Accuracy of Echocardiography in Assessing Left Ventricular Dimensions and Volume

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SUMMARY The accuracy of determining left ventricular function from echocardiography was assessed in 26 children (group I) with cineangiographically determined normal left ventricular function (LV) and 28 children (group II) with large left ventricular volumes. Conventional LV echo dimensions were compared to the cineangiographic LV anterior-posterior minor axis (LVmA) and LV. Very good correlations were found in group I between LV end-diastolic echo dimensions (LVEDD) and cine LVmA (r = 0.91) and between LVEDD and LV end-diastolic volume (LVEDV) by cine in group I (r = 0.86). In group II correlations were less accurate between LVEDD and diastolic LVmA and between LVEDD and LVEDV. There was poor correlation between the cine and echo percent of shortening (r = 0.41) and velocity of circumferential fiber shortening (VCF) (r = 0.51). This study demonstrates that M-mode echocardiography is a very useful method for determining LV dimensions in children with normal LV volume, but is less accurate in children with left ventricular volume overload or with abnormal septal orientation or postoperative status after ventriculotomy.

ECHOCARDIOGRAPHY provides a unique, noninvasive method to visualize internal cardiac structures in adults and children. The technique is particularly appropriate for infants and children since it causes no discomfort and can be carried out in the parents' presence, thus minimizing the patients' anxiety. Many investigators have examined the accuracy of determining left ventricular dimensions and function by echocardiography in adults, and have found good statistical relationships between echocardiographic and angiocardiographic measurements. The correlation has been less precise in children1-3 and infants.4 More recently, however, Cahill et al.5 have shown excellent correlation between LV cineangiographic and echo dimensions.

The purpose of this study was to determine: 1) the feasibility and accuracy of determining left ventricular end-diastolic and end-systolic dimensions and volumes from the echocardiogram in infants and children with normal left ventricular volumes, 2) the effect of LV volume overload and ventricular surgery on the accuracy of the echocardiographic method.

Materials and Methods

Echocardiograms and biplane cineangiograms were obtained on patients undergoing cardiac catheterization. Fifty-four patients (ages one week to 18 years) with good quality echocardiograms and cineangiograms were included in the study. Patients were grouped according to left ventricular volumes into two groups. Group I consisted of 26 patients with normal left ventricular volumes, defined as being in the range of the normal predicted volume ± 2 std (74% to 124% of normal predicted volumes).6 Group II consisted of 28 patients with left ventricular volumes greater than 124% of predicted normal volumes. Each group was further divided into two subgroups: (a) patients with normal orien-

tation of the ventricular septum and no previous ventricular surgery; (b) patients who had ventricular surgery for ventricular septal defect or tetralogy of Fallot or had lateral rotation of the ventricular septum. All groups were similar in age and body surface areas. The patients selected had a wide variety of congenital cardiac lesions; none had arrhythmias or abnormal septal motion on the echocardiogram.

All echocardiograms were obtained within 24 hours of cardiac catheterization using a Smith-Kline Ekoline 20 ultrasonoscope. Patients were examined in the supine position utilizing transducers with frequencies of 2.25 MHz (½ inch diameter), 3.5 MHz (½ inch diameter) or 5 MHz (¾ inch diameter). The transducer was placed in the third or fourth intercostal space perpendicular to the chest wall at the left sternal border with the beam directed posteriorly in order to obtain the mitral valve echogram. From the same position, the transducer was rotated to scan cardiac structure from the left atrium to the left ventricle. The transition area (A-V groove) can be determined by the motion of the left atrium which moves posteriorly in ventricular systole and anteriorly in mid and late ventricular diastole, while the ventricular wall moves anteriorly in ventricular systole.

The left ventricular echocardiographic dimensions were measured from the endocardial echo of the posterior LV wall to the endocardial echo of the left side of the interventricular septum at the level of the chordae tendineae (fig. 1), and at the level of the posterior mitral leaflet. Echocardiograms were recorded on a strip chart recorder at a paper speed of 100 mm/sec. End-diastolic dimensions were measured at the onset of the QRS (LVEDD), and end-systolic dimensions at the point of maximum systolic excursion of the left ventricular posterior wall (LVESD).

In 29 patients the heart rates during the cineangiogram and echo were comparable (less than 15 beats/minute variation). The percent shortening in left ventricular cine and echo dimensions was calculated in all patients by the equation:

\[
\text{% shortening} = \frac{\text{LVEDD} - \text{LVESD}}{\text{LVEDD}} \times 100
\]

The ejection time was determined from aortic pressure recording which represents the time from the beginning of
the aortic upstroke to the dicrotic notch. The ejection time on the echocardiogram was measured from the opening to the closure of the aortic valve from the echo of the aortic root. The velocity of circumferential fiber shortening (VCF) was calculated in 20 of the 29 patients who had identical (difference less than 5%) cineangiographic and echocardiographic ejection times by the equation:

\[
VCF = \frac{LVEDD - LVESD}{LVEDD \times \text{ejection time}} \text{ Sec}^{-1}
\]

All left ventricular volume data were obtained from biplane cineangiograms filmed during diagnostic cardiac catheterization. Patients over 6 months of age were sedated with meperidine (1 mg/kg), chlorpromazine (0.5 mg/kg/day) and promethazine (0.5 mg/kg). Biplane cineangiograms were filmed at 60 frames per second in the posterior-anterior and lateral projections following the injection of 1.0 to 1.25 ml per kg body weight of Renografin 76 into the right ventricle, main pulmonary artery or left ventricle. All ectopic beats were excluded. The anteroposterior and lateral cine projections of the left ventricle were drawn and all results were corrected for linear magnification. Left ventricular volumes were calculated at end-diastole (LVEDV) and end-systole (LVESV) according to the area-length method of Dodge et al. The left ventricular minor dimension (LVmA) was calculated using the left ventricular area and longest length from the lateral projections. The LVmA was also measured at the mid-equator of the ventricle. Normal predicted LV volumes were calculated for each patient based on height, weight and age. In ten patients (five with normal LV volume and five with LV volume overload) the LVmA was calculated in the lateral and left anterior oblique views.

**Results**

The diagnoses, ages, and body surface areas as well as the cineangiographic and echocardiographic data of all patients are shown in tables 1 and 2.

In 43 patients, LV echo dimensions could be recorded at the posterior mitral leaflet and the chordae. In these patients there was no difference between the two dimensions (fig. 2). Table 3 shows the average LV echo dimension measured at the mitral valve or at the chordae with the standard deviation (SD) and standard error of the mean (SEM). The mean end-diastolic dimension measured at the mitral valve in both groups was not different from the mean end-diastolic dimension measured at the chordae. End-systolic dimension measured at the chordae averaged 91% (group 1) and 90% (group II) of end-systolic dimension measured at the chordae. The difference between the two values was not significant. The diastolic mitral dimension/chordal dimension ratios in the two groups were: group I = 1.01 ± 0.02 (SEM); group II = 1.02 ± 0.02. The systolic ratios of these dimension were: group I = 1.11 ± 0.04; group II = 1.14 ± 0.04, and there was no difference between subgroup a and b in each group. The slightly higher ratio at end systole might be due to the fact that the shortening of the ventricular fibers at the mitral valve is less than the shortening of the fibers at the equator of the ventricle or that the echo measurement at the mitral valve is more reliable for determining the systolic LV dimension. When patients were divided by age, however, we found that only the dimension at the posterior mitral leaflet could be recorded in six of 14 infants. Therefore the echo dimensions used were measured at the chordae in all but six infants, and at the posterior mitral leaflet in 43 patients. In the following discussion echo dimension will refer to the dimension obtained at the chordal level.

In all patients except one (patient 20 in group II), left ventricular echo dimensions underestimated the cine LV minor axis (figs. 3, 4). The relationship between echo LVEDD and cine minor axis in subgroup Ia was similar to subgroup Ib, \( r = 0.91 \) (fig. 3). In subgroup IIb, however, echo LVEDD further underestimated the LVmA as compared with Ila (fig. 4), and the \( r \) values in subgroups Ila and IIb were 0.74 and 0.70, respectively.

At end systole, the echo dimensions more consistently underestimated the cine dimensions and the correlation coefficient was worse than at end diastole (figs. 3, 4). The results were similar between subgroup Ia \( (r = 0.80) \) and subgroup Ib \( (r = 0.71); \) fig. 3. The difference was more variable in patients with large LV volume (fig. 4). The echo-cine dimension relationship in Ila \( (r = 0.60) \) was different from IIb \( (r = 0.58) \).

The relationship between LV echo dimension measured at the mitral valve and cine LVmA is shown in figures 5 and 6. In group I LV echo dimension underestimated LV cine dimension in all but one patient at end diastole \( (r = 0.89) \) and in all but three patients at end systole \( (r = 0.70), \) fig. 5. The echo dimension at the mitral valve in group II also underestimated cine LV minor axis at end diastole \( (r = 0.64) \) and at end systole \( (r = 0.66) \). The relationship between the
echo dimension and cine dimension at end systole and end diastole for the mitral valve dimension was similar to the relationship for the chordae dimension in the different subgroups.

Different mathematical models (linear, exponential and polynomial) were used to determine the best method for assessing LV volume from the LV echo dimension. The best models are presented below and shown in figures 7 and 8.

The relationship between echo LV end-diastolic dimension and left ventricular end-diastolic volume was very good for patients in group I ($r = 0.93$). This relationship was similar in subgroups Ia and Ib (fig. 7). The relationship for patients in group II was less precise and cannot be used for predicting end-diastolic volume. Patients in subgroup Ib ($r = 0.60$) tended to have larger EDV for the same LV echo dimensions compared with patients in IIa ($r = 0.76$, fig. 7).

### Table 1. Summary of Cineangiographic and Echocardiographic Data: Group I - Normal LV Volumes

<table>
<thead>
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<th>Patient No</th>
<th>Age (yr)</th>
<th>BSA (m²)</th>
<th>Diagnosis</th>
<th>Systolic LVVMA (cm)</th>
<th>Diastolic LVVMA (cm)</th>
<th>LV Volume % predicted</th>
<th>HR</th>
<th>LVEDD (cm)</th>
<th>LVESD (cm)</th>
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### Table 2. Summary of Cineangiographic and Echocardiographic Data: Group II - Large LV Volumes

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<th>LV Volume % predicted</th>
<th>HR</th>
<th>LVEDD (cm)</th>
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Mean 5.51 ±0.79

| Mean 5.51±0.79 |

**Abbreviations:** Abn. PV = abnormal pulmonary valve; AR = aortic regurgitation; ASD = atrial septal defect; BAV = bicuspid aortic valve; BSA = body surface area; Coarse = coarctation of the thoracic aorta; CHF = congestive heart failure; DORV = double outlet right ventricle; EDV = left ventricular end-diastolic volume; LV = left ventricular; LVESD = left ventricular end-systolic dimension; LV echo = left ventricular echo; LVVMA = left ventricular volume; MS = mitral stenosis; PAPVR = partial anomalous pulmonary venous return; PS = pulmonary stenosis; TGA = transposition of the great arteries; TOF = tetralogy of Fallot; TR = tricuspid regurgitation; VSD = ventricular septal defect.
Figure 8 shows the relationship between LV end-systolic dimensions by echo and LV end-systolic volumes calculated from cine. In group I, there was no difference between subgroups Ia and Ib ($r = 0.87$). There was a much greater scatter of points for patients in group II compared with group I. In group II, LVESV was significantly larger for a given LV echo dimension in subgroup IIb ($r = 0.67$) as compared to Ila ($r = 0.64$).

There was poor correlation ($r = 0.41$) between the echocardiographic and cineangiographic determinations of % LV shortening in the 29 patients with comparable heart rates at the time of cine and echo. In each group, the difference in heart rate had no effect on the % of shortening by cine vs echo. Figures 9 and 10 show the relationship between the % of shortening by echo and cine. The correlation was poor in all subgroups ($r = 0.29$ to 0.48). The correlation between the calculated VCF by cine and by echo in the 20 patients with comparable heart rates and ejection times was also poor ($r = 0.51$).

### Discussion

Since echocardiography is a noninvasive technique with which to measure ventricular dimensions, many investigators$^4$-$^7$-$^{14}$ have attempted to determine the accuracy of this technique in determining ventricular function. The results of these studies have shown considerable variation between the echocardiographic and cineangiographic LV dimensions.

The variability in the correlation reported by previous investigators could be related in part to the selection of patient groups and in part to the technique of echocardiography. Since the usefulness of the method depends on its accuracy in patients of different ages and with different hemodynamics, in this study we included 54 consecutively studied patients with normal LV volume or LV volume overload. In each group the patients who had previous ventricular surgery or abnormal ventricular septal orientation (severe anterior or posterior rotation of the plane of the ventricular septum on cineangiogram) were analyzed
separately to determine the effect of these variables on the echo-cine dimension relationship. All patients with an arrhythmia or abnormal motion of the ventricular septum were excluded from the study. To insure objectivity in this study, the echocardiographic measurements were made by investigators independently from those who determined LV cineangiographic dimensions. Thus, the study provides an objective evaluation of single beam echocardiography as a tool for determining LV dimension in children with normal or increased LV volume.

In group I, the correlation between LV echo dimension and LV lateral cine dimensions was good and there was no difference between subgroups Ia and Ib. This indicates that end-diastolic dimensions can be determined accurately in children with normal LV volume. This relationship at end systole was less predictable and the variations in LV end-systolic echo dimension were more marked. In group II the echo LVEDD in patients with previous ventricular surgery (IIb, fig. 4) was relatively smaller than echo LVEDD in patients with no previous surgery for the same LVmA. These findings indicate that the standard echo technique for determining LV dimension is not reliable in patients with volume overload, and is affected by previous ventricular surgery or rotation in the ventricular septum. Goldberg and coworkers suggested that the LV echo dimension passing the posterior mitral leaflet might better represent the true LV dimension. The correlation between LV echo dimension at the posterior mitral leaflet with the dimension at the chordae
The lines represent the best fitting equations shown at the top of the figure.

Figure 7. Left ventricular end-diastolic volume as a function of LV chordal echo end-diastolic dimension (LV EDD) in groups I and II. The lines represent the best fitting equations shown at the top of the figure.

was similar in all patients above two years of age, and in eight of 14 patients less than two years of age. In the remaining six infants echo LV dimension could only be measured at the posterior mitral leaflet. The data showed that left ventricular echo dimension at the chordae was equal to LV echo dimension measured at the mitral valve in end diastole but less at end systole (table 1, fig. 2). Although the difference was not significant, the small difference at end systole suggests that the dimension at the mitral valve might more accurately reflect the true LV end-systolic dimension for the following reasons: 1) measurement made at the mitral valve assures one of the relatively fixed position in the short as well as the long axis of the left ventricle; 2) the persistence of the mitral valve echo in diastole and systole gives some reassurance that the ventricle has not moved very much, or at least that the mitral valve rotation or shift out of plane of the echo beam is minimal; 3) the mitral valve echoes are more easily separated from the echocardium than the chordal echoes.

One important finding in this study is the underestimation of the LV minor axis by echo as compared with cine. Meyer suggested that this difference is due to the fact that the angiographic dimension is measured to the visible dye which includes the trabeculation and the papillary muscles while the echo includes only the distance from the endocardial surface. Indeed the cine minor axis includes the trabeculation and could be larger than the echo dimension. Another possible explanation is that the lateral cine minor axis is larger than the more oblique echo axis. In a previous study we have shown that the lateral minor axis is shorter than the LV minor axis in the anterior-posterior view. Furthermore, the lateral LV minor axis was compared with the left anterior oblique axis (which approximates the echo axis) in ten patients (fig. 11). The lateral LVmA was equal to the left anterior oblique axis in these patients. The fact that the LV echo dimension underestimated the lateral cine dimension suggests that the echo beam does not intercept the ideal LV dimension, but a smaller LV dimension.

In group II, the error in measuring echo LV end-diastolic dimension is relatively large, i.e., for a given cine minor axis, the echo dimension varied by more than 100% and on the average underestimated the cine dimension by 39% (fig. 4). The LV in these patients is more spherical than patients in group I, and the LV dimension at the equator is larger than the dimension at the base which approximates the echo dimension at the mitral valve. The fact that the end-diastolic echo dimension measured at the mitral valve was equal to the echo dimension measured at the chordae (table 1), points to the difficulty of transecting the minor axis at the center of the heart (the point where the minor axis intersects the major axis). Indeed the technique could be in error but the data

Figure 8. Left ventricular end-systolic volume as a function of LV chordal echo end-systolic dimension (LV ESd) in groups I and II. The lines represent the best fitting equations shown at the top of the figure.

Figure 9. Comparison of percentage of shortening of chordal echo dimension and LV cine minor axis.
presented here were obtained using the same methods described by other investigators.1,3

Interestingly, the relationship between echo and angiographic LV dimensions in adults seems to be related to the geometry and the size of the ventricle.6,8,12,14,16,20 The discrepancies between echo and cine dimensions in children with large LV volumes may be due to changes in LV geometry in children with LV volume overload,18 or to a rotation of the ventricular septum and the difficulty in obtaining a true LV minor axis perpendicular to the ventricular septum.

In an attempt to predict LV volume from LV echo dimension, we used different mathematical models and selected the most accurate model (figs. 7 and 8). The data indicate that determining LV end-diastolic volume from the LV echo dimensions is very reliable in children with normal volume at end diastole (fig. 7) but is not accurate in patients with volume overload (fig. 7) or at end systole (fig. 8). This finding is expected, because a small variation in LV echo dimensions is exaggerated when compared with LV volume.

Lack of closer correlation in systole between the two methods suggests that other variables may affect the accuracy of echocardiographic dimensions. Measurements by cine and by echo were not made simultaneously, so that any alteration in the left ventricular volume caused by a change in the heart rate or sympathetic tone between determinations could appear as an error in the echo determinations. In adults the correlation between heart rates during cine and echo was poor (Pombo et al.,7 r = 0.38, Belenkie et al.,8 r = 0.26 and Feigenbaum et al.,17 r = 0.51); yet these studies showed very good correlation between LV cine and echo dimensions. In the study by ten Cate et al.,18 the correlation of heart rate during cine and echo was similar to ours (r = 0.79) and their echo-cine volume correlation was excellent. Recently Gutgesell et al.21 have shown that the percent change in LV diameter was independent of heart rate. To examine the effect of heart rate, we divided groups I and II into two subgroups: a, when the difference between echo and cine heart rate was less than 15 beats per minute, and b, when the difference was more than 15 beats per minute. In group I differences in heart rates had no effect on the correlation of echo dimensions with cine volumes both in systole and in diastole (r = 0.90). In group II the correlation of echo dimensions with cine volumes was poor whether the difference in heart rate was less or more than 15 beats per minute (r = 0.44 in diastole and 0.45 in systole). Thus it seems that the heart rate does not play a significant role in explaining the disparity of LV dimensions by cine and echo and does not account for the difference in correlation in group II compared to group I.

Another contributing factor for the lack of closer correlation between echo and cine systolic dimensions might be a change in left ventricular spatial orientation from diastole to systole. This was examined in our patients by drawing left ventricular images in diastole and systole. Figure 12 shows the diastolic and systolic images of left ventricular cine in the anteroposterior and lateral views. Fixed points on the image of the spine were used as reference points. The intersect of the longest axis and minor axis in diastole was used as reference point A. The intersect of the longest length and the minor axis in systole was noted as point B. The angle between the diastolic and systolic minor axis was measured (fig. 13). The distance (reflected on X, Y, and Z axes) between A and B was also measured and was represented as percent of the diastolic minor axis (fig. 14). The X axis represents the right-left relationship (positive being toward the right): Y axis represents the superior-inferior
relationship (positive being superior); and Z axis represents the anteroposterior relationship (positive being anterior) (fig. 12).

The angular rotation of the minor axis from end-diastole (O) to end-systole (X) varied from 0° to 26° in the AP view and from 0° to 48° in the lateral view (fig. 13).

Figure 14 shows the relative displacement of the center of the left ventricle from diastole to systole expressed as a percent of the left ventricular diastolic minor axis. There was marked variability in left ventricular spatial orientation resulting from ventricular contractions.

In the AP view the lateral displacement (on the X axis) of the center of the heart ranged from zero to 0.9 cm (mean 0.3 ± 0.2 cm) in group I and from zero to 0.8 (mean 0.2 ± 0.16 cm) in group II. In the lateral view the displacement on the Z axis averaged 0.43 ± 0.30 cm in group I and 0.4 ± 0.2 cm in group II. A lateral displacement in the AP view on the X axis (right to left as shown in fig. 12) or upward movement on the Y axis will have more effect on the echo dimension (anterior-posterior along the Z axis). In our patients the average displacement along the X and Y axis in groups I and II was approximately 10% which gives an average error of 7% in end-systolic echo dimension for the X axis and similar error for the Y axis. Combining the two errors (0.93°) results in a dimension equal to 87% of the true dimension. It is interesting to note that end-systolic echo dimension measured at the chordae averaged 90% of the dimension measured at the mitral valve. This finding indicates that the error is probably minimized when one is obtaining echo dimension at the mitral valve.

The shape of normal sized left ventricle is prolate ellipsoid, and becomes more spherical as it dilates. Recently Johnson et al. have shown very poor correlation between echo and angio measurements of LV dimensions in adult patients with severe aortic insufficiency. This poor correlation was explained on the basis of altered geometry of the left ventricle caused by severe aortic insufficiency. The method of determining volumes by cubing the echo dimension is based upon the assumption that the long axis (LA) is equivalent to twice the angiographically measured minor axis (D). Teichholz et al., however, have recently shown that as the shape of the left ventricle varied with heart size, the LA/D ratios ranged from 1.2:1 to 3.2:1. Villoria et al. also showed that the LVM/A is more than one-half of the longest axis in patients with LV volume overload, but was approximately equal to one-half of the LA in patients with LV pressure overload. Meyer et al. also showed that using D3 was inappropriate in younger patients for reasons discussed above. Therefore, volume measurements based on D3 would underestimate the small ventricle and overestimate the large ventricle. In the present study we have clearly shown that the correlation of LV dimensions by echo and cine in patients with normal LV volumes is significantly better than the correlation in patients with large LV volumes. On the lateral cines of our patients, the minor axis was equal to 0.58 ± 0.17 of the long axis in patients with normal LV volume and 0.64 ± 0.02 in patients with large LV volumes. Furthermore, the AP minor axis was always larger than the lateral axis. The variation in ventricular geometry makes it impossible to determine ventricular volume from one minor axis without advance knowledge of the shape of the ventricle.

Kaye et al. have shown good correlation of mean veloc-
ity of circumferential fiber shortening of LV dimension by echo and by cine in children. In the present study we compared the percent of shortening in the minor axis by echo and cine in patients with comparable heart rates. The poor correlation was due to the error in determining LV end-systolic dimension by echo. Furthermore, the calculation of VCF also showed poor correlation as anticipated.

In summary, although echo dimensions by single crystal transducer tend to underestimate true LV dimension, LV end-diastolic volume can be determined from echo dimension. The most reliable relation is in patients with normal LV volumes. LVESV echo dimension has no consistent relation to true LV systolic diameter. Significant errors, therefore, can be introduced in determinations of LVESV, stroke volume, ejection fraction, percent shortening and VCF. The discrepancy in systolic parameters by echo as compared to cine may be due to configurational changes in the LV and to changes in the spatial orientation of LV from diastole to systole relative to the echo beam. The changes due to spatial orientation could be minimized when measuring the echo dimension at the mitral valve. Single beam echocardiography, however, is perhaps more useful in following LV volume changes in the same patient. It can be anticipated that two-dimensional echocardiography will offer a more accurate method for determining ventricular dimension and volume.

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