100% oxygen with lowering of pulmonary arterial diastolic and mean pressure in one, attests to the ability of Doppler ultrasound to follow small changes in pulmonary arterial pressure resulting from pulmonary vascular reactivity. The practical value of being able to follow pulmonary vascular reactivity noninvasively is obvious. As a follow-up tool, infants undergoing therapy that affects pulmonary arterial pressure can be monitored, and the effect of therapy evaluated. This technique may have an application in the newborn with persistent pulmonary hypertension or severe lung disease and a PDA.

In conclusion, Doppler flow velocity across the PDA can predict pulmonary arterial pressure over a wide range of values at different ages. Significant elevation of systolic pulmonary arterial pressure may be asso-

**FIGURE 8.** Doppler spectral display and simultaneous pressure tracing from patient 8 (table 2), who had suprasystolic systolic pulmonary arterial pressure. The right-to-left systolic pressure gradient is reflected by the right-to-left Doppler flow, which is more prolonged than that seen in all other group 2 patients. Flow toward the transducer (descending aorta to MPA) is above the zero line. Abbreviations are as in previous figures.
associated with either bidirectional or continuous left-to-right shunting. Transductal Doppler flow velocity can also be used to follow the effect on pulmonary arterial pressure of pulmonary vasodilation.

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