Echocardiographic Assessment of Left-to-Right Shunt Volume in Children with Ventricular Septal Defect

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With the technical assistance of Deanne E. Shute, B.A.

SUMMARY  Echocardiograms were performed in 20 infants and children with isolated ventricular septal defects (VSD) undergoing cardiac catheterization. The magnitude of the left-to-right shunt was expressed as the pulmonary-to-systemic flow ratio (Qp/Qs) and was compared to a ratio of the echographic left atrial (LA) diameter to the aortic root (Ao) diameter (LA/Ao). The Qp/Qs was also compared to LA/m². Thirty-three normal children served as controls. The LA/m² and Ao/m² were significantly larger in normal infants under one year of age than in children above one year. The LA/Ao, however, was not influenced by age or size. A strong linear relationship was found between Qp/Qs and the LA/Ao (r = 0.96). The LA/Ao measurement appears to be helpful in the noninvasive assessment of the left-to-right shunt in patients with VSD.

VENTRICULAR SEPTAL DEFECT (VSD) has been reported to have an incidence of approximately 2/1000 live births. Cardiac catheterization is usually reserved for selected patients because of the potential morbidity and the impracticality of frequent serial studies. A simple, safe and noninvasive technique for the accurate, serial assessment of left-to-right shunt volume in patients with VSDs would be extremely valuable.

Several recent reports have shown echocardiographic measurements of the left atrial (LA) diameter to be useful in estimating the magnitude of the left-to-right shunt in patients with VSD and patent ductus arteriosus (PDA). However, the reliability of the LA diameter as the sole index of shunt volume is uncertain when comparing patients of markedly different body sizes and ages.

We have investigated the feasibility of a ratio of the echocardiographic LA diameter to the aortic root (Ao) diameter for the quantitation of the Qp/Qs in children with isolated VSD. Since the aortic valve annulus is a relatively non-compliant fibrous structure and unlikely to be affected by the hemodynamics of left-to-right ventricular shunts, we were particularly interested in determining whether the LA/Ao ratio would adjust for the wide range in body size present in the normal pediatric population. This study was initiated to test the hypothesis that normalizing the LA diameter by the LA/Ao ratio would permit the rapid and reliable identification of patients with dilated left atria due to increased pulmonary blood flow and that in the absence of other causes of LA enlargement, the LA/Ao ratio would also serve as an index of left-to-right shunt volume expressed as Qp/Qs.

Methods

Echocardiograms were performed on 20 consecutive patients aged three weeks to 15 years with isolated VSD documented by cardiac catheterization. All echocardiograms were done within 24 hours of catheterization.

During cardiac catheterization pulmonary and systemic blood flows were measured by the Fick principle utilizing a single, rapid sequence oxygen saturation series. Oxygen saturations were determined by an American Optical reflectance oximeter. Oxygen consumption in infants was assumed from the data of Cayler et al. and from LaFarge and Miettinen for children three years or older. The volume of the left-to-right shunt was expressed as the pulmonary to systemic flow ratio (Qp/Qs). Biplane cineangiography was used to confirm the diagnosis of VSD and to rule out the presence of any other cardiac anomalies.

Echocardiograms were performed using a Unirad ultrasonoscope and Tektronix Model 174 strip chart recorder. An Aerotech 2.25 mHz transducer, 0.5 inches in diameter and focused at a tissue depth of 5 cm, was used in patients older than six months. Infants less than six months of age or 0.4 m² were evaluated using a 5.0 mHz, 0.25 inch unfocused Aerotech transducer. The transducer was placed in the third or fourth left intercostal space at the left sternal border. The transducer was directed in a continuous sweep from the

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mitral valve in a cephalad and medial direction to the aorta. Mitral-aortic continuity and the accurate identification of the endocardial surface of the left atrial wall were thereby confirmed. Particular attention was paid to maintaining the transducer perpendicular to the chest wall and clear identification of at least one aortic valve cusp was required for measurement of the echogram. The gain of the instrument was adjusted to record the clearest images from the aorta and posterior left atrial wall. Care was taken to avoid the LA wall adjacent to the A-V junction since prominent diastolic wall motion may be present in this location.

The Ao diameter was measured from the anterior edge of the anterior aortic wall echo to the anterior edge of the echo originating from the posterior aortic wall at the end of ventricular systole, using the reference depth scale produced by the ultrasonoscope (fig. 1). The diameter of the LA was measured from the anterior margin of the posterior aortic wall echo to the anterior margin of the left atrial wall echo at the end of ventricular systole.

The LA and Ao diameters respectively were measured over three consecutive cardiac cycles and average dimensions were calculated. If individual measurements differed by more than 10%, a total of six cardiac cycles was used to obtain the average. The LA/Ao ratios were derived using the averages in each case. All the echocardiographic measurements were performed by one of the authors (ABL) without prior knowledge of the respective hemodynamic state.

Echocardiograms were also obtained from 33 children aged two days to 13 years without any evidence of cardiac disease, employing identical methods to those described above. The LA/Ao ratios in these children were considered as echocardiographic controls and were compared to the patients with VSD using Student's t-test. The LA/Ao ratios in the VSD group were also compared to the respective Qp/Qs ratios obtained at cardiac catheterization by linear regression analysis.

Results

The clinical and echocardiographic data in the 20 patients with VSD are summarized in table 1 and the control group in figure 2. Twelve patients with VSD had Qp/Qs ≥ 2:1, whereas eight had ratios less than 2:1. Five children with the largest shunts had clinical signs and symptoms of congestive heart failure at the time of their evaluation. All were being treated with digitalis and diuretics. An additional five patients, not in congestive failure at the time, were also receiving digitalis.

The smallest Qp/Qs ratios were obtained in two patients who were catheterized electively at four and 12 years respectively. The LA/Ao ratios in these two boys were not different from the control group.

Pulmonary vascular resistance (Ṙ) was calculated in 18 patients and was elevated (i.e., above 3 units) in four. The highest Ṙ (8 units) was obtained in a 21-month-old girl who was below the third percentile for both height and weight and who had evidence of increasing right ventricular hypertrophy on serial electrocardiograms. Catheterization revealed systemic pressure in her pulmonary arteries and Qp/Qs = 1.7:1.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Echocardiogram of the aortic root (Ao) and left atrium (LA) in a patient with ventricular septal defect. Ao is measured from anterior edge of anterior aortic wall to anterior edge of posterior aortic wall. LA is measured from anterior edge of the posterior aortic wall to the anterior edge of the posterior left atrial wall. Horizontal lines are 1 cm depth markers.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Comparison of LA/m², Ao/m² and LA/Ao in 33 control children. Horizontal lines indicate means in each group. LA/m² and Ao/m² vary with patient age above and below one year. LA/Ao is not affected by age.
Table 1. Clinical Summary of Patients with VSD

<table>
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<tr>
<th>Age (years)</th>
<th>BSA(m²)</th>
<th>CHF</th>
<th>Rp(u)</th>
<th>Qp/Qs</th>
<th>LA(mm)</th>
<th>Ao(mm)</th>
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Abbreviations: BSA = body surface area; CHF = congestive heart failure; Rp = pulmonary vascular resistance; a = resistance units, mm Hg/L/min/m²; Qp/Qs = pulmonary-to-systemic flow ratio; LA = left atrial diameter; Ao = aortic root diameter.

The echocardiographic diameters of both the LA and Ao relative to body surface area are larger in normal infants below one year of age than in children above one year (fig. 2). The LA/m² in the former is 42 ± 17.2 (mean ± 1 SD) and in the latter is 22.7 ± 8.5 (P < 0.01). Similarly, the Ao/m² is 49 ± 5.6 under one year and 24.3 ± 5.1 over one year (P < 0.01). However, the relationship between the LA diameter and the Ao diameter (LA/Ao) remains constant throughout infancy and childhood.

The echocardiographic findings in the control group are compared to the patients with VSD in figure 3. The mean LA/m² in the entire control group is 27.5 ± 9.1 mm²/m², with a range of 16.6 to 52.2 mm²/m², whereas the VSD group mean is 45.5 ± 18.6 mm²/m², with a range from 22.9 to 92.0 mm²/m². Though the difference between the two groups is statistically significant (P < 0.01), there is considerable overlap, in part resulting from the normal variability in LA/m² due to age. The aortic root diameter in all but one

Figure 3. Comparison of LA/m² and LA/Ao in control children and patients with VSD. A) LA/m² results in considerable scatter and only fair separation of VSD with Qp/Qs ≥ 2:1 from control. B) LA/Ao permits a greater degree of separation between controls and patients with large VSD. Solid and dashed horizontal lines denote the mean and one standard deviation respectively.
The LA/Ao ratio improves the separation between control and VSD groups by minimizing age-dependent variability. The mean LA/Ao among the controls is 0.93 ± 0.12, with a range of 0.6 to 1.12. In 32 of 33 control studies LA/Ao ≤ 1.10; the one exception being 1.12. Patients with VSD have a mean LA/Ao = 1.29 ± 0.3 and a range from 0.8 to 1.92. The difference between these two groups is highly significant (P < 0.001).

Patients with Qp/Qs ≥ 2:1 had LA/Ao ratios greater than 1.10, whereas six out of eight patients with small left-to-right shunts (Qp/Qs < 2:1) had ratios less than 1.10. The two exceptions had LA/Ao = 1.2.

The Qp/Qs is also compared to the LA/Ao ratio and LA/m² in figure 4. Though both measures of LA size demonstrate strong linear correlations with the Qp/Qs, there is considerably less scatter when the LA/Ao ratio is utilized (r = 0.96). The relationship is expressed by the equation: LA/Ao = 0.3 (Qp/Qs) + 0.59. In the absence of any left-to-right shunt (i.e., Qp/Qs = 1.0) the LA/Ao ratio predicted from the regression equation is 0.89. This compares favorably to the measured control value of 0.93 ± 0.12. The regression equation may also be expressed as: Qp/Qs = 3.3 (LA/Ao) - 1.97.

The largest Qp/Qs ratios were observed in the five patients with congestive heart failure at time of catheterization. The Qp/Qs ratios varied from 3:1 to 4:4:1 in these children. The presence of congestive heart failure, however, did not alter the linearity of the relationship between LA/Ao and Qp/Qs.

Four patients, including one with congestive cardiac failure, had elevated pulmonary vascular resistance. The increased Rp appears to have contributed to a reduction in left-to-right flow in three of the four patients with Qp/Qs from 1.7 to 2.4 since all had large defects visualized at open heart surgery. Nevertheless, the LA/Ao ratios in these four children maintained the close linear correlation with the Qp/Qs and did not appear to be adversely affected by the elevation in pulmonary vascular resistance.

**Discussion**

Cardiac catheterization has been and remains the definitive procedure for obtaining accurate hemodynamic and anatomic data in patients with congenital heart disease but is limited by the impracticality of performing frequent serial assessments. Echocardiography has the advantage of being noninvasive, simple, and devoid of any harmful sequelae. It is, therefore, ideally suited to serial evaluations in children with congenital heart disease.

Hirata et al.9 have reported an excellent correlation between the LA diameter measured by echocardiography and the size of the LA determined by cineangiography. Carter and Bowman10 subsequently showed that the echographic LA diameter divided by the body surface area was directly proportional to the volume of the left-to-right shunt in patients with isolated VSD (r = 0.87). In contrast, in children with isolated patent ductus arteriosus, Laird and Fixler4 have recently reported no relation between the LA diameter/m² and the Qp/Qs measured at cardiac catheterization. Brown et al.5 have shown a considerable variation in the diameter of the normal left atrium related to the body surface area and have found overlap between normal controls and patients with LA enlargement. Our findings in children support the data of Brown and colleagues and demonstrate the important influence of age on the size of the LA and Ao relative to body surface area. Both the LA and Ao diameters are proportionately larger in the young infant than in children older than one year of age. Thus, analysis of LA/m² throughout the pediatric age range would produce substantial variability.

In an attempt to assess LA enlargement independent of variations in patient size and age, Silverman et al.4 and Brown et al.5 have advocated the use of a ratio of the LA diameter to the Ao diameter at the level of the aortic valve. The former report an LA/Ao ratio of 0.86 in premature infants without left-to-right shunts, whereas the latter found a ratio of 0.99 in normal adult controls. It is possible that this variability in the LA/Ao ratio is due to the wide difference in patient age and size in these two groups. Indeed, the LA/Ao ratio may increase slightly with age. However, the variability may also be explained by the technique employed.
in measurement. The Ao root diameter was measured at the end of ventricular systole by Silverman and during diastole by Brown. The latter dimension is often slightly smaller than the systolic Ao width. Using the method described by Silverman, the LA/Ao ratio in our control group was 0.93 ± 0.12, which compares favorably with the two previously reported series. Utilizing the regression equation derived from our patients, the predicted LA/Ao ratio in the absence of any left-to-right shunt is 0.89. This, too, is quite compatible with the previously reported control values.

The LA/Ao ratio is helpful in distinguishing VSD patients with large shunts from those with small or hemodynamically insignificant shunts. All but one child in the control group had LA/Ao ratios ≤ 1.10, the one exception being 1.12. Similarly, patients with small left-to-right shunts had ratios below 1.10 in six of eight cases. In contrast, all children with flow ratios greater than 2:1 had LA/Ao ratios exceeding 1.10 with a mean of 1.51 ± 0.22. The aortic root diameter in only one patient (table 1, number 13) was significantly greater than previously reported controls and our own control group. The echogram from the anterior aortic wall in this boy was not a single line as is usual but rather a band of multiple echoes making precise identification difficult. The anterior edge of this band was utilized in the measurement of Ao in an attempt to maintain consistency with the other patients and controls. However, this may have resulted in the overestimation of Ao and consequent underestimation of the LA/Ao ratio. It is, therefore, important to obtain the sharpest images from all tissue interfaces in order to minimize variability due to artifact.

When the LA/Ao ratio is compared to Qp/Qs (fig. 4) there is a linear relationship with an excellent correlation ($r = 0.96$). Use of LA/m² yielded a correlation coefficient of 0.85 which is highly compatible with the coefficient of 0.87 obtained by Carter and Bowman. However, there is considerably more scatter when LA/m² is utilized compared to the LA/Ao ratio.

The presence of congestive heart failure and/or elevated pulmonary vascular resistance does not appear to alter the strong correlation between the echographic LA/Ao ratio and the Qp/Qs obtained by catheterization. Indeed, the echographic measurements in the five patients reported in this series who were in heart failure at the time of their evaluation maintained striking linearity despite Qp/Qs as high as 4.4:1. It is possible that the contribution of the elevated left ventricular end-diastolic pressure to overall LA size is negligible in the presence of torrential pulmonary blood flow due to the VSD. The four children with increased Rp also did not depart appreciably from this linear relationship. The decrease in flow resulting from the elevated Rp appears to be paralleled by a similar change in the LA diameter.

It is important to note the limitations in the calculation of Qp/Qs by the Fick method using oximetric data. This technique may not reliably detect small differences in pulmonary blood flow in patients with extremely large shunts. Conversely, the Fick method may not permit the accurate quantitation of small shunts. Despite these problems, the Fick principle is the most widely used standard technique for calculating shunts during cardiac catheterization and for this reason we have chosen it as our standard for comparison.

It must also be emphasized that the LA/Ao ratio may not be valid in predicting left-to-right shunt volume in patients with VSD complicated by other lesions. Other anomalies may alter the relationship of the LA to the Ao. It is, therefore, of critical importance to perform a complete echocardiographic examination, particularly if the echocardiogram is to be used as a screening procedure. Dilatation of the aorta produced by aortic regurgitation or systemic hypertension may result in an underestimate of the left-to-right shunt volume. Left atrial enlargement secondary to a mitral valve abnormality, e.g., mitral stenosis or endocardial cushion defect, may produce an overestimate of the Qp/Qs. It is also necessary to exclude atrial septal defects and abnormalities of the left ventricular myocardium. Finally, the use of the LA/Ao ratio presupposes a constant anatomic relationship between these two structures. Care must be taken to rule out d or l-transposition of the great vessels and double outlet right ventricle.

We have had the opportunity to perform serial echocardiographic examinations in several children over a short period of time during which left-to-right shunt volume may be presumed to have remained unchanged. Only one of these children was included in the present study since the others did not undergo cardiac catheterization at the time of their echocardiograms. The LA/Ao ratios in all were quite similar but the number of patients was too small to achieve statistical significance. We believe that echocardiography may be employed in a serial fashion in patients with isolated VSD to assess changes in the shunt volume during infancy and childhood. It may prove to be useful in identifying children in whom the Qp/Qs remains elevated from those in whom the left-to-right shunt diminishes during childhood. The pulmonary valve echo may aid in the identification of patients in whom decreased shunting is the result of elevated pulmonary vascular resistance. Such information could significantly aid in the selection of patients for cardiac catheterization and corrective surgery.

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References

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