Echographic Determination of Left Ventricular Volumes in Pediatric Patients

By Richard A. Meyer, M.D., James Stockert, Ph.D., and Samuel Kaplan, M.D.

SUMMARY
The purpose of this study was to validate the accuracy of determining left ventricular (LV) volumes by echocardiography in infants and children. Thirty-one patients between the ages of two months and 15 years underwent left ventriculography (biplane antero-posterior and lateral cine). Ventricular volumes using an ellipsoidal model were calculated for end diastole from the cineangiograms. There was a strong correlation \( (r = 0.856) \) between the echographic minor dimension (Be) and the minor lateral cine dimension (Bc) at end diastole. A similar correlation \( (r = 0.899) \) existed between the LV volume in end diastole measured by cineangiography and Be. The correlation coefficient between the echo minor dimension and the lateral minor cine dimension in end systole was 0.753.

A relation between ejection fraction (EF) and the echo minor dimension measurements in end diastole and end systole was formulated, which permitted estimation of the EF from the echo measurements. As a result of this study, it was concluded that the LV minor dimension can be measured reliably by echocardiography in children and from these measurements LV volumes, ejection fraction, and hence, stroke volume can be estimated.

Additional Indexing Words:
Minor axis dimensions  End-diastolic volume  Ejection fraction
Noninvasive techniques  Congenital heart disease

THE ABILITY TO MEASURE left ventricular (LV) volumes and the ejection fraction during the cardiac cycle permits evaluation of the function of the heart. Investigators have demonstrated in adults\(^1\)\(-\)\(^5\) that the minor dimension of the left ventricle, measured noninvasively by the use of echocardiography, correlated significantly with left ventricular volumes measured by angiographic methods. The linear regression equations obtained from adults are inappropriate for children since the adult LV dimensions are usually greater than 5 cm while those of children are usually less than 5 cm.

The purpose of this study was to demonstrate in children that the LV minor axis dimension measured by diagnostic ultrasound correlates significantly with the minor axis dimensions and volumes measured by angiography. It was further shown that the echographic measurements, when substituted into the appropriate equations, could then provide accurate estimates of LV volumes and ejection fraction.

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Methods and Materials
Echocardiograms were obtained in 31 patients between the ages of two months and 15 years, who had a variety of congenital cardiac defects and who underwent cardiac catheterization and selective angiography (table 1). The ultrasonic examinations were obtained using a Hoffrel ultrasonoscope (Model 101 and 704 EKG slow sweep module). The transducers* included a 5.0 MHz, a 3.5 MHz, and a 2.25 MHz transducer focused at 5 cm. Each had an active crystal diameter of \( \frac{3}{4} \) inch and outer diameter of \( \frac{1}{4} \) inch. With the patient in a supine position, the transducer was positioned along the left sternal border in the third to fifth intercostal space until a strong anterior mitral valve echo was recorded. From the mitral position, the transducer was rotated so that prominent endocardial echoes from the free wall of the left ventricle were recorded as well as identifiable echoes from the left ventricular septum. If the septal echoes were indistinct, placing the patient in a slight left lateral decubitus position was helpful. In order to obtain the true lateral minor dimension of the LV cavity perpendicular to the major axis, as well as to standardize the recording technique from patient to patient, the left ventricle was scanned inferiorly and superiorty along its major axis with the transducer until echoes corresponding to the structures found at position 1 (fig. 1A) were identified. In that view, echoes from portions of the anterior and posterior mitral valve were also visualized. Position 1 provided the most accurate lateral minor dimension echoes, at the maximal circumference of the left ventricle, which were then recorded on polaroid film. Left ventricular minor dimensions (Be) were measured as the distance between the left septal echo and the LV endocardial echo in end diastole (Bd) and end

* Aerotech Laboratories.
Table 1

Summary of Echocardiographic and Cineangiographic Data in 32 Patients

<table>
<thead>
<tr>
<th>Patient</th>
<th>Diagnosis</th>
<th>Age (years)</th>
<th>Echographic</th>
<th>Estimated ejection fraction</th>
<th>Angiographic</th>
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<td>Bes (cm)</td>
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<td></td>
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<td>2.0</td>
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<td>1.4</td>
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<tr>
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<td>2.2</td>
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<tr>
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<tr>
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Abbreviations: Bed = lateral minor axis dimension in end-diastole; Bes = lateral minor axis dimension in end-systole; AI = aortic insufficiency; ASD = atrial septal defect; band = band pulmonary artery band; coarct = coarctation of the thoracic aorta; MI = mitral insufficiency; PDA = patent ductus arteriosus; PH = pulmonary hypertension; PS = pulmonic stenosis; Shunt = Waterston anastomosis; TOF = tetralogy of Fallot; VSD = ventricular septal defect; C-TGA = corrected transposition of the great arteries; A-V = arterio-venous.

Several investigators have observed from angiographic studies of canine left ventricular dimensions that the minor axis dimension may actually increase during early isovolumic contraction. In our patients the bulging of the minor dimension during isovolumic contraction was manifested echographically by a posterior movement of the endocardium, which coincided with the R wave of the electrocardiogram. In order to avoid a spuriously large echo minor dimension, which would affect the estimated ventricular volume, the end-diastolic measurement on the echogram was taken at the onset of the Q wave of the ECG rather than the R wave.

The patients were premedicated with droperidol and nembutal prior to cardiac catheterization and children between one and five years of age received ketamine anesthesia. Cine angiograms were obtained in the antero-posterior (AP) and lateral projections at 60 frames per second. Left ventricular volumes were calculated by assuming an ellipsoidal configuration, using the major dimension measured directly from the AP view and the minor dimensions from both the AP and lateral projections: Volume = πAB²/6 (fig. 2). Only cardiac cycles free of arrhythmia were used for calculations. The values obtained from both the lateral and antero-posterior projections were corrected for magnification.

Results

Minor Axis Measurements by Angiocardiography and Echocardiography

The correlation between the echographic dimension in end diastole and the minor lateral cine

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dimension was strong ($r = 0.856$) and the regression formula from these data was: $Be = 1.08Bc - 0.71$ (fig. 3) (where $Be$ is $B_{echo}$ and $Bc$ is $B_{cine}$). The relatively smaller dimension obtained by ultrasound compared to the cineangiogram was attributed to the following: 1) the radioopaque dye filled the interstices of the endocardium and the ventricular outline was drawn to the limits of the visible dye, whereas the ultrasound was reflected from the peaks of the endocardium; 2) the plane of the septum generally was not perpendicular to the camera since a left anterior

**Figure 1**

A — Schematic diagram showing cardiac structures in relation to the transducer. B — Echogram corresponding to transducer position 1 showing proper echoes for measuring left ventricular dimensions. AMC = anterior mitral leaflet; $Bd = $ end-diastolic dimension; $Bs = $ end-systolic dimension; $CW = $ chest wall; $LA = $ left atrium; $LV = $ left ventricle; $LVED = $ left ventricular end-diastolic internal dimensions; $PMC = $ posterior mitral leaflet; $PPM = $ posterior papillary muscle; $RV = $ right ventricle; $RVED = $ right ventricular end-diastolic dimension.

**Figure 2**

Diagram of left ventricle in AP and lateral projection showing where cineangiographic measurements were made. To calculate left ventricular volume, the ellipsoidal model $V = \frac{\pi}{6}AB^2b$ was used. $A = $ major axis dimension; $AP = $ antero-posterior; $B = $ lateral minor dimension; $B_1 = $ $AP$ minor dimension; $Lat = $ lateral.

**Figure 3**

Comparison of the echographic and angiographic lateral minor axis dimension in end diastole. Solid line is line of identity and the dashed line is the regression line. $df = $ degrees of freedom; $r = $ correlation coefficient.
not obtained. However, the left anterior oblique projection was obtained in five patients and the echo dimension compared within 1–2 mm of the cineangiogram.

In end systole the echographic dimension and the lateral cine minor dimension correlated well in 24 patients (fig. 4), but the absolute values differed markedly. The disparity of absolute values was related to the difficulty encountered drawing an accurate left ventricular cavitary outline at end systole because of the papillary muscles and interstices. In addition, the error introduced by drawing the ventricular outline to the limits of the visible dye was exaggerated because of muscle thickening during systole. Therefore, it appeared that the ultrasound measurement was a more reliable cavitary dimension than the cine dimension.

Angiographic Volume Measurements and Echographic Minor Axis Dimensions

The correlation \( r = 0.889 \) between the LV end-diastolic volume (LVEDV) measured by cineangiography and Bed at end-diastole was strong (fig. 5). The regression formula derived from this data was LVEDV = 27.7 Becho - 42.2. Previous investigators have suggested that cubing the echo dimension improves the relationship between the echo dimension and the LVEDV. Our data did not support this view and the relationship between the echo dimension squared or cubed and the LVEDV decreased as follows: for Be\(^2\) \( r = 0.881 \) and for Be\(^3\) \( r = 0.863 \).

Correlations were not determined between the echo measurements in end systole and LV end-systolic volumes (LVESV) because of the marked disparity of absolute values between the minor axis dimension found by echo and angiogram.

The data of our echo dimensions and LV end-diastolic volumes were plotted together with the data obtained from the studies in adults performed by Pombo, Fortuin and their associates (fig. 6). From the data points the following regression equation was derived: LVEDV = \(-19.1 + 14.6B_{0} + 0.62B_{0}^3\) \( r = 0.936 \) and is a multiple correlation coefficient. This equation is shown in figure 7 along with the confidence interval for the mean (narrow band) and the prediction interval for a future observation (wider interval).\(^{15-19} \)

\(^{15} \) A regression equation can be used to predict the value for an individual future observation of the same population, i.e., an observation not included in the regression calculations. The 95% confidence interval is an interval such that the probability the interval will encompass the true mean of the population at a given X value is 95%.\(^{18} \) The 95% prediction interval is an interval such that the probability the interval will encompass any future observation at a given X value is 95%\(^{18} \) (X being the echo dimension).
LV VOLUMES BY ECHO

**End Diastole**

![Graph showing the relationship between LV volume and Be (cm).](image)

**Figure 7**

Comparison of echographic measurements and angiographic volumes in end-diastole including data points from two studies in adults (solid triangles — Pombo, open circles — Fortuin, and X's — present study). Solid line is curvilinear regression line derived from data. \( r = \text{multiple correlation coefficient} \). The relationship, which was consistent with the theoretical expectation, was observed between the calculated volumes and Be over a range of 2–8 cm for end diastole. It became apparent that a linear regression equation for any 3 cm interval of Be would provide a good estimate of volume for that interval because it represents a tangent to the cubic relationship for that interval; however, it would be unsatisfactory over a large range.

Although there was good correlation between the measured echo dimensions and volume determined by cineangiogram, variation of the left ventricular volume from patient to patient was reflected in the 95% prediction interval (the wider interval in figure 7). The variation in volumes may result from the variability of the ratio of the major and minor dimensions to the lateral minor dimension. The minor dimension on the AP projection of the angiogram in our patients averaged 12% larger than the minor dimension on the lateral projection (fig. 8, left panel).

**Discussion**

The left ventricular volume estimated from the echo dimension (Be) using the linear regression equation \( \text{LVEDV} = 27.7 \text{Be} - 42.2 \) correlated well with the volumes calculated from biplane cineangiograms over a range of 2–5 cm. However, for values of Be greater than 5 cm, the predicted volumes were less than those estimated from the angiograms. Conversely, the regression equation used in adult patients worked well for measurements of Be between 5–8 cm; but was not satisfactory for values of Be smaller than 5 cm. Since volume of the left ventricle is a function of the lateral minor axis dimension to the third power, a curvilinear relationship between volume and Be would be anticipated. This theory was further substantiated when the data points from our study and the adult studies were plotted together (fig. 6) and a curvilinear relationship between the echo dimension and the calculated ventricular volumes was observed. Therefore, the cubic regression equation \( \text{LVEDV} = -19.1 + 14.6 \text{Be} + 0.62 \text{Be}^3 \) was derived from the empirical data points on the graph (fig. 6).
In addition, the average ratio of the major dimension to the lateral minor dimension was 1.5 (fig. 8B, right panel). The data in figure 8 suggest that a constant relationship between the lateral minor dimension and the AP major and minor dimension may not exist from patient to patient. It further suggests that the left ventricle is not always circular at its maximum circumference. Ultrasound measures only the lateral minor axis of the left ventricle and not the major or other minor axis which also enters the equation for computing the volume of an ellipsoid. However, when the ratios of the major axis and the AP minor axis to the lateral minor axis remain relatively constant, then the echo dimension can be used to estimate the volume of the left ventricle. If these ratios vary from patient to patient, then some variability will exist between the calculated volumes by angiography and the measured echo dimension and thus widen the 95% prediction interval.

Analysis of the angiograms revealed similar LV configurations in patients with the same diagnosis (e.g., tetralogy of Fallot, coarctation of the aorta, ventricular septal defect, etc.). If the patient population were subdivided into similar diagnostic groups, separate regression lines for each group could be obtained and perhaps the present 95% prediction interval would be narrowed. In addition further experience should improve the prediction interval.

Ejection fraction was estimated from the echo measurements alone based on the following assumptions: 1) the left ventricle approximates an ellipsoidal configuration and 2) the left ventricle contracts symmetrically along the major axis with little shortening in the major dimension. Analysis of the biplane angiograms in our patients demonstrated that the average shortening of the major axis dimension amounted to 6%, whereas the average change in the minor axis was 21%. When the echo dimension was used to calculate the change in the minor axis dimension during systole, the average percent of shortening was 39%. Since the ultrasound beam reflects from the peaks of the endocardium and not from the valleys of the interstices, it may provide a more accurate measurement of the left ventricular internal dimension. Regardless of which technique is more accurate, the relative amount of change in the minor axis exceeded the relative change in the major axis with systole. Similar observations in human subjects have been made by other investigators using radiologic methods. It has been further shown that the percentage change in left ventricular minor axis dimensions with systole correlated significantly in a linear fashion with the percentage change of ventricular volume in systole.

Therefore, a mathematical relation for ejection fraction using only the echo measurements in end diastole and end systole was derived (see appendix). In adults, the extent of shortening in the major axis during ejection is about 20%. In our patients, the extent of shortening amounted to only 6%. Thus the mathematical relation for varying degrees of shortening in the major axis is demonstrated in figure 9. Good agreement between the equation and the ejection fraction calculated by independent observers from angiograms was demonstrated by the data in figure 9 and supports the use of the equation to determine ejection fraction echographically over a range of 4–8 cm.

![Figure 8](image-url)  
**Figure 8**  
Comparison of the angiographic lateral minor axis dimension (Lat-B cime) to the AP minor axis dimension (AP B cime) and the AP major axis dimension (AP A cime).

![Figure 9](image-url)  
**Figure 9**  
Mathematical relation of the ratio of end-systolic dimension to end-diastolic dimension. The solid lines represent changes in relationship assuming differences in percent shortening of the major axes. The data points represent the calculated ejection fractions obtained from angiographic studies in adults (solid triangles-Pombo; open circles-Fortuin).
LV VOLUMES BY ECHO

This study has demonstrated that echocardiography can reliably determine the left ventricular lateral minor dimension in children with congenital heart disease. From these measurements, a curvilinear regression equation was developed which permitted an estimation of the volume of a left ventricle having a minor dimension of 2–8 cm. In addition, a mathematical relation between ejection fraction and the echo dimensions in diastole and systole was shown. Stroke volume could then be estimated using the regression equation for the end-diastolic volume and ejection fraction. The stroke volume times heart rate provided cardiac output. Utilizing this technique, it is now possible in pediatric patients to measure non-invasively parameters of left ventricular performance directly, under basal conditions, as frequently as desired.

Acknowledgement

We thank Mr. Maurice E. Bubb, Data Analyst, Medical Computer Services, University of Cincinnati, for his invaluable assistance in analyzing our data.

Appendix

Mathematical derivation of ejection fraction.

\[ \text{LVEDV} = \pi \text{ Ad (Bed)}^3 / 6 \]
\[ \text{LVEDV} = \pi \text{ As (Bes)}^3 / 6 \]

Bed and Bes are the echo minor dimensions at end-diastole and end-systole. Ad and As are the major dimensions of the left ventricle at end-diastole and end-systole.

The stroke volume (SV), which is the difference between the above volumes, may be written as follows:

\[ \text{SV} = \frac{\pi \text{ Ad (Bed)}^3}{6} - \frac{\pi \text{ As (Bes)}^3}{6} \]

and changed algebraically to:

\[ \text{SV} = \frac{\pi \text{ Ad (Bed)}^3}{6} \left[ 1 - \frac{\text{As (Bes)}^3}{\text{Ad (Bed)}^3} \right] \]

Dividing both sides of the equation by LVEDV gives:

\[ \frac{\text{SV}}{\text{LVEDV}} = 1 - \frac{\text{As (Bes)}^3}{\text{Ad (Bed)}^3} \]

Since ejection fraction (EF) equals

\[ \frac{\text{SV}}{\text{LVEDV}} = \frac{\text{As (Bes)}}{\text{Ad (Bed)}^3} \]

Transposing the equation gives:

\[ \frac{\text{Bes}}{\text{Bed}} = \sqrt[3]{1 - \frac{\text{EF}}{\text{As}}} \]

References

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