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Clinical Utility of Two-Dimensional Doppler Echocardiographic Techniques for Estimating Pulmonary to Systemic Blood Flow Ratios in Children With Left to Right Shunting Atrial Septal Defect, Ventricular Septal Defect or Patent Ductus Arteriosus

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Range gated two-dimensional Doppler echocardiographic methods were evaluated for quantifying pulmonary (QP) to systemic (QS) blood flow ratios. Twenty-one patients were studied, 4 with patent ductus arteriosus, 6 with atrial septal defect and 11 with ventricular septal defect. The Doppler pulmonary to systemic flow (QP:QS) estimation method involved calculating volume flow (liters/min) at a variety of intracardiac sites by using imaging information for flow area and Doppler outputs to calculate mean flow velocity as a function of time. Area volume flows were combined to yield QP:QS ratios. The sites sampled were main pulmonary artery, ascending aorta, mitral valve orifice and subpulmonary right ventricular outflow tract. The overall correlation between Doppler QP:QS estimates and those obtained at cardiac catheterization (n = 18) or radionuclide angiography (n = 3) was r = 0.85 (standard error of the estimate = 0.48:1). These preliminary results suggest that clinical application of this Doppler echocardiographic method should allow noninvasive estimation of the magnitude of cardiac shunts.

Real-time two-dimensional echocardiography allows diagnosis of intracardiac as well as extracardiac shunts (such as atrial septal defect, ventricular septal defect and patent ductus arteriosus) by direct imaging of these defects (1–3) Despite previous attempts to quantitate shunt size noninvasively with echocardiographic techniques (4) such as left atrial to aortic root ratios (5,6) or ventricular chamber dimensions (7), neither M-mode nor two-dimensional echocardiography offers reliable quantitation of left to right shunt size

Recently, we have reported (8) the use of two-dimensional Doppler echocardiographic techniques for noninvasive measurement of cardiac output in human beings and for measurement of systemic (QS) and pulmonary (QP) blood flow in the presence of surgically created shunts in acute open chest canine models (9) This study was designed to assess the accuracy of two-dimensional Doppler echocardiography for quantitating the QP QS ratio in the presence of a simple congenital heart defect with isolated intra- or extracardiac left to right shunt Doppler-derived estimates of QP QS were compared with QP.QS determinations by oximetry or indicator-dilution curves during cardiac catheterization, or with QP QS estimates obtained by radionuclide scintillation techniques (10)

Methods

Patients. The study group consisted of 21 infants and children (aged 2 months to 13 years) with congenital heart disease, all having a left to right shunt Four had isolated patent ductus arteriosus (Table 1) Six patients had an atrial septal defect, one of the six (Patient 6) had undergone earlier aortic coarctectomy and underwent subsequent cardiac catheterization to evaluate possible recoarctation During the recatheterization, a small left to right atrial shunt was seen on angiography Nine patients had a ventricular septal defect, catheterization was performed in two of the nine to evaluate a coarctation and in one of the nine because of a loud residual murmur after operative closure of a ventricular

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Table 1. Results in 21 Patients

Case	Shunt	QP QS (QS = subpulmonary) Using MVO = QP[a]	QP QS (QS = subpulmonary) Using Ao = QP[a]	Cath/Nuclear
1	PDA	1 6 1	—	2 2 1*
2	PDA	1 8 1	1 6 1	1 7 1*
3	PDA	1 5 1	1 6 1	1 8 1
4	PDA	2 3 1	3 3 1	2 6 1*
		QP QS (QP = PA) Using MVO = QS[b]	QP QS (QP = PA) Using Ao = QS	
5	ASD	2 6 1	4 5 1	2 8 1
6	ASD	1 1	—	1 1, (PO Coarct, Angio L-R)
7	ASD	1 5 1	1 4 1	1 9 1
8	ASD	2 5 1	—	[2 7 1]
9	ASD	2 3 1	—	[2 3 1]
10	ASD	1 5 1	2 1	2 2 1
		QP QS (QS = Ao) Using MVO = QP	QP QS (QS = Ao) Using PA = QP	
11	VSD	3 1	—	[2 2 1]
12	VSD	2 1	1 4 1	[1 1], Angio L-R Coarct
13	VSD	4 3 1	—	6 1
14	VSD	1 1 1	1 5 1	[1 5 1]
15	LV-RA	1 1	—	1 1, Angio L-R
16	LV-RA	1 4	1 3 1	[1 4 1]
17	VSD	1 7 1	—	[3 2 1]
18	VSD	1 06 1	—	[1 1 1], Coarct
19	VSD	3 2 1	—	4 1
20	VSD	1 04 1	1 1 1	[1,21 1], VSD, PO
21	VSD	1 5 1	—	[1 5 1]

[a]Because all pulmonary blood flow in patent ductus arteriosus returns to the left atrium and crosses the mitral valve, if the atrial sepum is intact, and because the extracardiac shunt in patent ductus arteriosus is distal to the ascending aorta, both the mitral valve orifice and ascending Doppler flows equal systemic flow (QS) [b]Because the shunt in atrial septal defect is proximal to the mitral valve, mitral flow equals systemic flow (QS)

Angio = angiography, Ao = aorta, ASD = atrial septal defect, Cath = catheterization, Coarct = coarctation of aorta, [ ] = dye curve, L-R = left to right shunt, MVO = mitral valve orifice, RA = right atrium, * = radioisotope QP QS, PA = pulmonary artery, PDA = patent ductus arteriosus, PO = postoperative, QP = pulmonary flow, QS = systemic flow, VSD = ventricular septal defect

septal defect Two other patients had a left ventricular to right atrial shunt and were included in the group with ventricular septal defect With the exception of the three patients with coarctation who had a nonstenotic bicuspid aortic valve no patient had any other complicating abnormality

Control group. Twenty-five normal subjects, aged 2 months to 12 years with no evidence of cardiac disease, were studied as a control group

Catheterization and radionuclide techniques. The level and magnitudes of the shunts in 18 of the 21 patients were confirmed at cardiac catheterization and angiography Shunt magnitude was determined by either standard oximetric techniques (n = 12) or by indocyanine green dye-dilution curves performed in duplicate (n = 10) (11) Oximetric shunt determinations calculated the pulmonary to systemic flow (QP QS) ratio using saturation data averaged from two series. Oxygen consumption measurement for separate calculations of absolute QP or QS was not performed, nor were any assumed oxygen consumption values used If both dye-curve and oximetric shunt calculations were performed (four patients) the dye-curve QP.QS was used for comparison with the Doppler results Cardiac catheterization was performed after light sedation with Demerol, Thorazine and pentobarbital Patients were awake, quiet and breathing room air at the time of shunt determination for comparison with the Doppler results All Doppler studies were performed within 24 hours of catheterization Six studies were performed after premedication and within 1 hour of the catheterization determination, none were simultaneous

The remaining three patients, all with patent ductus arteriosus, were not catheterized but had presence of the ductus confirmed surgically and the shunt magnitude estimated by standard radionuclide scintigraphy (10) before surgery and on the same day as the Doppler echocardiographic study (Table 1).

Doppler echocardiographic techniques. All 21 patients with a left to right shunt and the control subjects underwent complete two-dimensional Doppler echocardio-

graphic examination with recording of anatomy and Doppler blood flow velocity at various sites (see later). Two-dimensional Doppler echocardiographic studies were performed with all patients at rest, breathing room air and in the supine position. The examiner knew the diagnosis but not the size of the shunt. We utilized an Electronics for Medicine (Honeywell) two-dimensional range gated pulsed Doppler scanner for all studies. This unit produces two-dimensional echocardiographic images with either a 3.5 or 5 MHz single element transducer mechanically swept through a 75° arc at 30 frames/s. Echographic images were obtained with the highest frequency applicable using low gain echo settings and a fairly bistable edge defined scan converter algorithm. We selected a scan converter program with little frame to frame averaging to aid definition of vessel walls. The transducer is stopped along any image line and a variable (0.2 to 2 cm in length) Doppler sample volume is positioned at any depth along that line to allow accurate localization of the site of Doppler flow sampling and of the angle of Doppler sampling relative to the direction of flow within the imaged plane. The angle of the sample relative to the direction of flow within the elevational or azimuthal plane, that is, the plane perpendicular to the plane of imaging, could not be determined; however, small deviations from sampling exactly parallel to the direction of flow (angles 0 or 180°) are of no practical importance because the cosine of the sampling angle (see later) would still be close to unity.

When the operational mode of the unit is switched from real-time imaging to Doppler, pulsed Doppler sampling is performed only within the selected area. Doppler sample volume width for the 3.5 MHz transducer at 6 cm depth (6 dB) is ± 2 mm in a water tank. In Doppler mode, the Doppler shift is sampled at 13,500 times/s in a range of 0 to 6 cm and at 7,800 samples/s in a cm range of 6 to 10 allowing unambiguous detection of velocities up to 143 cm/s when sampling parallel to flow at less than 6 cm depth and up to 85 cm/s at a 6 to 10 cm depth. Except for subcostal or apex aortic views, which in the two oldest patients (9 and 12 years of age), involved interrogation of the aorta at a depth of 7 to 8 cm (Fig. 1), all of the Doppler flow sampling was performed within the 0 to 6 cm depth range.

Determination of blood flow velocity. Two flow velocity outputs were available from the scanner in the Doppler mode; the first is an audio signal of the Doppler shift frequency and the second is a quantitative fast Fourier transform spectral analysis waveform with spectra calculated 200 times/s. The two-dimensional images were recorded on videotape and stop-frame page prints. The Doppler spectral output and simultaneous electrocardiographic trace were recorded both on a strip chart recorder (100 mm/s paper speed) and on videotape.

The fast Fourier spectral output of the Doppler shift is automatically converted by the instrument to velocity of flow in cm/s on the basis of this formula:

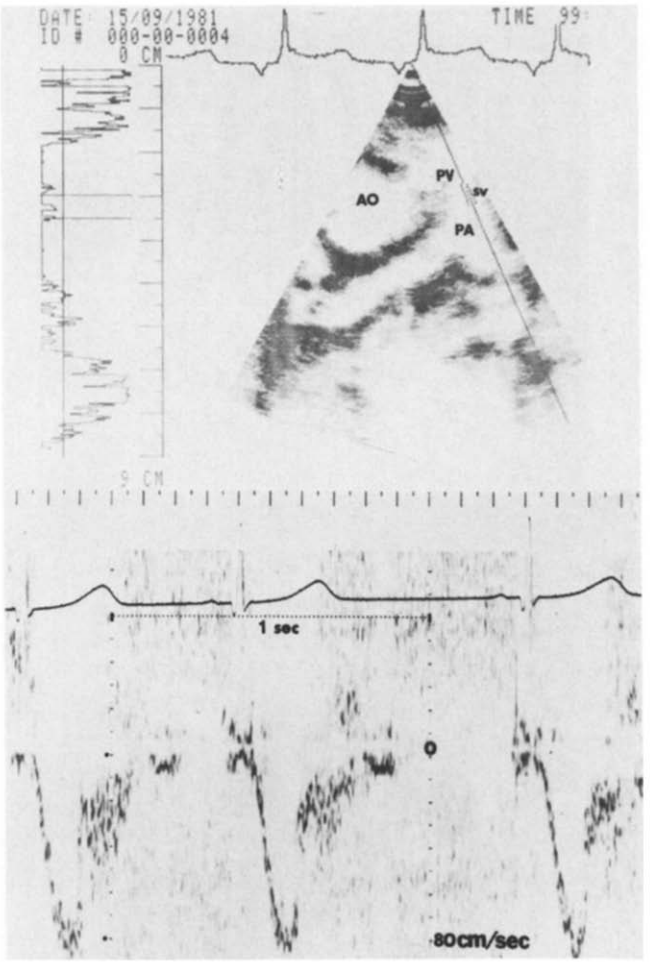

Figure 1. Short-axis echocardiographic view of the pulmonary artery (PA) with the sample volume located distal to the pulmonary valve (PV). The inner dimension the pulmonary artery at the level of the valve can be measured to the **faint line** near the labeling "SV" (sample volume) and sampling is essentially parallel to the direction of flow. The corresponding pulmonary artery flow waveform is shown in the lower panel. AO = aorta.

$$\text{Velocity of flow} = \frac{\text{Doppler frequency shift} \times \text{Velocity of sound}}{2 \times \text{Transmitted frequency} \times \text{Cosine } \theta}, \quad (1)$$

where cosine Θ = angle between Doppler beam and direction of flow. Although the conversion of Doppler frequency shift to cm/s velocity using the Equation 1 was performed by the instrument before display of the Doppler waveforms and the Doppler calibration was in cm/s, the equation was solved by the instrument as if the angle (Θ) was 0. Therefore, the angle correction is not applied automatically by this instrument, but was performed manually for all raw velocities (Table 2) or when the calculations converting flow velocity information to blood flow/min were performed (see later).

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Table 2. Doppler Flow Velocities (cm/s) (corrected for angle) in 25 Normal Subjects and 21 Patients With Left to Right Shunt

	Normal (n = 25)		PDA (n = 4)		ASD (n = 6)		VSD (n = 9) or LV-RA (n = 2)	
Site	Mean	Peak	Mean	Peak	Mean	Peak	Mean	Peak
MV	15 23 ± 0 52	75 74 ± 1 68	24 75 ± 4 22	104 8[a] ± 9 0	16 11 ± 1 56	68 78 ± 4 0	28 44[b] ± 3 56	108 74[b] ± 8 9
Aorta	24 2 ± 0 83	92 3 ± 1 86	29 2[a] ± 3 97	124 3[b] ± 9 9	19 46[b] ± 1 29	87 53 ± 4 3	22 29 ± 1 78	74 5[c] ± 3 4
PA	20 40 ± 0 86	78 13 ± 2 4	—	—	29 4[b] ± 3 6	100 28[c] ± 2 56	33 11[a d] ± 4 04	110 4[b d] ± 13 2

[a] $p < 0.05$, [b] $p < 0.01$, [c] $p < 0.001$ (all compared with normal velocities), [d] n = 4

ASD = atrial septal defect, LV-RA = left ventricular-right atrial shunt, MV = mitral valve, PA = pulmonary artery, PDA = patent ductus arteriosus, peak velocity = peak *diastolic* velocity for mitral valve, peak *systolic* velocity for pulmonary artery and aorta, mean velocity = mean temporal velocity which was determined by planimetry, VSD = ventricular septal defect See text for details

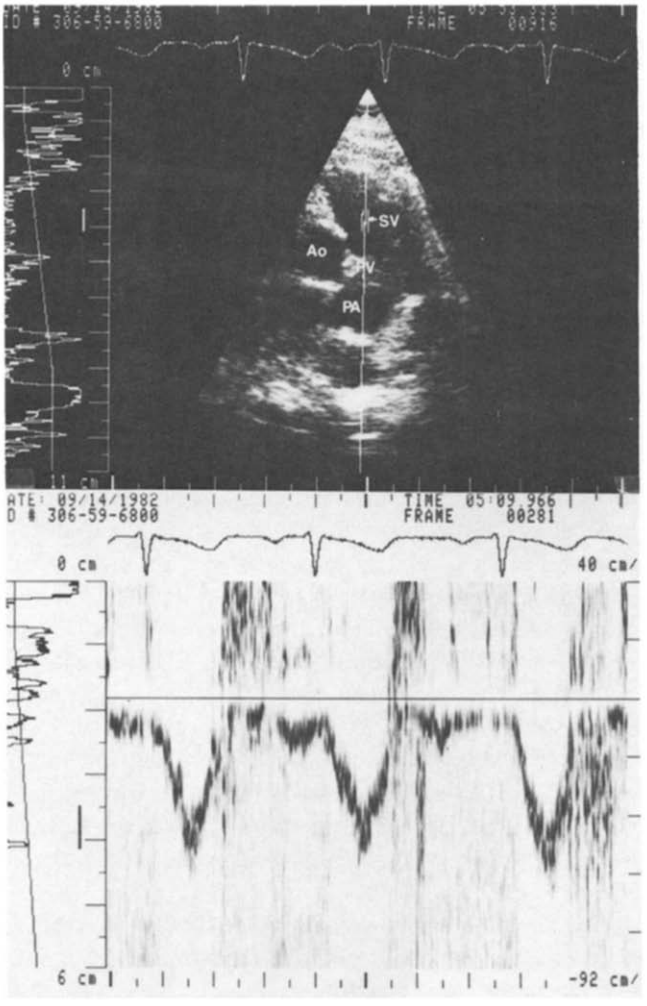
All Doppler interrogation was obtained at 3 5 MHz regardless of the imaging frequency utilized Two-dimensional Doppler echocardiographic studies included interrogation of the main pulmonary artery, ascending aorta and mitral valve orifice in all patients and control subjects The subvalvular right ventricular outflow tract was studied only in patients with patent ductus arteriosus

Main pulmonary artery flow (Fig. 1). Main pulmonary artery Doppler flow was measured by positioning the sample volume within the main pulmonary artery distal to the pulmonary valve in a parasternal short-axis plane echocardiographic view The position of the sample volume was adjusted so that the pulmonary valve leaflets did not cross through it Flow curves were maximized to achieve the cleanest signal with the highest velocity by rocking the scan plane superiorly and inferiorly The angle of incidence between direction of flow and sampling within the plane of imaging was estimated by eye during the examination Later measurement with a protractor demonstrated that the angle was always less than 15° Pulmonary artery diameter was measured between inner walls of the vessel on the electrocardiographic-gated still frame of the two-dimensional echocardiographic short-axis view in early to mid-systole, after most of the noticeable expansion of the vessel had occurred Pulmonary artery diameter was measured at the level of the pulmonary valve.

Subvalvular right ventricular flow (Fig. 2). Flow through the subvalvular right ventricular outflow tract was measured in the patients with patent ductus arteriosus from the parasternal (two patients) or subcostal short-axis (two patients) view with the sample volume placed just proximal to the pulmonary valve The transducer was rotated and the sample volume adjusted so that sampling was as parallel as possible to the apparent direction of flow within the subvalvular right ventricular outflow area Mean angle of Doppler sampling relative to direction of flow was 20° Right ventricular outflow tract size was measured as an inner dimension at end-diastole at a point just inferior to the pulmonary valve This technique was used only for the patients with patent ductus arteriosus who were the youngest in the series, because it provided the only technique for obtaining systemic blood flow in that group

Ascending aortic flow (Fig. 3). Ascending aortic flow measurements were made from subcostal or apical left ven-

Figure 2. Short-axis echocardiographic right ventricular outflow view The corresponding flow recorded in the right ventricular outflow tract proximal to the pulmonary valve (PV) is seen below Abbreviations as in Figure 1 A sampling angle of 35° was later estimated



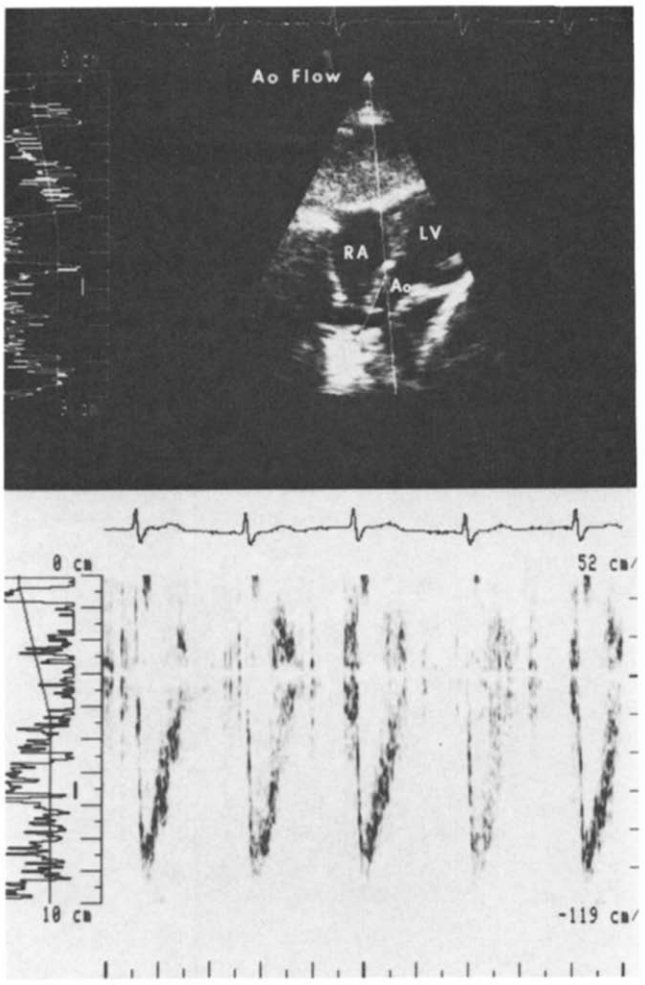


Figure 3. Subcostal echocardiographic left ventricular (LV) outflow view showing sampling of the aorta (Ao). The sample cursor is next to the "A" in Ao and the estimated sampling angle is shown by the **slanted line** to the right of the cursor which shows the presumed direction of aortic flow. The sample volume has a length of 0.5 cm and is located 6 cm from the transducer. Pulsatile aortic flow waveforms are shown in the lower panel. RA = right atrium.

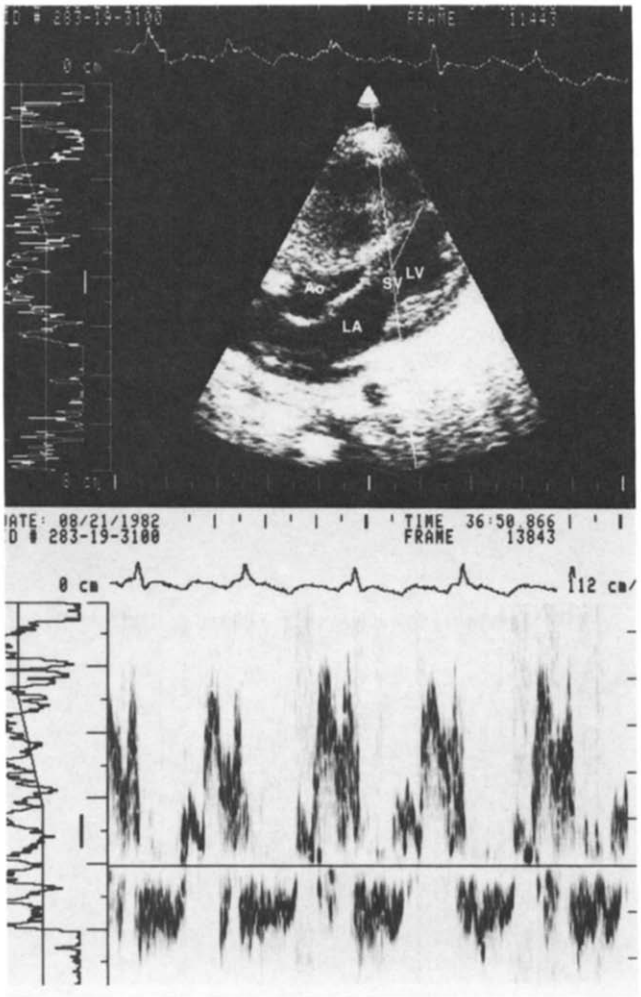


Figure 4. Oblique echocardiographic two chamber view (patient with ventricular septal defect) showing sampling of the left ventricular (LV) inflow just inferior to the mitral valve with a corresponding mitral flow trace shown in the **lower panel**. LA = left atrium; other abbreviations as before.

tricular outflow tract views with the sample volume placed just distal to the aortic valve. Aortic root size was measured as an inner diameter just above the level of the valve in early to mid-systole. When viewed from an apical left ventricular outflow tract plane, Doppler sampling was at an angle of 0 to 15°. When viewed from a subcostal left ventricular outflow tract plane, Doppler sampling angle was 35° or less in all instances. The choice of aortic view was dictated by the quality of the aortic images and the clarity of the Doppler signal. In all but two patients, Doppler flow was interrogated at 0 to 6 cm depth. In the other two patients, flow was sampled at 6 to 10 cm depth, but peak velocity was near or below the Nyquist limit of 85 cm/s (the maximal unambiguously detectable velocity) at the angles used.

Transmitral flow (Fig. 4). Transmitral valve flow was recorded in the left ventricular inflow tract from apical views. Doppler sampling angle was less than 10° except in two patients (Fig. 4). The mitral valve orifice dimension was measured by digitalizing the maximal two-dimensional echocardiographic orifice area through the middle of the valve leaflets on a parasternal short-axis view. Frame by frame analysis was used to detect maximal mitral valve opening. Because the mitral valve is not maximally opened throughout diastole, a correction factor was calculated for the phasic diastolic variations of mitral valve orifice size as follows: the maximal orifice area on the two-dimensional echographic image was multiplied by the arithmetic ratio of the mean to maximal diastolic mitral valve leaflet separation measured from a derived M-mode trace (Fig. 5). When multiplied by the maximal two-dimensional mitral valve orifice area, this mean to maximal correction factor yielded a measure of the mean mitral flow area throughout diastole (12).

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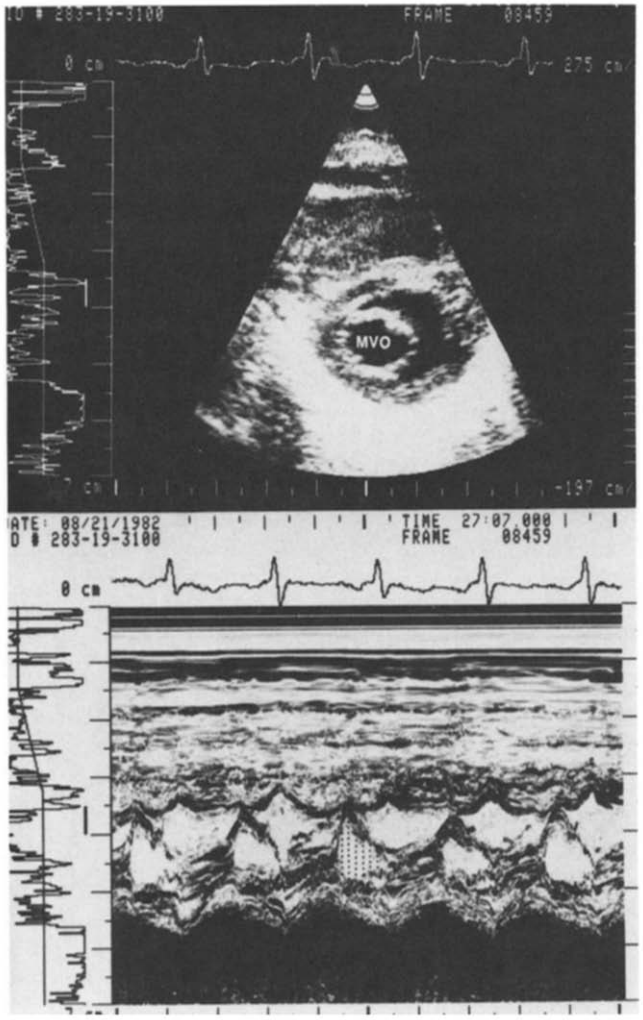

Figure 5. Short-axis echocardiographic view at the level of the mitral "fishmouth" shows the mitral valve orifice (MVO). The corresponding mitral valve M-mode echocardiogram is shown in the **bottom panel.** The **dotted lines** show equally spaced measurements of mitral valve leaflet separation during diastole, the maximal leaflet separation being the second one. All measurements would be averaged to provide mean leaflet separation to allow calculation of the mean to maximal mitral valve separation measurement. This is multiplied by the two-dimensional mitral valve orifice size to yield a mean diastolic mitral valve orifice area (see text for details).

Studies on control group. In the control group, angle-corrected flow velocities were obtained in three areas: the mitral valve inlet, the main pulmonary artery and the ascending aorta. These were used for comparison with the flow velocities obtained in the patient groups after correction for angle. No dimensional measurements of aorta, pulmonary artery or mitral valve orifice were obtained in the control group, and, therefore, no volume flows were calculated.

Studies on patient groups. *Patent ductus arteriosus.* In patients with patent ductus arteriosus, pulmonary flow (QP) was calculated as pulmonary venous return through the mitral valve orifice and as flow in the ascending aorta, because they are the same when the ventricular septum is intact. The systemic flow (QS) was calculated as systemic venous return by measuring flow within right ventricular outflow tract in the subpulmonary region.

Atrial septal defect. In patients with an atrial septal defect, QP was measured in the main pulmonary artery and QS was quantified at the mitral valve and in the ascending aorta.

Ventricular septal defect. In patients with a ventricular septal defect or a left ventricular to right atrial shunt, QP was calculated as transmitral valve flow. In four of nine patients with a small ventricular septal defect, QP could also be calculated in the pulmonary artery.

Analysis of Doppler flow records. *Peak Doppler diastolic (mitral) and systolic (all other sites) flow velocities* were read directly from the recorded calibrated page prints (cm/s) using a Numonics computer graphics analysis system.

Sampling angles were measured with a protractor between the sample line cursor and the angle cursor (Fig. 2) on the two-dimensional freeze-frame images. The angle cursor had been set along the presumed direction of flow during the course of the study. Both peak and mean flow velocities were corrected for angle before comparison between control and patient groups.

Mean temporal flow velocities (mean temporal V) at each sampling site were determined by digitizing and integrating the area under Doppler flow curves over three consecutive entire cardiac cycles with the Numonics computer and dividing by the time for those beats. To accomplish this, we traced the middle of the densest portion of the gray scale display along the velocity curve (Fig. 1 to 4). This is the modal velocity or most frequent velocity shift present in the signal. In tracing Doppler records for great arteries or the subvalvular or right ventricular outflow tract, the flow records were traced to zero during diastole (9). For mitral valve records, the flow was traced to zero during systole (12). The mean velocities were then corrected for sampling angle by dividing the mean velocity by the angle between Doppler beam and direction of flow. For calculation of QP:QS in each individual patient, flow records selected for analysis were matched for RR interval for the sampling sites used.

Calculations of volume flow by Doppler technique. Systemic and pulmonary flows were calculated according to the following formula:

$$Q = \frac{\text{Mean temporal V} \times \text{Vessel (or mitral valve) flow area} \times 60\ \text{s/min}}{\text{Cosine } \Theta}, \quad (2)$$

where Q = flow in ml/min and mean temporal V = mean temporal velocity of flow in cm/s. As stated previously, the correction for cosine Θ, that is, the cosine of the incidence angle between Doppler beam and direction of flow, had previously been applied to all peak velocity measurements or tracings of mean velocities with graphics analyzer. Therefore, no angle corrections were necessary at this time.

The ratios of the resulting pulmonary and systemic flows were then calculated When two sites were available for determination of a single flow, either for QP or for QS (described in Methods), the average of the two determinations was used for that flow when calculating QP QS in the overall regression analysis

Repeatability of measurements. To determine repeatability, all measurements were made in duplicate by one investigator To test interobserver variability, all calculations of flows were performed by two independent investigators who were unaware of the other's results, patient identity, or shunt magnitude by catheterization or nuclear study They were, however, aware of the site of the shunt

Statistical analysis. Mean, temporal and peak velocities at the different anatomic sites were compared between the control and the different shunt groups by the unpaired Student's *t* test Linear regression was used to compare QP.QS determined by Doppler technique with QP QS calculated by catheterization or nuclear techniques Linear regression was also used for comparing Doppler QP QS determinations obtained from different intracardiac flow sampling sites in the same patient, yielding a correlation coefficient, as well as a standard error of the estimate for the regression analysis

Results

Doppler studies adequate for quantitation were obtained from at least one pulmonary flow (QP) and one systemic flow (QS) measurement site in all 21 patients Adequate Doppler velocity traces were obtained for the aorta, mitral valve and pulmonary artery for all of the 25 control subjects

For the four patients with patent ductus arteriosus, QP was calculated using the mitral valve flow in all, and in three QP was also measured in the ascending aorta, QS was calculated by measuring flow velocities in the subvalvular right ventricular outflow tract in these patients

For the six patients with atrial septal defect, QP was measured at the main pulmonary artery and QS was quantified at the mitral valve in all six patients and in the ascending aorta in three of the six as well

For the 11 patients with ventricular septal defect or left ventricular to right atrial shunt, QP was calculated at the mitral valve orifice In four patients, those with the small shunts, QP could also be calculated in the main pulmonary artery (see later) In all 11 patients, QS was measured in the aorta

In four patients with a left to right shunt, QP:QS at catheterization was less than 1 1 1 Three of these patients were studied for assessment of other lesions, and one underwent catheterization to delineate a suspected left ventricular to right atrial shunt In these patients, the presence of a shunt was demonstrated only by visualization of contrast passage from left to right on cineangiogram Oximetry did not suggest measurable shunting Shunt magnitude was calculated using indocyanine green dye-dilution curves in two of these four patients (Table 1)

Comparison of mean temporal and peak flow velocities between control subjects and patients with a left to right shunt (Table 2). *Subpulmonary flow velocities* The subpulmonary right ventricular outflow tract was interrogated only in the group with patent ductus arteriosus and was not studied in other patient groups or normal subjects Subpulmonary right ventricular outflow tract flow velocities will not be discussed further All of these records were similar to that shown in Figure 3

Mitral valve flow velocities Mean mitral valve velocity was statistically higher than normal only in the ventricular septal defect group (probability [p] $< 0\ 05$) Peak velocities, however, were statistically higher than normal in patients with ventricular septal defect and with patent ductus arteriosus ($p < 0\ 01$ and $p < 0\ 05$, respectively) Patients with atrial septal defect had mitral valve flow velocities comparable with those of control subjects Mitral valve flow curves in the patients with ventricular septal defect with shunts greater than 1 5 1 had ± 6 dB spectral width between 20 to 30 cm/s at peak diastole These degrees of spectral spread suggest some disorganization of flow compared with normal flow

Aortic flow velocities Ascending aortic peak flow velocities were statistically higher than normal in patients with patent ductus arteriosus ($p < 0\ 01$) and significantly lower than normal in patients with ventricular septal defect ($p < 0\ 001$) Mean aortic flows were statistically higher in patients with patent ductus arteriosus and lower in patients with atrial septal defect ($p < 0\ 01$) than in control subjects

Pulmonary flow velocities Pulmonary artery peak flow velocities were higher than normal in the four patients with ventricular septal defect in whom they were measurable ($p < 0\ 01$); in the other seven patients with ventricular septal defect, peak flow velocities in the pulmonary artery were too high to be quantified, because they exceeded the Nyquist limit of 143 cm/s at 0 to 6 cm sampling depth (Fig 6) All patients with ventricular shunt had spectral broadening of the pulmonary flow curves reflecting turbulence with a ±6 dB spectral width greater than 30 cm/s Pulmonary artery peak flow velocity was also higher than normal in the group with atrial septal defect ($p < 0\ 001$), however, all velocities in this group were measurable because they were below the Nyquist limits Pulmonary artery velocity curves in the group with atrial septal defect had spectral widths between 20 to 30 cm/s at peak systole In all patients with patent ductus arteriosus, pulmonary flow curves showed spectral broadening of flow waveforms greater than 20 cm/s spectral width and flow velocities higher than the maximal nonambiguous detection limit (Nyquist frequency) Furthermore, flow reversal often occurred in late diastole with ductal flow toward the transducer Doppler waveforms in the pulmonary artery in this group were, therefore, unquantifiable

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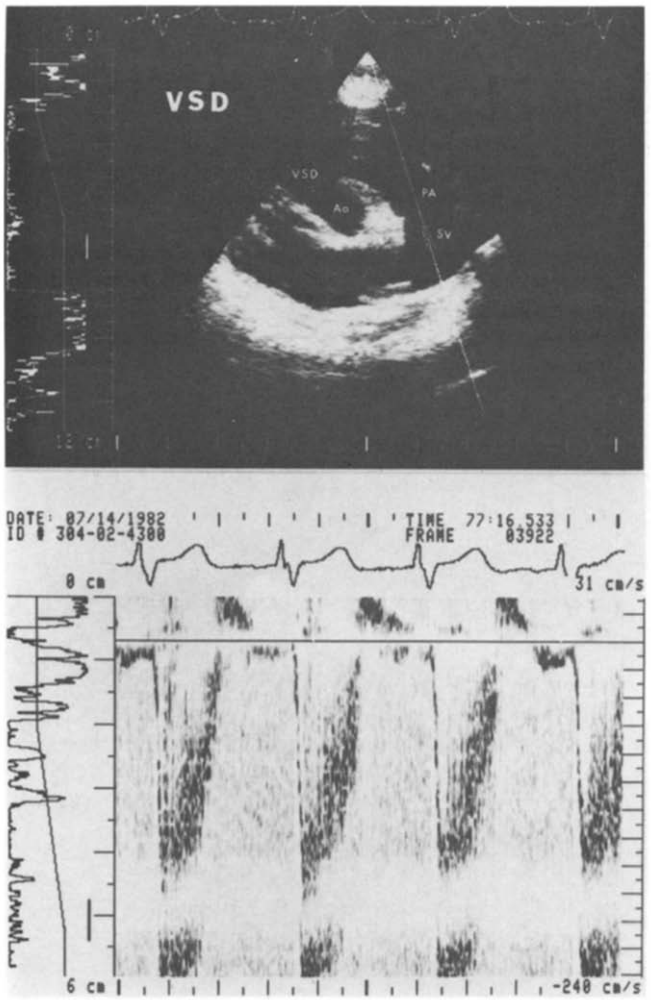

Figure 6. Pulmonary artery (PA) sampling in a patient with a ventricular septal defect (VSD). The latter is imaged at the right side of the subaortic (Ao) left ventricular outflow tract in this short-axis view. In the **lower panel**, flow is spectrally broadened and has too high a velocity to be quantified (see text for details).

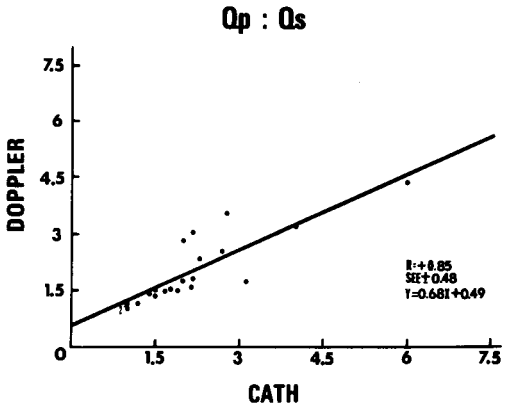

Figure 7. Pulmonary to systemic flow ratio (QP:QS) (21 values) calculated by Doppler measurement compared with QP:QS by catheterization (CATH), which includes the results obtained by radionuclide angiography in three patients with patent ductus arteriosus. The correlation coefficient for the linear regression analysis is 0.85, with a standard error of the estimate of ± 0.48:1. The equation for the linear regression is shown below.

Correlation of Doppler flow with catheterization/nuclear-derived QP:QS (Table 1). Figure 7 shows pooled data combining the three lesions. When two sites were available for determination of a single flow, either for QP or QS, the average of the two determinations for that flow was used when calculating QP:QS.

The correlation coefficient for invasively determined QP:QS versus Doppler estimated QP:QS was 0.85 (standard error of the estimate [SEE] = 0.48:1) and the line of regression passed close to the origin. The slope (0.68) of the regression relation suggests underestimation of shunting by Doppler technique at high QP:QS ranges.

In the presence of patent ductus arteriosus, Doppler QP:QS, using flow through the mitral valve orifice as QP, correlated well (r = 0.75) with the invasive measurements. However, the correlation improved if the ascending aortic flow was used for estimating Doppler QP.

In patients with atrial septal defect, Doppler QP:QS ratios calculated with aortic-determined QS flows were comparable in accuracy with those derived by the mitral valve orifice method for QS.

In patients with ventricular septal defect, Doppler QP:QS using flow at the main pulmonary artery as QP was available in only four patients (r = 0.69) with small shunts, but in these, it did not appear as useful as the mitral valve orifice method for QP determination. The low correlation coefficient is partially due to the narrow range of shunt magnitudes. The mitral valve orifice method correlated (r = 0.90) more closely to QP:QS determinations obtained by invasive measures.

While pulmonary artery velocities might be resolvable in a higher portion of patients with ventricular septal defect using a high pulse repetition frequency (PRF) or continuous wave Doppler, flow downstream from a restrictive orifice such as a ventricular septal defect is probably not laminar and probably does not have a flat flow profile across the vessel. Thus, two of the major assumptions in this Doppler volume flow method are probably unfulfilled in this situation.

Correlations were quite high between volume flows obtained from two different intracardiac sampling sites when they related to the same flow, either pulmonary or systemic, in the same patient. Correlation of QP at the mitral valve with QP in the aorta was 0.92 in patients with patent ductus arteriosus. In patients with atrial septal defect, correlation of QS using aorta versus the mitral valve was 0.9. In ventricular septal defect, correlation of QP using the mitral valve method versus the pulmonary artery site was 0.88.

These high correlations, although for small numbers of observations, confirm the internal consistency of the method

Interobserver variability and error of repeatability. All flow calculation determinations were highly repeatable, the standard errors of the means of repeated measurements in control subjects, as well as groups with cardiac shunt, were within 5% when comparing duplicate measurements of the same flow curves Interobserver variability was also less than 5%

Discussion

Previous work (13) has suggested that the noninvasive Doppler echocardiographic technique can be used to measure blood volume flows accurately when compared with invasive measures of cardiac output Our initial experiences with open chest dogs (14) suggested that this technique was highly accurate, especially using fast Fourier transform Doppler velocimetry devices Nonetheless, in our earlier attempts to apply these techniques to children (8), difficulties were encountered in achieving accurate dimensional measurements of flow area

Methodologic considerations. Several factors probably contributed to more reliable results in this study A new higher resolution 5 MHz probe was available for study of the smaller infants Furthermore, the suprasternal notch view was avoided for aortic imaging because of difficulties with dimensional determinations of aortic size in this view The subcostal and apical left ventricular outflow tract views provided a better method for interrogating aortic flow in a plane relatively parallel to the direction of flow, which in children usually is within the maximal focus zone of most mechanical scanners, that is, about 4 to 6 cm from the transducer

Finally, the mitral valve orifice method, developed and validated in our laboratory as an alternate site for cardiac output determination in adults, further aided in the performance of these studies, because the pulmonary artery velocities could not be used to calculate pulmonary flow in patients with patent ductus arteriosus or some of those with a ventricular septal defect The mitral valve orifice method provided a site for pulmonary flow calculation in those patients

Accuracy of flow measurement from various sites. The number of patients in each of the categories in our study is small and the difference in the nature of the shunts gives different physiologic significance to the Doppler flows calculated at the various sites Furthermore, the catheterization data were derived to yield a QP QS ratio rather than provide absolute comparisons of Doppler- and catheterization-derived pulmonary or systemic flow It, therefore, appears to us inappropriate to project from these data much information regarding the relative accuracy of these various sites for flow measurement Despite these small numbers, use of the great artery sites, such as the aorta, for a QP determination in patent ductus arteriosus or for a QS determination in patients with atrial septal defect yielded a closer correlation for QP QS than Doppler measurements using the mitral valve orifice method for these groups Although the mitral valve orifice Doppler method yielded very encouraging results in our initial experimental and clinical studies, improved high frequency images, especially of the aorta, may still make the great arteries the sites of choice for measurement of Doppler flow when the walls of these great arteries can be imaged clearly

A fundamental assumption in the Doppler method, aside from the dimensional determinants, is that flow, for the most part, is laminar and organized and has a flat velocity profile across the vessel or valve inlet It has been suggested by Seed and Wood (15) and McDonald (16) that in the intact circulatory system, large vessels have a generally flat velocity profile In our method, going downstream from the site of the shunt, that is, the pulmonary artery in atrial septal defect and the mitral valve in ventricular septal defect or patent ductus arteriosus, may have avoided the potential problems of abnormal flow profiles near shunt sites (9)

Improving the accuracy of the method. Underestimation of shunt ratios by the Doppler technique at higher flows may arise because of our crude method for correction of the pulmonary artery and aortic sizes for pulsations during the cardiac cycle Pulsations of the aorta and pulmonary artery are noticeable in patients with large shunts, therefore, if flow was calculated using a less than maximal vessel dimension, the resulting flow might be underestimated Frame by frame analysis throughout the cardiac cycle is tedious, but it provides a more accurate estimate of the mean cross-sectional flow diameter for these pulsatile vessels Although such correction for systolic expansion has not been necessary in most normal studies, it may prove necessary at high shunt flow volumes Nonetheless, our present results for the correlation of QP QS are better than our previously reported results for either absolute pulmonary or systemic flows

When two different sites were used to calculate flow in a specific vascular bed, for example, the mitral valve as well as the aorta for QS in the presence of an atrial septal defect, the results were internally consistent and quite highly correlated The availability of an additional site as a cross check occasionally points out the errors in determination of either the mean flow velocity or, more commonly, the vessel dimensional component

In our series, Doppler studies were not performed in the cardiac catheterization laboratory simultaneously with invasive shunt calculations, primarily because the Doppler method using multiple flow sampling sites requires considerable time for acquisition of imaging and flow data Rapid and more acceptable tape review and light pen measuring and tracing techniques available on the scanner in real-time

and playback modes could significantly speed up the studies to a more acceptable examination time

Implications. We have presented our initial experiences applying Doppler flow measurement techniques to a group of infants and children with shunts These preliminary data suggest that a two-dimensional Doppler echocardiographic method can provide an accurate estimate of pulmonary to systemic flow ratios that should be useful in diagnostic evaluation and serial assessment of children with a simple left to right shunt

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