Doppler Color-Flow Imaging Assessment of Shunt Size in Atrial Septal Defect

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Two-dimensional echocardiography and pulsed-Doppler studies have not proved to be reliable methods of assessing left-to-right shunt size in atrial septal defect. Doppler color-flow imaging displays the transatrial jet, providing a new dimension with the potential capability of quantifying left-to-right shunt size. Twenty-three patients with atrial septal defect were studied by color-flow imaging and cardiac catheterization. The defect size measured by two-dimensional echocardiography, the maximal color-flow jet width in the atrial septum, and the maximal color-flow jet area in the right atrium were correlated with cardiac catheterization--derived left-to-right shunt size. Correlation coefficients were 0.57 \( (p<0.01) \), 0.67 \( (p<0.001) \), and 0.65 \( (p<0.01) \), respectively. Atrial septal color-flow jet width distinguished patients with less than a 2:1 left-to-right shunt size ratio (eight patients, jet width <15 mm in all) from patients with greater than a 2:1 left-to-right shunt size ratio (15 patients, jet width >15 mm in all). These results indicate that Doppler color-flow imaging can distinguish left-to-right shunt size in atrial septal defect accurately enough to influence decisions with regard to subsequent patient management. \( (Circulation\ 1988;78:522-528) \)

Natural history studies of the patient with atrial septal defect (ASD) reported between 1950 and 1970 revealed a poor prognosis.\(^1\)\(^-\)\(^3\) Approximately 90% of these patients by age 70 became seriously disabled by pulmonary hypertension and congestive heart failure. In these studies, therefore, surgical closure of the ASD was recommended upon diagnosis.

However, these early studies were largely confined to patients with a clinically detected ASD, who would therefore tend to have large (\( >2:1 \)) left-to-right (Qp/Qs) shunts. In a study of 39 ASD patients with a small (\( <2:1 \)) left-to-right shunt, who were followed for 5–21 years (mean, 11.6 years), there was no evidence of deterioration.\(^4\) This presumed better prognosis of the patient with a small ASD has led some researchers to recommend closure of the ASD only when it exceeds a certain magnitude of shunting, varying from 1.5:1,\(^5\) to 1.7:1,\(^6\) to 2.0:1.\(^7\)

Numerous noninvasive techniques have been applied to quantify Qp/Qs in ASD, for example, radionuclide angiography,\(^8\) two-dimensional echocardiography alone\(^9\) or with saline contrast,\(^10\)\(^-\)\(^11\) and pulsed Doppler.\(^12\)\(^-\)\(^15\) Potential problems arise with recently described combined echocardiographic and Doppler methods. In one method,\(^12\) five separate cardiac velocities or measurements are required, each with potential sources of error, for example, pulmonary artery diameter, which may be difficult to measure, and mean pulmonary artery flow velocity, which may be difficult to measure planimetrically because of turbulence. There are also other factors that confound the measurements, for example, valvular regurgitation, high cardiac output states, and anomalous pulmonary venous return.

Doppler color-flow imaging superimposes intracardiac blood flow and cardiac anatomy. ASD is displayed as a jet crossing the atrial septum, traversing the right atrium, and entering the right ventricle. Several preliminary studies have characterized the ability of this technique to detect and quantify ASD.\(^16\)\(^-\)\(^20\) The aim of this study was to determine whether color-flow imaging could quantify Qp/Qs.

Patients and Methods

During an 18-month period from May 1, 1986 to November 1, 1987, a total of 23 adult patients with newly diagnosed ASD (either initially diagnosed clinically, echocardiographically, or by cardiac cathe-

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terization) had Doppler color-flow imaging (Aloka 860, Tokyo, Japan) and cardiac catheterization performed. Twenty-one patients had a secundum ASD, one patient had a primum ASD, and one patient had a sinus venosus ASD. Echocardiographic and catheterization studies were performed within 24 hours of each other in 11 patients, within 1 week in one patient, and within 20 to 136 days (mean, 53 days) in the remaining patients. Their ages ranged from 20–77 years (mean, 44 years); five were men. Full oximetric and left and right heart hemodynamic studies were performed on all patients. Only patients without anomalous pulmonary venous drainage were included in the study. Qp/Qs was calculated with mixed venous oxygen content as 3(superior vena cava oxygen content) + 1(inferior vena cava oxygen content)/4.21

On echocardiographic study, the image that best demonstrated the transatrial jet, and which best defined the jet width, was used for analysis. This was most often obtained by a modified apical four-chamber view taken from the lower left parasternal border. Subcostal views were attempted on all patients. In one patient, the transatrial jet was not detectable transhoracically, and transesophageal study was performed.

Doppler color-flow imaging was performed with a 2.5 MHz or 3.5 MHz phased-array transducer. The Aloka 860 codes approaching flow in red and receding flow in blue. Pulse repetition frequency varied from 4 to 8 kHz depending on the depth setting. The maximum depth for color-flow imaging was 18 cm. The color filter was set at high. The flow display scanning angle was either set at 53°, 47°, or 28° and at 15, 20, or 30 frames/sec, respectively. To adjust the gain settings for color-flow imaging, the gain was initially reduced to zero and then progressively increased until some background noise appeared, in addition to normal intracardiac flow patterns (at approximately 60% of the maximal gain setting). In one patient, transesophageal study was performed with a 5-MHz Aloka esophageal transducer with the Aloka 860 machine while the patient was sedated with intravenous diazepam and after topical anesthesia of the back of the throat with lidocaine spray.

Three specific measurements were taken. Defect size (mm) (from the two-dimensional echocardiogram) was measured in the same view as that used to assess jet width and jet area but with the color flow switched off. Jet width at the interatrial septum (mm) was measured inside the atrial septum along the line of the atrial septum, which was often not perpendicular to the long axis of the transatrial jet (Figure 1). Jet area was measured in the right atrium (cm²).

These three measurements were made by retrospective frame-by-frame analysis from the videotape, and they represent the mean of the three clearest maximum measurements from three separate cardiac cycles.

The measurements of jet width and jet area were both chosen to represent the Doppler color-flow image of transatrial flow in ASD. A single measurement of each, rather than the mean value over one cardiac cycle, was chosen because we were interested in finding a simple representative measurement to correlate with Qp/Qs. The maximum measurement of each was chosen to enhance reproducibility and to minimize the chance of selecting a measurement in which all flow was not being demonstrated because of a poor acoustic window or improper beam alignment.

In addition, right ventricular maximal diastolic minor axis dimensions in the apical four-chamber view (mm) and peak pulmonary artery velocity (m/sec) were also determined.

Observer Variability

Mean interobserver variability was assessed for the determination of defect size, jet width, and jet area; this was 5.9 mm (3–11 mm), 3.5 mm (0–8 mm), and 4.2 cm² (0.9–8.5 cm²), respectively. One patient with jet width less than 15 mm was diagnosed as having a jet width greater than 15 mm by the second observer. There was concordance in the other seven patients with jet width less than 15 mm. Mean intraobserver variability for jet width was 2 mm (0–8 mm).

Statistical Methods

Echocardiographic measurements were compared with cardiac catheterization Qp/Qs by linear regression analysis. Subgroups of measurements were compared with each other by the unpaired t test.
Results

Left-to-Right Shunt Size (Qp/Qs)

Defect size. The correlation between defect size, determined by two-dimensional echocardiography alone, and Qp/Qs is shown (Figure 2, top). The r value of 0.57 (p = 0.0065) decreased to 0.43 (p = 0.06) when the patient with a Qp/Qs of 8.8 was omitted from the statistical comparison. When the patients were grouped together, the mean value of defect size in patients with a Qp/Qs less than 2:1 was significantly different from patients with a Qp/Qs greater than 2:1 (Table 1), but there was too much overlap for this to be clinically useful (Figure 2, bottom).

Jet width. The correlation between jet width and Qp/Qs is shown in Figure 3, top. The r value of 0.67 (p = 0.0006) marginally increased to 0.71 (p = 0.0003) when the patient with a Qp/Qs of 8.8 was omitted from the statistical comparison. When the patients were grouped together, the mean value of jet width in patients with a Qp/Qs less than 2:1 was significantly different from patients with a Qp/Qs ranging from 2:1 to 3:1, and patients with a Qp/Qs greater than 3:1 (Table 1; Figure 3, bottom). Two patients with different jet widths and Qp/Qs are shown in Figure 4.

Jet area. The correlation between jet area and Qp/Qs is shown in Figure 5, top. The correlation coefficient of 0.65 (p = 0.0013) decreased to 0.52 (p = 0.019) when the patient with a Qp/Qs of 8.8 was omitted from the statistical comparisons. When the patients were grouped together, the mean value of jet area in patients with a Qp/Qs less than 2:1 was significantly different from the jet area in patients with a Qp/Qs greater than 2:1 (Table 1), but there was too much overlap for this to be clinically useful (Figure 5, bottom).

Total Pulmonary Flow

Correlation coefficients for defect size, jet width, and jet area that were correlated with total pulmonary flow were 0.83 (p = 0.002), 0.16 (p = 0.04), and 0.57 (p = 0.06), respectively. When the patient with the 8.8:1 shunt was excluded from the statistical comparisons, these values changed to 0.52 (p = 0.12), 0.57 (p = 0.08), and −0.25 (p = 0.50), respectively.

Shunt Flow

Correlation coefficients for defect size, jet width, and jet area correlated with shunt flow (total pulmonary flow minus systemic flow) were 0.86 (p = 0.0008), 0.66 (p = 0.03), and 0.65 (p = 0.03), respectively. When the patient with an 8.8:1 shunt was excluded from the statistical comparisons, these correlation coefficients changed to 0.74 (p = 0.01), 0.84 (p = 0.002), and 0.15 (p = 0.67), respectively.

Other Measurements

Right ventricular dimension was not significantly different in patients with less than 2:1 Qp/Qs compared with patients with greater than 2:1 Qp/Qs (Table 1). Right ventricular maximal diastolic minor axis dimension in the apical four-chamber view was normal (<45 mm²) in three of eight patients (37%) with less than 2:1 Qp/Qs compared with three of 15 patients (20%) with greater than 2:1 Qp/Qs (p = 0.3). Peak pulmonary velocity was significantly lower in patients with less than 2:1 Qp/Qs than in patients with greater than 2:1 Qp/Qs (Table 1), but there was considerable overlap. Peak velocity was 1.0 m/sec or less in four of eight patients (50%) with less than 2:1 Qp/Qs compared with one of 15 patients (7%) with greater than 2:1 Qp/Qs (p = 0.02). Mean pul-
monary artery pressure was not different between the two groups (Table 1).

**Body Surface Area**

When defect size, jet width, and jet area were divided by body surface area, the correlation coefficients with Qp/Qs were not significantly different (0.63, \( p = 0.002 \); 0.63, \( p = 0.002 \); and 0.60, \( p = 0.004 \), respectively). Neither right ventricular dimension nor peak pulmonary velocity divided by body surface area correlated significantly with Qp/Qs (0.40, \( p = 0.07 \); and 0.20, \( p = 0.39 \), respectively).

**Discussion**

This study demonstrates a significant correlation between echocardiographically determined defect size and Qp/Qs and shunt flow, and between jet width inside the atrial septum determined by Doppler color-flow imaging and Qp/Qs and shunt flow. Previous investigators\(^1,4,9\) have also reported on the hemodynamic significance of the size of the ASD. Dexter\(^1\) reported an inverse correlation between the size of the ASD and the transatrial pressure gradient. When the defect was small (<16 mm diameter or <2 cm\(^2\)), the normal 5–mm Hg pressure gradient from the left to the right atrium was maintained to a variable degree, depending on the size of the defect. With defects of over 2 cm\(^2\), the pressure difference between the two atria was practically abolished.

The relation between ASD size and Qp/Qs has been studied by Forfar and Godman,\(^9\) and they found a poor, but significant, correlation between ASD diameter (determined by balloon sizing at cardiac catheterization) indexed to body surface area and Qp/Qs (\( r = 0.49, p < 0.01 \)).

The accurate determination of ASD diameter by two-dimensional echocardiography alone is technically difficult because of normal "septal dropout" and because of the high resolution required to display the true edges of a septal defect. Forfar and Godman\(^9\) compared two-dimensional echocardiography sizing of the ASD with balloon sizing at cardiac catheterization and found too much overlap for two-dimensional echocardiography alone to permit accurate ASD sizing. In addition they, like us, found much overlap in defect size between patients with less than 2:1 Qp/Qs and greater than 2:1 Qp/Qs, and this may also partly reflect the inaccuracy of ASD sizing by two-dimensional echocardiography alone. Transesophageal echocardiography may better define the atrial septum to allow for a more accurate determination of ASD size as reported in a recent preliminary study\(^20\) that showed a correlation (\( r = 0.66, p < 0.05 \)) between defect size and surgical measurement.

In our study, strongest correlation occurred between jet width in the atrial septum and Qp/Qs. The correlation coefficient was 0.67 with all patients, and it was 0.71 when the patient with an 8:8:1 shunt was excluded from statistical comparisons. A pos-

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**Table 1. Comparison of Intracardiac Blood Flow and Cardiac Anatomy in Patients With Small and Large Left-to-Right Shunts**

<table>
<thead>
<tr>
<th>Patient group</th>
<th>Defect size (mm)</th>
<th>Jet width (mm)</th>
<th>Jet area (cm(^2))</th>
<th>Right ventricular dimension (mm)</th>
<th>Peak pulmonary velocity (cm/sec)</th>
<th>Mean pulmonary artery pressure (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qp/Qs&lt;2:1</td>
<td>14.7±7.3</td>
<td>10.4±2.7</td>
<td>5.9±3.4</td>
<td>46.4±6.2</td>
<td>1.0±0.1</td>
<td>19.4±9.5</td>
</tr>
<tr>
<td>Qp/Qs&gt;2:1</td>
<td>24.3±6.6</td>
<td>22.2±4.8</td>
<td>9.5±2.6</td>
<td>49.5±8.6</td>
<td>1.3±0.2</td>
<td>15.7±7.4</td>
</tr>
</tbody>
</table>

\( p = 0.004 \)  
\(<0.0001\)  
\( 0.009 \)  
\( 0.413 \)  
\( 0.011 \)  
\( 0.329 \)

All data are mean±SD.  
Qp/Qs, left-to-right shunt ratio.
Figure 4. Doppler color-flow echocardiogram of jet crossing left atrium. Top panel: Four-chamber view depicting transatrial jet in a patient with secundum defect. Jw, jet width (between arrows) measured 29 mm; Qp/Qs measured by cardiac catheterization was 3.3:1. Bottom panel: Four-chamber view depicting transatrial jet in a patient with primum defect. Jw, jet width (between arrows) measured 11 mm; Qp/Qs measured by cardiac catheterization was 1.5:1. ra, right atrium; lv, left ventricle; la, left atrium; rv, right ventricle.

Possible explanation for such diverse correlation coefficients caused by that patient (who had a defect size and jet width of 33 mm and 31 mm, respectively) is that the correlation is not entirely linear and that beyond the largest jet width, the increase in shunt size is somewhat exponential. There was sufficient precision to distinguish patients with a Qp/Qs less than 2:1, 2:1 to 3:1, and greater than 3:1. The practical importance of the correlation between jet width and Qp/Qs, however, lies in identifying patients with a Qp/Qs less than 2:1 and those with a Qp/Qs greater than 2:1, where there were no overlapping patients with the first observer and only one overlapping patient with the second observer. Thus, a jet width of greater than 15 mm should warrant surgical closure of the defect on the assumption that a Qp/Qs greater than 2:1 is an indication for surgery.4,7

In this study, we considered a Qp/Qs greater than 2:1 as the definition of a significant shunt because this has been the traditional cutoff point. There was too much overlap of Qp/Qs and jet width in the eight patients with a jet width less than 15 mm to permit a clear separation within this group, that is, a Qp/Qs greater than 1.5:1 or greater than 1.7:1. Although this may reflect a poor correlation between small jet widths of less than 15 mm and a Qp/Qs less than 2:1, it may also reflect the relatively small number in this group, the relative imprecision of accurate Qp/Qs determination by oximetry23 as well as the nonsimultaneity of echocardiographic and catheterization studies.

There are several reasons, both practical and theoretical, that make the assessment of jet width an attractive, noninvasive marker of Qp/Qs. First, it is a single measurement and has less chance of error than previously described echocardiographic and Doppler methods that require several measurements. Interobserver and intraobserver error by the reader of the study was relatively small. We did not address the error that may accrue from different sonographers performing the study, however, and this methodology may produce further error. Second, jet width may be precisely measured because
the exact position of the jet is defined by the atrial septum. Third, it can detect even small ASDs, barely larger than a patent foramen ovale (which measures 2–5 mm²); the smallest defect size in our study was 8 mm, with a 5 mm jet width. Fourth, it represents a more accurate method of measuring ASD size than twodimensional echocardiography alone. In our study, jet width was larger than defect size in seven patients, indicating an underestimation of defect size by two-dimensional echocardiography in these patients, which represented 30% of our patient population. Thus, jet width provides an accurate assessment of the functional size of the ASD, which is probably the main determinant of Qp/Qs, and not ASD size.9

It is important to emphasize the technical aspects of the color-flow study with respect to obtaining the correct views and measurement of the transatrial jet. The transatrial jet flow is displayed as maximally as possible, and among patients, the optimal view may vary, consisting of an apical four-chamber view, a parasternal four-chamber view, an oblique short-axis view, or a subcostal view. The jet is measured inside the atrial septum, along the line of the visualized ASD (i.e., along a line drawn from the upper and lower ends of the atrial septum).

We found a significant correlation between jet area and Qp/Qs, but there was too much overlap for this to be clinically useful. Valdes-Cruz and coworkers18 reported a similar correlation between jet area and Qp/Qs in a combined study of 11 patients and three open-chest dogs (r = 0.58). There are several explanations for the relatively poor correlation between jet area and Qp/Qs. First, a single maximum measurement of jet area probably does not correlate strongly with the total left-to-right flow in any one cardiac cycle. Second, the jet area may not represent true left-to-right flow; rather, it may be an underestimate because low-velocity transatrial flow is not depicted, and it may be an overestimate because it partially represents turbulence of flow that has already entered the right atrium from the vena cava. Third, it is sometimes difficult to accurately measure by planimetry the irregular jet area in the right atrium, particularly adjacent to the tricuspid valve; this is demonstrated in the large interobserver variability of measurement.

We also demonstrated various degrees of significant correlations between defect size, jet width, jet area, and pulmonary and shunt flow. Other investigators have also reported significant correlations between jet area and shunt flow.16,18,20 However, it is not clear from the literature at what magnitude shunt flow becomes clinically important; rather, Qp/Qs has been the traditional method of assessing patients. Nevertheless, these correlations corroborate the relation with Qp/Qs and the importance of ASD size in determining the magnitude of Qp/Qs.

We did not find a significant difference in right ventricular size between patients with a Qp/Qs less than 2:1 in comparison to patients with a Qp/Qs greater than 2:1. Our findings are commensurate with the idea that there is only a crude correlation between Qp/Qs and right ventricular dimension in ASD.24 Peak pulmonary velocity was significantly different between the two groups, but there was too much overlap to use this as an accurate discriminator between patients with a Qp/Qs less than and greater than 2:1.

This study did not address the sensitivity of color-flow imaging for the detection of ASD. Previous researchers have demonstrated sensitivities of 70%17 and 97%19 compared with cardiac catheterization. During this study, we had two patients with ASDs that were not demonstrated by regular “trans-thoracic” color-flow imaging for a sensitivity of 92%. The first patient (not included in this study) had a partial anomalous pulmonary vein detected by catheterization and a small sinus venosus defect detected only at surgery. Previously, when a child, she had had closure of a secundum ASD, and the anomalous venous drainage was not repaired. At echocardiography, there was a large right ventricle with increased pulmonary flow velocity, suggesting a left-to-right shunt, but no transatrial jet was detected. The second patient (included in this study) had chronic obstructive lung disease with mild pulmonary hypertension and a small 1.5:1 Qp/Qs shunt at cardiac catheterization. At echocardiography, which was technically difficult because of a poor acoustic window, there was right ventricular enlargement, normal pulmonary flow velocity, mild pulmonary hypertension, but no evidence of a transatrial jet. This patient underwent a truncalesophageal echocardiographic and color-flow study that demonstrated a sinus venosus defect, with the transatrial jet width measuring 5 mm, which is in keeping with a shunt less than 2:1.

Study Limitations

There are several limitations regarding the results of this study. First, our observations need to be corroborated with other color-flow imaging devices because there is a reported variability in the quantification of jet widths measured by different devices.25 Second, we examined adult patients, and therefore, our findings cannot be necessarily applied to children. Third, our results refer primarily to patients with secundum defects. The associated mitral regurgitation of a primum defect may affect the dynamics between jet width and shunt ratio. The technical difficulties of imaging the optimal width of a sinus venosus defect may be greater than for a secundum defect. Fourth, it should be stressed that a jet width less than 15 mm does not exclude the possibility that Qp/Qs is greater than 2:1, and it does not exclude the possibility that it represents a “significant shunt” as some research centers regard a Qp/Qs as a significant shunt. Fifth, we only examined eight patients with jet widths less than 15 mm. It is theoretically possible that some patients
with small (<15 mm) jet widths will have a relatively hyperdynamic circulation with substantially increased jet velocities, and the jet width alone may underestimate Qp/Qs in those patients.

In summary, our study demonstrates a significant correlation between the width of the transatorial jet inside the ASD and Qp/Qs in adult patients with predominantly secundum ASD. Assessment of jet width permitted a clear separation of patients with a Qp/Qs less than 2:1 from patients with a Qp/Qs greater than 2:1. Although this study did not address the indications for ASD surgical closure, certain researchers recommend surgery only when Qp/Qs is greater than 2:1. The finding of a jet width greater than 15 mm would permit recommendations for surgery, with this criterion, and obviate the need for cardiac catheterization. A finding of a jet width of less than 15 mm, however, does not exclude a Qp/Qs greater than 2:1, and it does not exclude a "significant shunt" as defined by a Qp/Qs greater than 1.5:1.

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References

Key Words: atrial septal defect, Doppler color-flow imaging, left-to-right shunt
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