Noninvasive Doppler echocardiographic evaluation of shunt flow dynamics of the ductus arteriosus

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ABSTRACT The pulsed Doppler technique was used to record the flow velocity patterns in the ductus arteriosus and the pulmonary artery in 26 patients with either isolated or complicated patent ductus arteriosus (PDA). In all patients, abnormal Doppler signals indicating left-to-right (L-R) or right-to-left shunt flow or both were obtained at the site of the ductus arteriosus. These Doppler flow patterns determined within the ductus coincided with the direction of ductal flow seen on the contrast two-dimensional echocardiogram. No Doppler signals of shunt flow were demonstrated in any of 42 control subjects. The peak, mean, and diastolic velocities of the L-R shunt flow within the ductus were measured from the ductal flow velocity profiles. With the Doppler-derived measurements of the mean and diastolic velocities, patients with normal pulmonary arterial pressure and those with evidence of pulmonary hypertension could be correctly identified. In addition, the mean velocity of the diastolic antegrade flow portion obtained from the proximal left pulmonary artery, which was related to ductal L-R shunting, was measured in 16 patients with isolated PDA. This Doppler flow determinant showed a good linear correlation with the L-R shunt ratio determined by Fick’s method (r = .88, p < .01). Our technique permits the noninvasive evaluation of shunt flow dynamics in patients with PDA.


ALTERATION of Doppler flow patterns in the pulmonary artery and descending aorta has been useful in the diagnosis of patent ductus arteriosus (PDA). Two-dimensional echocardiography has allowed visualization of the ductus from the parasternal, suprasternal, and subxyphoid windows. Recent reports have demonstrated that two-dimensional/Doppler echocardiography is a highly sensitive technique for detection of ductal patency. However, few studies have been reported concerning the assessment of shunt flow within the ductus. We therefore designed the present study to (1) evaluate the ability of two-dimensional/Doppler echocardiography to determine the direction of shunt flow in the ductus and (2) assess the pulmonary-to-systemic peak pressure ratio and the degree of left-to-right (L-R) shunting with Doppler-derived indexes of the flow velocity.

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Methods

Patients. We studied 26 patients with PDA between 1 day and 3.5 years old. Diagnosis of PDA was confirmed by cardiac catheterization and surgery. The PDA was an isolated anomaly in 16 and was associated with transposition of great arteries in four patients, pulmonary atresia with intact ventricular septum in two, ventricular septal defect and coarctation of aorta in two, atrophic septal defect in one, and total anomalous pulmonary venous connection in one.

Control group. This group consisted of 42 patients (ages 1 day to 6 years) who were proven not to have a PDA by cardiac catheterization and angiography. Diagnoses in these patients included ventricular septal defect in 12, Kawasaki disease in 10, valvar pulmonary stenosis in eight, atrophic septal defect in seven, valvar aortic stenosis in two, tetralogy of Fallot in two, and transposition of great arteries in one.

Two-dimensional and Doppler echocardiographic studies. All patients were studied with a pulsed Doppler echocardiographic system (Hewlett Packard, Model 77020 AC) with a 5 MHz shallow focus, 3.5 MHz, and 2.5 MHz transducers during cardiac catheterization. The sample volume could be positioned at any depth, which permitted the precise location of the sample volume within the two-dimensional echocardiographic image. The Doppler pulse repetition frequency was automatically optimized to maximize the velocity measurement capability at any selected sample depth. The flow velocity was corrected for angle and displayed in centimeters per second. The baseline for Doppler waveforms was electronically adjusted to eliminate the discontinuity caused by aliased signals. Furthermore, a trans-
ducer with optimal frequency was used to avoid "aliasing" signals. When pulsed Doppler velocities exceeded the maximal value that could be measured by pulsed Doppler instrument, a continuous-wave system was used.

Two-dimensional and Doppler echocardiographic examinations were performed from a precordial approach with parasternal short- and long-axis planes.

Short-axis plane. From the standard short-axis plane at the base of the heart, the transducer was angled superiorly to identify the main pulmonary artery and its bifurcation into right and left pulmonary arteries.

Long-axis planes. The transducer was placed in the second or third left intercostal space parallel to the sternum, rotated clockwise, and directed inferiorly (figure 1). In neonates and small infants, similar planes were achieved from the second intercostal space or subclavicular area to the right of the sternum with leftward and inferior angulation. In three children over 2 years old, the transducer was rotated counterclockwise from the parasternal long-axis plane and directed leftward and superiorly. In these planes, the ductus was imaged above the left pulmonary artery–main pulmonary junction.

Ductal flow was recorded with the sample site at the center line of the ductus near the main pulmonary artery orifice (figure 1). In addition, the sample volume was placed within the ductus midway between its aortic and pulmonary ends when the ductal flow pattern was bidirectional. In this study, with the sample volume within the ductus, a L-R ductal shunt from the descending aorta to the main pulmonary artery was recorded as a flow toward the transducer and a right-to-left (R-L) ductal shunt as a flow away from the transducer. Continuous-wave Doppler was performed from the left high parasternal border aiming the Doppler beam inferiorly and leftward. Waveforms were considered optimal when the highest velocities with a clear distinct envelope were obtained during both systole and diastole for a minimum of three beats. Doppler profiles and simultaneous electrocardiograms were recorded at 100 mm/sec and were stored on video tape for a later playback and analysis in stop motion mode. When we traced the Doppler wave forms, we used the maximal flow velocity envelope because these were turbulent flows and no modal velocity could be delineated. The Doppler determined peak velocity of the L-R shunt flow within the ductus was measured at the peak of the flow velocity curve (figure 2, A). The mean velocity of the L-R shunt flow signal was obtained by measurement of the flow envelope area on the flow velocity curve by planimetry and dividing by L-R shunt flow time. Diastolic flow velocity in this study was measured at ventricular end-diastole, defined by the peak of the R wave on the reference electrocardiogram. These measurements were averaged for 3 consecutive beats. Furthermore, we determined the spatial localization of L-R shunt flow in the pulmonary artery by mapping flow velocity profiles at multiple sample sites within the main pulmonary artery (center, left, and right lateral wall, superior and inferior wall) and its major pulmonary branches in parasternal short- and long-axis planes (figure 3). From flow mapping studies in the pulmonary artery, the diastolic antegrade flow from the main pulmonary artery to its major pulmonary branches was assessed at the sample site within the proximal left pulmonary artery in 16 patients with isolated PDA by means of the long-axis plane (figure 1). The degree of this abnormal Doppler signal was estimated by the mean velocity of the antegrade wave in diastole (figure 2, B).

Contrast echocardiographic examination. In 14 patients with PDA, contrast echocardiography was performed to verify the direction of shunt flow through the ductus. A 5% glucose solution of 2 to 5 ml was injected into a peripheral vein or the radial artery in four small infants with isolated PDA and into the left ventricle, the right ventricle, or the descending thoracic aorta near the ductus in seven during cardiac catheterization. In the other three patients with associated defects, selective contrast injections were done in the main pulmonary artery and descending thoracic aorta near the ductus. The L-R shunting through the ductus on the contrast two-dimensional echocardiogram was confirmed by the contrast echo seen flowing from the ductus into the main pulmonary artery. The presence of R-L shunting was made when the contrast echo was visualized flowing from the ductus into the descending aorta. Using the reference electrocardiogram, we also analyzed the phases of the appearance of the contrast echo from the pulmonary artery or descending aorta into the ductus.

Cardiac catheterization. The pulmonary-to-systemic peak pressure ratio (Pp/Ps) was measured in 23 patients with PDA except for two patients with pulmonary atresia and one with transposition of great arteries by the simultaneous use of two matched fluid-filled catheters connected to a Statham P23Db.

![FIGURE 1. PDA viewed in the parasternal long-axis plane. Note that ductus was imaged above the left pulmonary–main pulmonary artery junction with longitudinal section of descending aorta. Sample sites within either the ductus or the left pulmonary artery are shown with Doppler cursor lines. A = anterior; P = posterior; S = superior; I = inferior; M-PA = main pulmonary artery; L-PA = left pulmonary artery; DA = ductus arteriosus; Desc. Ao = descending aorta.](image-url)
FIGURE 2. A, Method for determining the peak, mean, and diastolic velocities of L-R shunt flow within the ductus. The arrows show where the peak (P) and diastolic (D) velocities are measured. Mean velocity is determined by measurement of L-R shunt flow envelope area (A) by planimetry and divided by L-R shunt flow time (T). B, Method for determining the mean velocity of the diastolic antegrade flow signal in the proximal left pulmonary artery. The area under the diastolic antegrade flow portion of Doppler flow profile (A) was measured by planimetry and the measurements were divided by the flow time (T). 0 represents the zero velocity baseline.

strain gauge. In one patient with transposition of the great arteries, Pp/Ps was measured as the simultaneous peak pressure ratio of the left ventricle and radial artery. The Pp/Ps was separated into three grades to assess the relation between Pp/Ps and the Doppler-determined ductal flow velocity profile: grade I = 0.2 to 0.39, grade II = 0.40 to 0.79, and grade III = 0.80 to 1.25. The L-R shunt ratio was calculated from blood oxygen saturation measurements (Fick principle) in 16 patients with isolated PDA. Pulmonary arterial oxygen saturation was estimated by averaging values of the left and right pulmonary arteries. In three patients with isolated PDA, Doppler flow velocity patterns were assessed before and after closure of the ductus by inflation of the balloon with a balloon catheter (Millar Laboratories).

Statistics. Linear regression analyses were performed with the least-squares method, and the standard error of the estimate was determined. The Student t test was used to test for differences in mean values between the two groups. Statistical significance was indicated by a p value < .05.

Results

Detection of Doppler signal of shunt flow. The ductus was visualized clearly from two-dimensional echocardiographic planes in all patients with PDA. The ductus was not seen as a cylinder-shaped structure in one subject who had a small residual shunt after surgical ligation of the ductus. In the control subjects, the ductus was not imaged. However, an echo dropout giving a false impression of a ductus was found in 10% of the patients.

In contrast, an abnormal Doppler signal consistent with the patency of the ductus was demonstrated in all patients with PDA. One patient with residual shunt after surgical ligation of the ductus had an abnormal Doppler signal indicating continuous L-R shunting at the ductal region. In the control subjects, no abnormal Doppler signal was present in the area of the echo dropout.

Direction of Doppler signal at the ductus and correlation between Doppler and contrast echocardiographic findings. In seven patients, continuous flow toward the transducer was recorded from the sample site in the ductus and the peak phase was located in mid-to-late ventricular systole on the reference electrocardiogram. In these patients, the L-R shunt was observed in both systole and diastole by contrast echocardiography, and contrast bubbles did not cross the ductus from the main pulmonary artery to the descending aorta. In seven patients, the Doppler flow recorded in the ductus was bidirectional. Doppler-determined R-L shunting was seen as a flow away from the transducer in systole and L-R shunting occurred in diastole. In these patients, contrast echocardiography demonstrated that the R-L shunt flow across the ductus was always seen in the systole. In five of these seven patients with a bidirectional shunt across the ductus, blood oxygen saturation was measured at both ascending aorta and the descending thoracic aorta near the ductal area. Differences of arterial oxygen saturations between these blood sample sites were not significant in two patients who had Doppler-determined R-L shunting in early-to-mid systole (figure 4). In the other three patients with hemodynamically significant R-L shunting, which showed differences of arterial oxygen saturations of 5% to 30% between two blood sample sites, the peak phase of Doppler determined R-L shunting was observed during mid-to-late systole.

Relationship between Doppler-derived indexes of the flow velocity in the ductus and the Pp/Ps. The sample volume was positioned within the ductus and the angle of intercept (Q) was less than 20 degrees in all subjects. In seven patients, high-speed continuous L-R shunt flow waveforms toward the transducer were obtained with the continuous-wave system. We performed flow mapping studies at multiple sample sites of the ductus and the pulmonary artery by pulsed Doppler echocardiography to assess from where these
high-velocity signals were recorded. In these seven patients, high-speed continuous flow waves toward the transducer were obtained only within the ductus in six patients and in the ductus plus inside the left lateral and superior walls of the main pulmonary artery near the ductus in one patient. Doppler-determined peak flow velocity correlated well with Pp/Ps by means of linear regression analysis, but there was much scatter between the two variables (r = -.84, SEE = 68.3) (figure 5). In addition, as shown in figure 6, patients with a higher Pp/Ps showed significantly lower peak mean, and diastolic flow velocities measured in the ductus even in the presence of associated congenital heart disease. Doppler-derived indexes of mean and diastolic flow velocities correctly distinguished between the patients with normal pulmonary pressure and those with evidence of pulmonary hypertension (p < .01).

Spatial localization of the L-R shunt flow through the ductus in the pulmonary artery. In 20 of 26 patients (77%), the L-R shunt flow through the ductus was observed in diastole inside the left lateral and superior walls of the main pulmonary artery and just distal to the pulmonary valve (figure 3). In these patients, antegrade flow in diastole was present inside the low right lateral wall of the main pulmonary artery and at the proximal major pulmonary branches. These characteristic flow patterns observed in the pulmonary artery were not significantly different in the presence of associated congenital heart disease, although it was difficult to analyze the flow direction on the short-axis plane in the transposition subgroup. In the other six patients, the L-R shunt flow through the ductus was directed to a more central area of the main pulmonary artery, and diastolic antegrade flow was seen in proximal major pulmonary branches. In 42 control subjects, antegrade flow in diastole was not observed at the main pulmonary artery and its major pulmonary branches.

Relationship between diastolic Doppler signal in the left pulmonary artery and L-R shunting. As shown in figure 7, the diastolic antegrade flow obtained from the proximal left pulmonary artery disappeared when the ductus was closed by inflation of the balloon with a balloon catheter. The left pulmonary arterial flow waveforms could be obtained by a parasternal long-axis approach in all patients in whom measurements were attempted in this study, and the angle of intercept was always less than 30 degrees. As shown in figure 8, there was a

FIGURE 3. Spatial localization of Doppler determined L-R shunt flow through the ductus in the pulmonary artery. The sample volumes are positioned at multiple sites within the main pulmonary artery and its proximal major pulmonary branches on two-dimensional long- and short-axis planes of the main pulmonary artery. L = left; R = right; R-PA = right pulmonary artery; other abbreviations as in figure 1.
FIGURE 4. Doppler echocardiogram (top) and contrast two-dimensional echocardiogram (bottom) in a patient with PDA associated with transposition of great arteries with intact ventricular septum. The sample volume was positioned within the ductus midway between its aortic and pulmonary ends. The zero line is shown traversing the image. The electrocardiogram is displayed to show the timing. The L-R shunt is in diastole and R-L shunt is in early-to-mid systole. On contrast echocardiograms in which the contrast injection was made into the left ventricle, R-L shunt across the ductus is seen in early-to-mid systole (No. 2 in bottom panel) and the negative contrast echo (arrow) in the main pulmonary artery corresponding to ductal L-R shunt is observed in diastole (No. 3 in bottom panel). Note that L-R shunt flow through the ductus is directed to the superior wall of the main pulmonary artery. Abbreviations as in figure 1.

Discussion

We examined whether combined two-dimensional and Doppler echocardiography could provide a noninvasive method for the evaluation of shunt flow dynamics through a PDA. Our two-dimensional echocardiographic imaging technique could not distinguish between a lumen size of less than 1 mm and a completely closed duct, as in a previous study. In addition, where the descending aorta and left pulmonary artery cross, some echoes gave a false impression of a ductus in the patients without PDA. Therefore we did not include the data on the size of the ductus. We noted that an abnormal Doppler signal could be detected at a very small ductal area even when the sample size exceeded the ductal diameter. These findings confirm that ductal patency can be evaluated by the Doppler method in patients with a very small PDA. Furthermore, no abnormal Doppler signal was seen in any of the control subjects. Thus the pulsed Doppler echocardiographic technique is a sensitive and specific method for the confirmation of PDA as suggested previously.

The Doppler results obtained in this study showed signals of a shunt flow above and below the zero line. The direction of the Doppler flow signal obtained from the ductus coincided with the direction of the contrast echo flow on the two-dimensional echocardiogram. In our experience, however, a systolic antegrade flow from the right ventricle to the main pulmonary artery that gave a false impression of R-L shunting through the ductus was often detected when a sample volume...
was positioned in just the pulmonary end of the ductus. The spatial variability of the flow direction was most likely caused by the movement of cardiac structures with the cardiac cycle. The sample site should be taken within the ductus midway between its aortic and pulmonary ends when confirming ductal R-L shunting. Spach et al. 13 examined the shunt dynamics in patients with PDA in various hemodynamic situations utilizing quantitative pressure data and qualitative flow data. Nakano et al. 14 analyzed the flow velocity patterns in the ductus in 20 patients with isolated PDA and complicated PDA using a catheter-tip electromagnetic flow velocity probe. Both of these groups reported that peak flow velocity of continuous L-R shunting occurred in mid-to-late systole. Spach et al. 13 demonstrated that a reversed pressure gradient across the ductus occurred

**FIGURE 5.** Linear regression analysis comparing Doppler-determined peak ductal flow velocity with systolic Pp/Ps measured at cardiac catheterization. TGA = transposition of great arteries; ASD = atrial septal defect; VSD = ventricular septal defect; TAPVC = total anomalous pulmonary venous connection.

**FIGURE 6.** Doppler-determined ductal flow velocity. A, Peak ductal flow velocity; B, mean ductal flow velocity; C, diastolic ductal flow velocity (all vs Pp/Ps). The degree of Pp/Ps is separated into three grades (see text). *p < .05; **p < .01. Symbols are as in figure 5.

**FIGURE 7.** Doppler flow velocity patterns obtained from the proximal left pulmonary artery in a patient with a large PDA. In panel 1, the ductus was closed by inflation of the balloon with a balloon catheter. The balloon was gradually opened (panel 2) and was fully opened in panel 3. Note the alteration of the degree of diastolic antegrade flow.

**FIGURE 8.** Comparison of the mean L-PA flow velocity derived from the diastolic antegrade flow portion with left-to-right (L-R) shunt ratio determined by Fick’s method in patients with isolated PDA. L-PA = left pulmonary artery.
in early systole in patients with a bidirectional shunt, although the phase of the R-L shunt flow was not described in detail. Nakano et al.\textsuperscript{14} reported that reversed R-L shunt flow across the ductus was seen in mid-to-late systole. In our Doppler studies, ductal R-L shunting occurred in early-to-mid systole in two patients with just a transient flow reversal; with a hemodynamically significant R-L shunt, the peak phases of R-L shunting were observed during mid-to-late systole. Of interest, Morris et al.\textsuperscript{15} have shown by analysis of the flow-pressure relationship across the ductus in lambs that (1) the blood flow through the ductus has a distinctive inertial characteristic and (2) the ejection of the right ventricle precedes that of the left. Both factors may explain the paradox that the ductal R-L shunt can be seen even when the aortic pressure is higher than the pulmonary pressure as observed by Spach et al.\textsuperscript{13} Thus a pulsed Doppler method permits the noninvasive evaluation of the direction of shunt flow within the ductus.

These results demonstrate that patients with a higher pulmonary arterial pressure tend to have lower velocities of ductal flow. Furthermore, these trends were not different in patients with isolated and complicated PDA. These observations appear to be consistent with previous experimental and invasive clinical studies showing that the pressure difference between systemic and pulmonary artery is an important factor in determining ductal L-R shunt flow.\textsuperscript{13, 14, 16} Recently, Marx et al.\textsuperscript{17} have shown that Doppler measurement of peak flow velocity across aortic-pulmonary shunts can be used to predict systolic pulmonary arterial pressure. Aortic-to-pulmonary arterial pressure drop was estimated according to the modified Bernoulli equation: $p = 4V^2$, where $P =$ the pressure drop (mm Hg) and $V =$ peak velocity (m/sec). Our data demonstrated that Doppler-determined peak flow velocity within the ductus correlated well with $Pp/Ps$ but there was a large variability between the two variables. In previous two-dimensional echocardiographic observations,\textsuperscript{7} the ductus was not necessarily cylindrical in shape. The presence of the deformity of the ductus appears to limit the estimation of a pressure drop across the ductus with the Bernoulli equation.

We assessed L-R shunt dynamics in the pulmonary artery by a flow mapping technique. In the majority of patients with PDA, L-R shunt flow through the ductus was directed preferentially to the left superior wall of the main pulmonary artery and to the pulmonary valve orifice, and it passed into the inside of the right lateral wall of the main pulmonary artery and major pulmonary branches. From these observations, we were concerned about the diastolic antegrade flow obtained from the major pulmonary branches. In this study, we evaluated the diastolic antegrade flow recorded in the proximal left pulmonary artery because this vessel was visualized in an orientation that makes the flow parallel to the Doppler cursor in a parasternal long-axis approach. This flow was confirmed to represent the diastolic component of the L-R shunt flow with a balloon catheter technique. It was interesting that there was a significant relationship between the degree of the diastolic antegrade flow signal obtained from the proximal left pulmonary artery and the L-R shunt ratio. Because of streaming, calculation of the L-R shunt ratios in patients with PDA is very difficult, especially when there is a large shunt. Our method to calculate the L-R shunt ratio is the only available reference standard for comparison with the Doppler-estimated L-R shunting. This may be related to some of the variability between the Doppler-determined flow velocity and the L-R shunt ratio. Recently, Wilson et al.\textsuperscript{3} reported that the diastolic antegrade flow signal observed in the main pulmonary artery was a characteristic pattern showing the presence of a PDA. They also showed that this Doppler signal was not present in patients with PDA showing dominant R-L shunting and severe pulmonary vascular obstructive disease. This finding was noted in one patient included in our study. The analysis of diastolic antegrade Doppler signals provides additional information in the estimation of L-R shunt flow.

In conclusion, our Doppler method provides an accurate assessment of both the presence of PDA and shunt dynamics in infants and children.

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