Noninvasive evaluation of the ratio of pulmonary to systemic flow in atrial septal defect by duplex Doppler echocardiography

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ABSTRACT The ratio of pulmonary to systemic flow (Qp/Qs) was noninvasively evaluated by duplex Doppler echocardiography in 22 patients with atrial septal defects (ASDs). Right and left ventricular stroke volumes (RSV, LSV) were determined from the recordings of ejection blood flow velocity and diameter at the level of the pulmonary and aortic orifices in each ventricular outflow tract. The ratio RSV/LSV, determined by the duplex Doppler echocardiography, was compared with Qp/Qs by oximetry. The RSV/LSV for 10 normal subjects was 0.99 ± 0.05 (mean ± SD), whereas the RSV/LSV for patients with ASD, 2.26 ± 0.63, was significantly higher than that for normal subjects (p < .01). In patients with ASD, a fairly good correlation was found between RSV/LSV and Qp/Qs (r = .92, p < .01; y = 1.11x − 0.30), and this high correlation was found even in patients with complications such as pulmonary hypertension, mitral and tricuspid regurgitation, Eisenmenger complex, and ventricular septal defect. We also found that semilunar valve regurgitation modified the value of RSV/LSV in accordance with the degree of regurgitation. These findings indicate that, with a few limitations, the Doppler index RSV/LSV is clinically useful in the estimation of the magnitude of the shunt flow in patients with ASD and that the limitations could be overcome by additional Doppler examination.


CARDIAC OUTPUT can now be accurately measured by quantitative Doppler echocardiography as a product of echocardiographic cross-sectional area of the ascending aorta and Doppler aortic flow velocity integral over systole.1-4 Recent articles5-9 have demonstrated that cardiac output can be also determined by Doppler quantitation of transmural flow or pulmonary arterial flow with the use of echocardiographic or angiographic views of cross-sectional area. Thus, we can noninvasively obtain the ratio of pulmonary to systemic flow (Qp/Qs) in various shunt diseases by first determining pulmonary and systemic flow with quantitative Doppler echocardiography and then dividing the former by the latter.7,11 Aortic flow is usually satisfactorily determined with little error; however, calculation of pulmonary flow sometimes results in significant errors9 that are mainly due to the inability to adequately visualize and measure internal pulmonary arterial diameter from the echocardiographic image.5,11 In determining pulmonary arterial flow in patients with atrial septal defect (ASD) and/or ventricular septal defect, another serious problem arises in many cases; pulmonary arterial flow is often too highly disturbed to allow determination of flow velocity from Doppler recordings.12,18

We studied a method for Doppler quantitation of pulmonary flow in patients with ASD using Doppler recordings of the right ventricular outflow tract, in which flow is possibly less disturbed than in the pulmonary artery.12 We validated this method of determining Qp/Qs in patients with ASD by comparing Doppler recordings of the right ventricular outflow tract with those of the pulmonary artery. Some additional technical developments were also tested in the measurement of valve orifice.

Methods

Patient selection. The study population consisted of 24 patients with ostium primum- or secundum-type ASD (11 male
and 13 female patients ranging in age from 3 to 69 years, mean 30) who underwent diagnostic cardiac catheterization and 10 normal subjects (eight men and two women ranging in age from 37 to 59 years, mean 49) who served as control subjects. Two of the 24 patients with ASD were excluded because the diameters of their pulmonary orifices could not be determined by echocardiography. In the other 22 patients all Doppler and echocardiographic recordings obtained were satisfactory. In the patients with ASD Qp/Qs ranged from 0.51 to 4.6. Seven patients had pulmonary hypertension (mean pulmonary arterial pressure over 20 mm Hg). The presence or absence of associated valvular heart diseases was determined by Doppler examination and/or contrast angiography. Patient characteristics and diagnoses are shown in table 1.

The interval between Doppler examination and cardiac catheterization was within 24 hr in 14 patients, within 1 week in three patients, within 3 months in two patients, and within 6 months in three patients. The clinical condition of the patients did not change between cardiac catheterization and Doppler examination.

Apparatus. We used a duplex Doppler echocardiograph (Hitachi EUB-10B or Toshiba SDS-21A with SSH-41A) for both imaging and determination of flow velocity. Two-dimensional echocardiographic images, M mode echocardiographic tracings, and Doppler-determined flow velocity patterns were obtained with the same transducer array (2.5 MHz for EUB-10B and 2.4 MHz for SDS-21A). Any cursor line could be interrogated for pulsed Doppler sampling and M mode echocardiographic tracing, and the ultrasound beam direction and the sample volume were monitored as a bright line and a spot on the line in the two-dimensional echocardiographic image. The sample volume was a cylinder with a diameter of 3 mm and a length of 2 mm at a depth of 7.5 cm for EUB-10B and with a diameter of 5 mm and a length of 2 mm at a depth of 10 cm for SDS-21A. The pulse repetition rate was 5.4 kHz for the former and 6 kHz for the latter. Doppler recordings were obtained in the Doppler mode, and sampling position was easily checked by switching the instrument from the Doppler to the real-time imaging mode. Doppler signals derived from structures were minimized by a high-pass filter, and all signals were analyzed in real time by the Chirp-Z transform for EUB-10B and by the fast-Fourier transform for SDS-21A, and were simultaneously displayed on an electrocardiogram, phonocardiogram, and M mode echocardiogram at a paper speed of 100 mm/sec. The flow velocity directed toward and away from the transducer was displayed above and below the baseline on the recording paper.

Ultrasound examination

Measurements in the right ventricular outflow tract. Each patient rested in a supine position and breathed in a relaxed way during Doppler examination. The transducer was placed, as usual, in the third intercostal space at the left sternal border and was angulated laterally to depict the right ventricular outflow tract and main pulmonary artery. Doppler recordings of flow velocity were obtained with the Doppler beam directed as parallel as possible to the long axis of the right ventricular outflow tract and with the sample volume positioned just at the pulmonary orifice at the center axis of the right ventricular outflow tract (figure 1A). We then advanced the sample volume to the main pulmonary artery and recorded the flow velocity pattern, which was then compared with that in the right ventricular outflow tract. The Doppler incident angle and the diameter of

<table>
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<th>TABLE 1</th>
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<td>Patients' characteristics and Doppler and catheter measurements</td>
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<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age (yr)</th>
<th>Sex</th>
<th>Diagnosis</th>
<th>HR (beats/min)</th>
<th>BSA (m²)</th>
<th>Doppler incident angle (degrees)</th>
<th>Doppler measurements</th>
<th>Catheter measurement of Qp/Qs</th>
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<td>26</td>
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<td>11</td>
<td>M</td>
<td>ASD</td>
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<td>1.45</td>
<td>0</td>
<td>23 89.7/75.5</td>
<td>1.19/1.15</td>
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<td>50 67.7/45.2</td>
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<td>25</td>
<td>44 70.5/24.0</td>
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HR = heart rate; BSA = body surface area; RVOT = right ventricular outflow tract; LVOT = left ventricular outflow tract; Eisenmenger = Eisenmenger complex; VSD = ventricular septal defect; TR = tricuspid regurgitation; PR = pulmonary regurgitation; MR = mitral regurgitation; PH = pulmonary hypertension; ECD = endocardial cushion defect; MSR = mitral stenosis associated with regurgitation.
the pulmonary orifice were measured from midsystolic echocardiographic images. In the measurement of the diameter of the pulmonary orifice, we asked patients to rest in a left decubitus position so that the pulmonary orifice would appear as parallel to the ultrasonic beam as possible. For the real-time echocardiographic images midsystolic inner diameter of the pulmonary orifice was measured as an interval between the points at which the pulmonary cusps originated.

Measurements in the left ventricular outflow tract. After measurements in the right ventricular outflow tract, the transducer was moved onto the cardiac apex and angled medially to depict the left ventricular outflow tract and the ascending aorta in a left anterior oblique equivalent view (figure 1, B). We positioned the sample volume just at the aortic orifice at the center axis of the left ventricular outflow tract and recorded the flow velocity pattern. We then advanced the sample volume into the ascending aorta to record the aortic flow velocity for the evaluation of the presence of flow disturbance. The Doppler incident angle was determined from the midsystolic gated echocardiographic image. The midsystolic diameter of the aortic orifice was determined from M mode echocardiograms (beam direction is displayed as a dashed line in B, upper right). A and B, bottom, Doppler recordings. RV = right ventricle; Ao = aorta; PA = pulmonary artery; LV = left ventricle; SV = sample volume; PCG = phonocardiogram; ECG = electrocardiogram.

![Diagram](image_url)

**FIGURE 1.** Measurements of the flow velocity and diameter in the right (A) and left (B) ventricular outflow tracts of a 15-year-old boy with ASD (patient 16). The Doppler beam and the sample volume are shown as a white cursor line and a white dot on the line, respectively, in the midsystolic frozen scan image (A and B, upper left), from which the Doppler angle against the flow vector is determined. The diameter of the pulmonary orifice is determined as an interval between inner walls (solid white line in A, upper right). The diameter of the aortic orifice is measured from the M mode echocardiogram (beam direction is displayed as a dashed line in B, upper right). A and B, bottom, Doppler recordings. RV = right ventricle; Ao = aorta; PA = pulmonary artery; LV = left ventricle; SV = sample volume; PCG = phonocardiogram; ECG = electrocardiogram.
TABLE 2
Flow disturbances detected by Doppler echocardiography

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>ASD</th>
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<tr>
<td>RVOT</td>
<td>10 (−)</td>
<td>22 (−)</td>
</tr>
<tr>
<td>PA</td>
<td>10 (−)</td>
<td>15 (−), 7 (+)</td>
</tr>
<tr>
<td>LVOT</td>
<td>10 (−)</td>
<td>22 (−)</td>
</tr>
<tr>
<td>Aorta</td>
<td>10 (−)</td>
<td>20 (−), 2 (NE)</td>
</tr>
</tbody>
</table>

Symbols (+) and (−) indicate presence or absence of flow disturbances.

RVOT = right ventricular outflow tract; PA = main pulmonary artery; LVOT = left ventricular outflow tract; NE = not evaluated.

velocity, \( f_{\text{dn}}(t) \) is instantaneous maximum Doppler shift frequency, \( f_0 \) is carrier frequency, \( c \) is sound velocity, and 0 is Doppler incident angle against the long axis of ventricular outflow tract. The integral of \( V_{\text{max}}(t) \) was determined as an area under the envelope of the Doppler shift frequency pattern with a digitizer (Cardio 80, Contron). When the Doppler incident angle was less than 20 degrees there was no need to correct \( V_{\text{max}}(t) \) for the angle. However, in the right and left ventricular outflow tracts, respectively, the Doppler incident angle failed to be less than 20 degrees in none (0%) and three (30%) of 10 normal subjects and nine (41%) and 18 (82%) of 22 patients; in these cases \( V_{\text{max}}(t) \) was corrected for the angle. Both RSV and LSV were calculated as averages of five consecutive cardiac cycles. Both ventricular stroke indexes were obtained by dividing stroke volumes by the body surface area. The ratio RSV/LSV was calculated for estimating \( Q_p/Q_s \).

In each record, the flow disturbance was evaluated from the spectral width of systolic Doppler frequency pattern. The flow disturbance was considered to be present if the 12 dB spectral width was greater than 45 cm/sec.

Catheter measurements. All patients underwent cardiac catheterization. Hemodynamic measurements were made with a No. 7F fluid-filled catheter connected to a pressure transducer (Statham P23Db). Oxygen saturation in blood was measured in pulmonary arterial (Spa), pulmonary venous (Spv), systemic arterial (Ssa), and mixed venous (Smv) (the inferior vena cava sample being weighed 3:1 in combination with the superior vena cava sample) samples. The \( Q_p/Q_s \) was calculated from the oxygen saturation in blood with the equation: \( Q_p/Q_s = (Ssa - Smv)/(Spv - Spa) \).

Statistical analysis. Results are expressed as mean ± SD. Student’s t test was applied to compare ventricular stroke indexes for the patients with ASD and normal subjects. The Doppler-determined RSV/LSV was compared with \( Q_p/Q_s \) by oximetry with a simple linear regression analysis.

Results

Interpretation of Doppler records. Ten normal subjects and 22 patients with ASD were examined; the results are listed in table 2. None of normal subjects had a flow disturbance in the right ventricular outflow tract or main pulmonary artery. While none of the patients had a flow disturbance in the right ventricular outflow tract, seven of 22 had pulmonary arterial flow disturbances (figure 2). None of these patients or normal subjects had a flow disturbance either in the left ventricular outflow tract or in the ascending aorta. On the basis of these findings, each stroke volume was determined with the flow velocity pattern and the diameter in the ventricular outflow tract.

Right and left ventricular stroke indexes and the Doppler-determined shunt ratio (RSV/LSV). The mean values of right and left ventricular stroke indexes for patients with ASD were compared with those for normal subjects (figure 3). The left ventricular stroke index for patients with ASD (40.6 ± 9.5 ml/m²) was not significantly different from that for normal subjects (46.1 ± 7.4 ml/m²). However, the right ventricular stroke index for patients with ASD (88.8 ± 26.9 ml/m²) was distinctly higher than that for normal subjects (45.8 ± 7.2 ml/m²; \( p < .01 \)).

The Doppler-determined index RSV/LSV for the normal subjects (0.99 ± 0.05) indicated the equivalence of RSV and LSV. The RSV/LSV for patients with ASD (2.26 ± 0.63) was significantly higher compared with that for normal subjects (\( p < .01 \), figure 4).

Estimation of \( Q_p/Q_s \) with Doppler-determined RSV/LSV. In all 22 patients the Doppler-determined RSV/LSV was compared with \( Q_p/Q_s \) by oximetry. The RSV/LSV correlated well with \( Q_p/Q_s \) (\( r = .92 \), \( p < .01 \); \( y = 1.11x - 0.30 \); figure 5). This good agreement was found even in patients with complications such as pulmonary hypertension (Nos. 6, 9, 11, and 19) and mitral and/or tricuspid regurgitation (Nos. 5, 76

FIGURE 2. Flow velocity patterns in the right ventricular outflow tract (left) and in the main pulmonary artery (right) of a patient with high left to right shunt flow. The flow velocity pattern in the right ventricular outflow tract represents a narrow spectrum in systole, which suggests absence of a flow disturbance. On the other hand, the flow is too highly disturbed in the main pulmonary artery to allow determination of the instantaneous maximal velocity.
6, 9, 11, and 19). In two patients with endocardial cushion defects (Nos. 6 and 19) the RSV/LSV was approximately the same as Qp/Qs. In a patient with ASD associated with a ventricular septal defect (No. 3) the RSV/LSV of 1.5 showed a good agreement with the Qp/Qs of 1.53. In a patient with Eisenmenger complex (No. 1) who had a dominant right-to-left interatrial shunt proved on cardiac catheterization, the RSV/LSV of 0.63 was distinctly lower than normal, but was comparable to the Qp/Qs of 0.51.

Semilunar valve regurgitation theoretically modifies the value of the Doppler-determined index RSV/LSV; thus, the effects of semilunar valve regurgitation on the RSV/LSV were extensively studied. In all normal subjects and patients with ASD, semilunar valve regurgitation was examined by Doppler echocardiography and its degree was evaluated by observing the point that regurgitant signals reached on the two-dimensional echocardiographic image. None of the patients had aortic regurgitation, and only four with ASD had pulmonary regurgitation. In patients with mild pulmonary regurgitation (regurgitation detected less than 1 cm from the pulmonary valve by Doppler echocardiography; patients 6 to 8), the RSV/LSV was similar to the Qp/Qs. However, in a patient with moderate pulmonary regurgitation (regurgitation detected up to 2 cm from the pulmonary valve by Doppler echocardiography; patient 19), the RSV/LSV was significantly lower than normal, but was comparable to the Qp/Qs of 0.51.

FIGURE 3. Doppler-determined indexes of right (left) and left (right) ventricular stroke index for patients with ASD and normal subjects. The right ventricular stroke index (RSI) for patients with ASD is significantly higher (p < .01), whereas the left ventricular stroke index (LSI) is within the normal range.

FIGURE 4. The Doppler-determined RSV/LSV in normal subjects and patients with ASD. The value of 2.20 ± 0.80 for patients with ASD is significantly higher than that for normal subjects (0.99 ± 0.05). Abbreviations as in Table 1.

FIGURE 5. Qp/Qs determined by oximetry compared with Doppler measurement of RSV/LSV. There is a high correlation between Qp/Qs and RSV/LSV (r = .92, p < .01, n = 22). The regression equation (solid line) is y = 1.11x - 0.30. Symbols as in figure 4.
raphy; patient 5) the RSV/LSV of 2.18 was higher than the Qp/Qs of 1.57.

Discussion

The usefulness of a pulsed Doppler echocardiographic technique in estimating Qp/Qs has been reported in young patients with a variety of congenital intracardiac shunt diseases such as ventricular septal defect, common atrioventricular canal, and tetralogy of Fallot.7 In these reports, the right and left ventricular output values were obtained from the measurements of pulmonary and aortic flow velocities and diameters, respectively. However, patients with ASD frequently have disturbed pulmonary flows due to high flow rates with or without dilated main pulmonary arteries. Doppler recordings in this study (figure 2 and table 2) revealed that seven of 22 patients had broadened spectral patterns on Doppler recordings of their main pulmonary arteries, which made it impossible to determine the envelope of Doppler shift frequency. In contrast, none of them had disturbed flow in the right ventricular outflow tract and this permitted us to obtain the velocity integral throughout the ejection period. These results are comparable to the previous phonocardiographic findings,12 which demonstrate that flow disturbances are more frequently exhibited in the main pulmonary artery than in the right ventricular outflow tract in young-to-elderly patients with ASD. Thus, we preferred to use the flow in the right ventricular outflow tract rather than that in the main pulmonary artery for the determination of RSV.

Flow velocity measured by the Doppler technique is essentially the cosine function of the angle between the Doppler beam and flow vector, and thus the Doppler incident angle should be taken into account when it exceeds a critical value because it might cause serious errors in determining flow velocity. In this study we failed to set the Doppler incident angle at less than 20 degrees (which causes 5% errors) in the right ventricular outflow tracts of nine of 22 patients and in the left ventricular outflow tracts of 18 of 22 patients, although we attempted to align the Doppler beam as parallel to the long axis of each of the tracts as possible. These observations differ from those of Sanders et al.7 They observed that the Doppler beam was adequately aligned parallel to the flow when they measured pulmonary and aortic flow in children with a variety of congenital shunt diseases. The differences between our results and those of Sanders et al. might be explained by the differences in the ages of the study populations or possibly by the differences in the locations of shunt lesions. In adult patients with ASD, the right ventricle often presents more marked dilatation than it does in children because of the long persistence of the right ventricular volume overload. In such an instance, the alignment of the Doppler beam parallel to the flow vector would likely be difficult, especially in the left ventricular outflow tract. Thus, in patients with ASD, and especially in adult patients, the Doppler incident angle should be taken into account in estimating not only left but also right ventricular output.

The major problem encountered in this investigation was the difficulty in obtaining a clear echocardiographic image of the pulmonary artery5,13; however, echocardiographically the pulmonary orifice could be more clearly imaged. In this study, we referred to additional real-time echocardiographic images to locate the conjunctive portion of pulmonary cusps to the orifice because moving anatomic structures are more easily recognized on real-time than on stop-frame images. Furthermore, accurate measurement of pulmonary orifice diameter would be possible if the pulmonary orifice were axially depicted on the echocardiographic images because vague images due to lateral resolution would be minimized.5 We kept the patients in a left decubitus position to reduce the covering effect of the left lung and searched for another echocardiographic window to depict the pulmonary orifice more axially. Thus, inner diameter of the pulmonary orifice was successfully measured axially in all but two patients who were excluded from the study.

In the present study the RSV showed good agreement with the paired measurements of the LSV in normal subjects. This observation confirms the facts14,15 that bronchial arterial flow does not exceed 2% of left ventricular output and that right ventricular output as determined by the dye-dilution technique is coincident with Fick’s calculation (difference less than 15%). In patients with ASD, right ventricular stroke index increased, but left ventricular stroke index was not different from normal. These findings suggest that the systemic flow is maintained at normal levels in patients with ASD. Although there is still controversy about whether the systemic flow is decreased or not in adult ASD patients without heart failure,16,17 it seems that the increase in pulmonary flow rather than the decrease in systemic flow accounts for the increase of Qp/Qs in patients with ASD.

In the patient with Eisenmenger complex who had a dominant right-to-left atrial shunt, RSV/LSV was less than 1 and was comparable to Qp/Qs. This finding indicates that our technique allows the evaluation of the right-to-left shunt as well as the left-to-right shunt, although further studies are needed to establish the
feasibility of this method for assessing Qp/Qs in patients with right-to-left shunt.

The Doppler-determined index RSV/LSV showed a good agreement with Qp/Qs in patients with ASD; however, extracardiac shunt diseases and semilunar valve stenosis and/or regurgitation might modify the value of RSV/LSV. The RSV/LSV in patients with pulmonary regurgitation is anticipated to overestimate Qp/Qs, since pulmonary regurgitation produces the augmentation of the Doppler measurement of RSV. The RSV/LSV of 2.18 was markedly higher than the Qp/Qs of 1.57 in a patient with moderate pulmonary regurgitation (regurgitant flow distributed up to 2 cm from the pulmonary valve), although we could estimate Qp/Qs from RSV/LSV with insignificant errors in patients with minimum pulmonary regurgitation (regurgitant flow detected less than 1 cm from the pulmonary valve). In patients with aortic regurgitation, RSV/LSV might underestimate Qp/Qs for similar reasons. However, aortic regurgitation is rarely associated with ASD, and none of our patients had aortic regurgitation. Also, these possible limitations could be overcome by performing additional Doppler echocardiographic examinations. RSV/LSV showed a good agreement with Qp/Qs even in patients with mitral and/or tricuspid regurgitation, which indicates that the Doppler technique permits us to estimate Qp/Qs in patients with mitral and/or tricuspid regurgitation.

Our results demonstrate that the Doppler technique allows the noninvasive evaluation of Qp/Qs with a high degree of accuracy and allows determination of the stage of ASD by the consecutive assessment of shunt magnitude. Furthermore, this technique appears promising in the evaluation of the surgical closure of ASD.

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References
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