Left Ventricular Volume from Paired Biplane Two-dimensional Echocardiography

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SUMMARY To evaluate the applicability of two-dimensional echocardiography to left ventricular volume determination, 30 consecutive patients undergoing biplane left ventricular cineangiography were studied with a wide-angle (84°), phased-array, two-dimensional echocardiographic system. Two echographic projections were used to obtain paired, biplane, tomographic images of the left ventricle. We used the short-axis view (from the precordial window) as an analog of the left anterior oblique angiogram, and the long-axis, two-chamber view (from the apex impulse window) as a right anterior oblique angiographic equivalent.

A modified Simpson’s rule formula was used to calculate systolic and diastolic left ventricular volumes from the biplane echocardiogram and the biplane angiogram. These methods correlated well for ejection fraction (r = 0.87) and systolic volume (r = 0.90), but only modestly for diastolic volume (r = 0.80). These correlations are noteworthy because 65% of the patients had significant segmental wall motion abnormalities. The volumes determined from the minor-axis dimensions of M-mode echograms in 23 of the same patients correlated poorly with angiography.

BIPLANE CONTRAST ventriculography is a standard method of obtaining left ventricular images from which volumes can be determined. This method retains its accuracy in the presence of geometric distortion related to regional contraction abnormalities. M-mode echocardiography is an accurate, noninvasive method of estimating left ventricular volume, but its reliability is considerably compromised by segmental dysfunction. Preliminary reports of experience with electrocardiographically triggered B-mode echocardiographic scanning techniques indicate that this single-plane, two-dimensional approach has a distinct advantage over the M-mode for calculating area ejection fractions. Gehrke used this technique to obtain volumes and ejection fractions in a group of 20 patients. The correlations with single-plane angiography were good, but the study included only two patients with coronary disease. The advantage of this technique over M-mode techniques of estimating volume was, therefore, not demonstrated. Furthermore, the technique for obtaining images by this method is tedious and the quality of published images marginal.

The development of an electronically phased, two-dimensional echocardiograph with a wide (84°) scanning angle and a small (2.5 cm²) transducer enabled us to obtain orthogonal biplane images noninvasively that are in some respects analogous to angiographic projections. Our method used both the precordial and the apex impulse location as imaging windows. The investigation that forms the basis of this report tested the capability of these biplane echographic left ventricular images to approximate biplane cineangiographic volume information in a group of patients in whom wall motion abnormalities were common.

Methods and Patients

In this prospective study, we examined 42 consecutive patients (table 1) studied by biplane, two-dimensional, sector scan echocardiography in whom biplane cineangiography was also performed. Of the 42 patients, 30 had satisfactory studies with both techniques. In four of six patients, the echogram was discarded because of inadequate images, and in two because of defective video tape. The angiograms were unsuitable for analysis in four of six patients because of inadequate opacification of the left ventricle, and in two because of ectopic beats.

All patients in this study had M-mode echocardiograms. In the 30 with adequate two-dimensional echograms, 24 were studied by commercially available equipment using standard methods for imaging the left ventricle in the minor axis. The remaining six were studied using the M-mode capabilities of the two-dimensional scanner. One study done using standard equipment was technically inadequate due to uncertainty about the identity of the minor axis. All studies
done using the M-mode incorporated with the two-dimensional scanner were eliminated due to poor visualization of the endocardium. Thus, only 23 M-mode echograms were analyzed. In these, the end-diastolic and end-systolic minor-axis dimensions were obtained and the volumes calculated according to a regression formula.4

We studied 30 patients, ages 23-73 years; 17 were male. Twenty-one patients had coronary disease, six had valvular disease, two had atrial septal defect and one was normal (table 1). Of the 21 patients with coronary disease, 16 had one or more areas of segmental wall motion abnormality. Both patients with atrial septal defects had paradoxical septal motion on M-mode echocardiography.

Patients were studied with a clinical prototype of a two-dimensional sector scanner commercially developed for cardiac use by Varian Associates, Palo Alto, California, and placed in our laboratory for clinical evaluation. The unit’s hand-held transducer face measured 2.5 cm² and had 32 elements excited as a phased array. The display consisted of 64 lines that radiated from a point source on a cathode ray oscilloscope screen, on which the images appeared in real-time at 30 frames/sec, with 1-cm calibration marks in two axes superimposed.

Recordings were made in two orientations in order to approximate orthogonal angiographic images. In the first, the beam passes through the left ventricular minor axis at right angles to the long axis of the heart (figs. 1 and 2). In normally oriented hearts, the beam runs from the right hip to the left shoulder. This projection is known as the transverse or short-axis view and was used as a left anterior oblique (LAO) equivalent. As shown, the septum and inferior walls are to the viewer’s left and the anterior and lateral walls to the viewer’s right. Identification of the right ventricle helped to define the septum, and visualization of the contiguous left lobe of the liver and diaphragm was often helpful in localizing the inferior wall. In order to come close to a reproducible, true, minor axis, we always tried to image the left ventricle at the level where the tip of the papillary muscles is separated from the wall. This point is just apical to the point where mitral motion ceases.

Table 1. Details of the Patient Population

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>No. of Patients</th>
</tr>
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<tbody>
<tr>
<td>Total patients studied</td>
<td>42</td>
</tr>
<tr>
<td>Satisfactory echo and angiogram</td>
<td>30/42</td>
</tr>
<tr>
<td>Echoes eliminated</td>
<td></td>
</tr>
<tr>
<td>Poor image</td>
<td>4/6</td>
</tr>
<tr>
<td>Tape defect</td>
<td>2/6</td>
</tr>
<tr>
<td>Angiograms eliminated</td>
<td></td>
</tr>
<tr>
<td>Inadequate contrast</td>
<td>4/6</td>
</tr>
<tr>
<td>Ectopy</td>
<td>2/6</td>
</tr>
<tr>
<td>Sex distribution</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>17/30</td>
</tr>
<tr>
<td>Female</td>
<td>13/30</td>
</tr>
</tbody>
</table>

Abbreviation: ASD = atrial septal defect.
The second view used in this study (figs. 3 and 4) was obtained by placing the transducer on the apex impulse location and aiming the beam toward the left atrium. The beam plane is parallel to and below the level of the interventricular septum and that structure is, therefore, excluded from this projection. This long-axis view is called the two-chamber apical view and was used as an analogue to the right anterior oblique (RAO) angiogram. It served as a long-axis view, orthogonal to the short axis. By our convention, the patient's left is on the viewer's right. The image is displayed with the apex at the top of the screen, the anterior wall to the viewer's right, the inferior wall to the viewer's left, and the left atrium and mitral valve at the bottom right. Before recording these images on tape, we always attempted to exclude the right ventricle and septum from this view and to maximize the size of the left ventricle by rocking the transducer in an anterior-to-posterior arc. At times, there was end-diastolic endocardial dropout as the maximum tomographic plane was achieved, necessitating the use of a slightly submaximal tomographic view. In obtaining this view, the anterolateral wall was the most difficult to image. This difficulty was usually overcome by careful transducer and gain manipulations or by slight changes in the elevation and pitch of the patient's trunk.

After the images were recorded on video tape, they were traced with a wax pencil on exposed x-ray film affixed to the face of a television monitor. During this tracing, care was taken to maintain constant head position to avoid parallax error, which was introduced by the displacement of the cathode ray tube back from the glass covering its face. Using the stop-frame mode of the tape recorder, and with reference to the simultaneous ECG, end-diastolic (peak of R wave) and end-systolic (end of T wave) frames from each of the projections were chosen. The end of the T-wave was chosen because of its concurrence with the aortic component of the second heart sound and because our video tape recorders could not be played in reverse; once the end-systolic frame was traced, the tape was slowly advanced to insure that the tracing was made at the smallest systolic volume and before the opening of the mitral valve. Since the television field rate is faster (60 frames/sec), the endocardium on a still frame is more difficult to see in the stop-frame mode than in real-time. The loss of visual integration imparted by motion also contributes to this difficulty. In tracing the echograms and the angiograms, the minor irregularities of the ventricular surface were ignored. The papillary muscles were excluded from the outline tracings, in accordance with common practice. Thus, the circular, elliptical or irregular outline was continued when a papillary muscle was encountered. A papillary muscle was recognized as either an angiographic filling defect or an echographic incropping of the wall. The designation of such a structure as

Figure 2. Upper left) Diagrammatic view of the beam plane for imaging the left ventricular short axis. Lower left) Diagrammatic representation of short-axis echograms at right. Upper right) Diastolic frame of short-axis echograph recorded on Polaroid film. Lower right) Systolic frame of same beat. A = anterior; D = diastole; L = left; LV = left ventricle; P = posterior; R = right; RV = right ventricle; S = systole; Sept = interventricular septum.
Transducer position and beam plane used to image the ventricle in the two-chamber, long-axis, apical view. LA = left atrium; LV = left ventricle; IW = inferior wall; A-LW = anterolateral wall.

Papillary muscle was made by careful observation of the real-time image. The same person traced all the echograms without knowledge of the angiograms. Another person retraced nine echograms randomly selected from the 30. Each of these was retraced four times. Two additional persons digitized the echograms and the angiograms.

Angiographic and two-dimensional tracings were manually digitized by a desktop computer (Hewlett-Packard 9820A) that was programmed to calculate left ventricular volume according to the method of Goerke and Carlsson,8,9 in which computations are based on a modification of Simpson’s rule. The two orthogonal projections are oriented along a common axis and ventricular outlines are traced with the digitizer. Each projection is divided into 20 sections along the common axis and the volume is calculated according to the formula:

\[ V = \frac{F}{4} \sum_{i=1}^{20} a_ib_i \]

where \( F \) is the total magnification factor calculated according to \( F = f_1f_2(f_1 + f_2)/2 \), \( f_1 \) and \( f_2 \) are the enlargement factors calculated for the two projections from the geometry of the recordings, and \( a_i \) and \( b_i \) are the axes of the \( i^{th} \) elliptical cut. For angiograms, the fac-
tors $f_1$ and $f_2$ are determined by the program from calculated orthogonal view area centroids, marked beam centers and measured tube-to-image distances. When the echoes are digitized, $f_1$ and $f_2$ are taken equal to 1, as there is no magnification involved in the method. Simultaneous plotting of the ventricular outlines with numeric readouts of the volumes and ejection fraction constitutes the output of the computer.

This algorithm assumes that it will be presented with two orthogonal long axes. However, in using the RAO and LAO angiographic views, the second long axis (the LAO) is most often foreshortened. In order to assess the impact of this foreshortening, we obtained radiographs of radiopaque casts of a variety of left ventricles. These casts were imaged in the RAO and LAO projections and the volumes calculated with our desktop digitizer-computer. The correlation coefficient between the calculated volume and the water-displacement volume of these casts was greater than $r = 0.95$. In spite of a wide variety of ventricular shapes and sizes, there were no outlying points. Foreshortening required systematically correcting calculated volumes by multiplying by a factor of 1.23. In applying this algorithm to our paired echocographic images, the condition of the algorithm that assumes common long axes is also not met. However, since the angiographic correlations are reliable after applying a correction factor, we used the same algorithm for analyzing the echograms because these are always the same in relationship to the heart and thus more reproducible in relationship to the cardiac axes than the angiogram.

Figure 5 shows the outlines of a computer-generated echogram and angiogram from the same patient. The discrepancy in size is mainly due to magnification of the x-ray (see Discussion). Data obtained from analysis of the 30 patients were evaluated statistically by linear regression analysis of paired volume data. Systolic and diastolic volumes were analyzed separately. In addition to the calculation of correlation coefficients, the standard error of the estimate was derived and the 95% confidence limits were plotted with each set of data.

### Results

#### End-diastolic Left Ventricular Volume

The correlation coefficient ($r$) between biplane echocardiographic left ventricular end-diastolic volume and biplane echocardiographic end-diastolic volume in 30 patients was 0.80. The relationship between the echographically derived data and the angiographic data is described by the linear regression equation:

$$\text{EDV}_{\text{echo}} = 0.7 \text{ EDV}_{\text{angio}} - 1$$

where $\text{EDV} =$ end-diastolic volume. The standard error of the estimate is 15 ml/m². The mean value for angiographic end-diastolic volumes was 70.7 ml/m², and 50.4 ml/m² for the echographic end-diastolic volumes. Thus, in these 30 patients, the echographic determination of end-diastolic volume underestimated the angiographic value by 30%. Figure 6 is a plot of these data. The outer lines are the 95% confidence limits of the data.

#### End-systolic Left Ventricular Volume

The correlation coefficient ($r$) between biplane echocardiographic left ventricular end-systolic volume and biplane angiographic end-systolic volume in 30 patients was 0.90. The relationship between the echographically derived data and the angiographic data is described by the linear regression equation:

$$\text{ESV}_{\text{echo}} = 0.7 \text{ ESV}_{\text{angio}} - 2$$

where $\text{ESV} =$ end-systolic volume. The standard error of the estimate is 8.5 ml/m². The mean value for the angiographic end-systolic volume was 33.8 ml/m², and 22.8 ml/m² for the echographic end-systolic volume. Thus, in these 30 patients, the echographically determined end-systolic volume underestimated the angiographic value by 33%. Figure 7 is a plot of these data. The outer lines on the graph are the 95% confidence limits of the data.

#### Left Ventricular Ejection Fraction

The correlation between ejection fraction calculated from the biplane echocardiographic end-systolic and end-diastolic volumes and that calculated from angiographic data in the 30 patients was good ($r = 0.87$). The relationship between the echographically and angiographically derived ejection...
FIGURE 6. Biplane angiographic (ANGIO) end-diastolic volumes are plotted against biplane echographic end-diastolic volume (EDV_{echo}) in 30 patients. Outer lines are the 95% confidence limits of the data. The standard error of the estimate is given at the end of the equation.

fractions is described by the linear regression equation:

$$\text{EF}_{\text{echo}} = \text{EF}_{\text{angio}} + 5$$

where \(\text{EF}\) = ejection fraction. The standard error of the estimate is 7.6%. The mean angiographic ejection fraction was 54.4%, and the mean echographic ejection fraction was 59.8%. Thus, in these 30 patients, there was a 10% overestimation of ejection fraction by the echographic technique. Figure 8 is a plot of these data. The outer lines on the graph are the 95% confidence limits of the data.

FIGURE 7. Biplane angiographic (ANGIO) end-systolic volume plotted against biplane echographic end-systolic volume (ESV_{echo}) in 30 patients. Outer lines are the 95% confidence limits of the data.
Interobserver and Intraobserver Variation

Regression analysis of the echographic volume data calculated by two observers yielded correlation coefficients for end-diastole, end-systole and ejection fraction of 0.82, 0.95 and 0.95, respectively. The measurements from the same observer varied ± 4%.

M-mode vs Angiography (table 2, fig. 9)

Volume data derived from the M-mode records in 23 patients were compared with their angiographic data by linear regression analysis. Correlation coefficients for end-diastolic and end-systolic volume and ejection fraction were 0.49, 0.56 and 0.64, respectively.

Discussion

We used a paired biplane echocardiographic technique to show that in a population where segmental wall motion abnormalities were prevalent, quantitative left ventricular volume information comparable in some respects to biplane angiographic data could be obtained noninvasively. The long-axis view used in this study was obtained from a new approach that uses the apex impulse location as an echographic window. In addition to providing a long-axis image, this view is unique in that it allows visualization of the anterolateral and inferior left ventricular walls, which are not usually seen by M-mode echocardiography. This apical view is analogous to the angiographic RAO projection, and, when combined with the short-axis view that served as an analogue to the LAO angiographic projection, provides paired, orthogonal, biplane images of the left ventricle.

One of the most important features of this study is that it was conducted using a population of patients with significant wall motion abnormalities (16 of 30 from myocardial infarction and two of 20 from atrial septal defect). Previous M-mode echocardiographic studies of patients with significant segmental disease have correlated poorly with angiography. Poor correlation was indeed the case when the 23 technically adequate M-mode echograms from our 30 patients were compared with their angiographic data. The correlation coefficients from linear regression of M-mode volumes and biplane echographic volumes on angiographic volumes are listed in table 2 and plotted in figure 9. These data underscore the discrepancy between volume information derived from M-mode, a one-dimensional source, and that from two-dimensional echo, a biplane source. The generally poor correlation between M-mode volumes and angiography in cor-

<table>
<thead>
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<th>Table 2. Correlation Coefficients</th>
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<td>Biplane echogram vs angiogram (n = 30)</td>
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<td>-----------------------------------</td>
</tr>
<tr>
<td>End-diastolic volume</td>
</tr>
<tr>
<td>End-systolic volume</td>
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<tr>
<td>Ejection fraction</td>
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Coronary disease has become an established fact. Our experience parallels that of others, and confirms that the close correlations obtained by early workers were due to the virtually complete elimination of patients with segmental disease from their studies.

In addition to having advantages over the M-mode technique, biplane echocardiography may have a slight advantage over single-plane angiography when both are compared with biplane angiography. This impression comes from comparing our results with reported results obtained from evaluation of both angiographic techniques.

While the correlations with angiography were reasonable, the two-dimensional echographic technique underestimated ventricular size by approximately 30%. This degree of underestimation appears to be caused by several factors. For example, figure 5 illustrates the difference between the short-axis echogram and the LAO angiogram, which shows a portion of the apex and a portion of the base, while the echogram shows only the minor axis of the left ventricle. Including the apex in the angiogram contributes to magnifying the angiographic volumes larger. Another difference between the echographic tracing and the angiogram is the difference in the size of the outlines. Much of this difference is due to the magnification of the image inherent in the angiographic technique. However, a portion of this size disparity is also because angiography, a shadow technique, always produces a maximally sized image that two-dimensional echocardiography, a tomographic technique, can only approach. In spite of these shortcomings, we selected the short axis as a LAO analogue because it yielded a highly reproducible 360° view of left ventricular wall motion, was orthogonal to the apical long-axis view, and was similar to the LAO angiogram.

The two-chamber apical view was selected because it seemed to have advantages over the other apical view, the four-chamber view. Although the four-chamber view also provides a long-axis view of the left ventricle, the axis of the tomographic slice can lie anywhere along the septum (a structure that occupies one-third of the ventricular circumference) and still produce a four-chamber view of the heart. By contrast, to obtain a two-chamber view, the septum and right ventricle must be eliminated, which limits the plane of the slice, and, in contrast to the four-chamber view, enhances reproducibility. In our experience, the two-chamber view has a somewhat higher yield of successfully imaged endocardium and apexes.

Originally, we considered combining the long-axis apical views, because this combination most closely fulfilled the assumption of our biplane algorithm that both planes share a common long axis. However, the generally excellent view of endocardial motion provided by the short axis, the standardizability and reproducibility of the two-chamber view, and the analogous relationship of these views to the angiogram impelled us to choose this combination for this study. The best predictor of angiographic volume was the end-systolic echographic image. There are three reasons for its apparent superiority. First, endocardial imaging was always better in systole. Second, walls that may have moved beyond the limit of the field or dropped out partially during atrial contraction, were usually well imaged during systole. Third, the LAO angiogram more closely resembles the true short axis of the left ventricle during systole.

While the correlation between echographic systolic volume and angiographic volume was at a level which approached clinical usefulness, the scatter and weaker correlation of diastolic volume measurements appear to make general clinical use of diastolic measurement a less secure practice. The poorer quality of the diastolic image appears to be an important reason for its weaker correlation with angiography. However, other factors were also operating to introduce scatter into our data. First, the echo studies were not performed simultaneously with the angiograms, but were separated in time by 1-3 days. Changes in basal state can introduce changes in cardiac size. Second, we did not combine systolic and diastolic values. Such a maneuver would have extended our range of values.
and partially obscured the weakness of diastole. Third, we examined only adult patients. Inclusion of very small hearts would have improved correlations, but would have obscured the reliability of this technique in the adult patient. Fourth, the ejection fractions in our patients were 22–84%. Prolonging our study so that patients at the extremes of cardiac function could be included would have also served to improve the apparent level of correlation. Fifth, angiograms varied in the percentage of the long axis represented in the LAO projection. This variation was probably less during systole, when the angiogram more closely resembles the echogram. Finally, the parallax error introduced by our tracing technique as well as the obfuscation of the faint endocardial boundary by the superimposed x-ray film are further causes for error.

Successful use of this technique will often hinge on the operator’s skill and experience, which are essential to obtaining optimal images. Imaging difficulties are most often encountered in the visualization of the anterior wall endocardium in the long-axis, two-chamber view. This image must be optimal for accurate volume analysis. Careful transducer and patient positioning and proper gain adjustments can usually bring this area into view. Proper patient positioning is also essential and often requires several changes in the degree of lateral recumbency. An extreme lateral position often brings the apex impulse into contact with the surface of the examining table, so the patient must be brought as close as possible to the edge of the bed to allow room for the transducer. We solved this problem by cutting out a section from the side of a thick (20.3 cm) foam rubber mattress and positioning the apex impulse over the excavated area. The use of apex impulse as an imaging window is facilitated by conducting the echographic examination from the patient’s left side.

The tedious nature of tracing ventricular outlines from a television screen will inhibit wide acceptance of this technique. The potential for parallax error, the obfuscation of the endocardial surface by the x-ray film, and the need for analyzing the data by planimetry or computer at a site and time removed from the actual tracing contribute to the inconvenience of the technique. The recent development of a prototype minicomputer-operated, light pen, digitizing system that can trace borders directly on the cathode-ray oscilloscope tube phosphor and can automatically compute and quickly display volume information on the same television screen promises to facilitate the evaluation of this technique.

The hazards, discomfort and expense of angiography often prevent it from being used repetitively and limit its application. A noninvasive technique for measuring left ventricular volume would permit the frequent re-evaluation of a wide variety of patients. A particular advantage of an echographic approach is that it has no influence on cardiac function and does not produce ectopic beats. It also does not require the injection of radioactive isotopes, whose costs and availability are disadvantageous to their use.

Based on this initial study, we feel that this technique may have wide applicability to the study of left ventricular function. Its acceptability depends on recognition of the limitations discussed above, and on the development of further refinements. In summary, we have introduced a biplane, two-dimensional echographic technique for obtaining left ventricular volumes that is relatively uncompromised by the presence of segmental ventricular disease. It can be used to measure systolic volume and ejection fraction with reasonable accuracy, but its capacity to measure diastolic volume, while statistically significant and superior to M-mode, is less than desirable for clinical application.

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References

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