Cross-sectional Echocardiography

I. Analysis of Mathematic Models for Quantifying Mass of the Left Ventricle in Dogs

H. L. Wyatt, Ph.D., Ming K. Heng, M.D., Samuel Meerbaum, Ph.D., John D. Hestenes, Ph.D., Julio M. Cobo, M.D., Robert M. Davidson, M.D., and Eliot Corday, M.D.

SUMMARY Cross-sectional echocardiography was used to quantify left ventricular mass noninvasively in 21 dogs. Short- and long-axis cross-sectional images of the left ventricle were reproducibly traced at endocardial and epicardial borders during stop-motion video-tape replay. We used area, length and diameter measurements to calculate left ventricular mass by seven mathematic models, including the standard formulas used with M-mode echocardiography and cineangiography. Calculated mass was compared with excised weight of the left ventricle by regression and percent error analyses. Formulas using short-axis areas and long-axis length resulted in higher correlation coefficients (0.94-0.95) and lower mean errors (6-7%) than for standard formulas. Since short-axis areas account for regional left ventricular irregularities, noninvasive quantification of left ventricular mass by cross-sectional echocardiography in dogs is most accurate with formulas using short-axis areas.

M-MODE ECHOCARDIOGRAPHY has been used to quantify left ventricular (LV) dimensions, yet the technique is limited by its one-dimensional approach. Cross-sectional echocardiography, with its two-dimensional visualization of the heart, has not only greatly enhanced the range of noninvasive cardiac diagnosis, but also provides new opportunities for quantification of LV volumes and mass. The primary source of errors in LV volume measurement by most of the currently available techniques is the inability to accurately assess endocardial asymmetries and irregularities such as those caused by the presence of papillary muscles and trabeculae carnae.1 Because good tomographic ultrasonic visualization of LV endocardial contours is possible in most dogs,2,4 quantification of cardiac size has become a distinct probability.

Cross-sectional echocardiographic quantification of LV dimensions and volumes has not been adequately validated, even though several preliminary clinical investigations4 suggested correlation with cineangiography. The lack of an absolute standard against which to compare echocardiographic measurements limits the implications of prior studies. Hence, techniques were developed in this laboratory for performing noninvasive cross-sectional echocardiography in closed-chest dogs.2,4 With this technique a variety of LV cross-sectional images may be recorded for detailed analysis of cardiac size, structure and function. The present study in closed-chest dogs was designed to determine the accuracy of LV mass assessment with
cross-sectional echocardiography. We developed several mathematic models and evaluated them by comparing calculated LV mass with postmortem LV weight.

**Methods**

**Echocardiographic Technique**

Cross-sectional echocardiographic studies in dogs were performed with an electronic phased-array sector scanner (Varian Associates, Palo Alto, California) that is similar in principle to a system described previously. Features of this system include real-time, high resolution, a 32-element transducer, an 84° sector angle, and a videotape recording rate of 30 frames/sec. The 84° sector angle enables the dynamic recording of entire cross sections of the left ventricle, using either short-axis or long-axis orientations.

Twenty-one dogs that weighed 18–35 kg were anesthetized with sodium pentobarbital (30 mg/kg) and ventilated with room air using a Harvard respirator. Each dog was placed on an examination table with the right chest wall positioned over a window in the table (fig. 1A). The transducer was directed upward on the right chest wall proximal to the area of maximal apical pulsation, usually at the fourth or fifth intercostal space, 2–6 cm from the sternal edge. Short-axis images were obtained at several levels of the left ventricle by moving the transducer along the chest wall in the direction of the LV apical position and by changing the angulation of the transducer in the same direction. The transducer position was adjusted until the short-axis image of the LV cavity was circular, in-

**Figure 1.** A) Examination table and transducer location for noninvasive echocardiographic studies in dogs. A section of the table top was removed to provide a window for placement of the echo transducer. The dog is lying on its right side with the transducer coming from below on the right chest wall in the fourth or fifth intercostal space about 2–6 cm from the sternum. B) Postmortem frozen canine heart in the orientation seen with the thorax open on the left side and with the echo transducer below on the right chest wall. The right ventricle is to the left and the anterior and anterolateral surfaces of the left ventricle are to the right with the left ventricular apex at the bottom right and the base of the ventricles with the atria and great vessels at the top. The left anterior descending coronary artery runs along over the interventricular septum and clearly demarcates the line of separation between left and right ventricles. Long needles were passed through the right chest wall from the transducer location and in the direction of the ultrasonic beam. Markers indicate the points of intersection of the needles with the anterior and anterolateral surface of the left ventricle. The two markers at the base of the left ventricle indicate the approximate plane of intersection of an echocardiographic long-axis section. C) Slab from the heart in figure 1B in the short-axis plane at a level just below and parallel to the markers indicated as the plane of an echocardiographic short-axis cross section. The orientation of this section is the same as the echo sections seen in Polaroid and in diagram (fig. 2), but is inverted from the sketch seen in figure 1A. The right ventricle is at the top left and the orientation of the left ventricle is as outlined in figure 2. The anterior wall is at the bottom left with the anterior papillary muscle projecting prominently into the left ventricular cavity; the interventricular septum is to the left and above; the posterior wall is above and to the right with the posterior papillary muscle projecting prominently into the left ventricular cavity; the lateral wall is at the bottom right.
indicating essentially perpendicular intersection of the left ventricle by the ultrasonic beam. Elongated or elliptical short-axis cross sections were rejected because they suggest an angular intersection and would present a distorted outline of the LV cavity.

In five anesthetized dogs, two long steel needles were passed through the thorax from the point of transducer contact on the chest wall upward along the direction of the ultrasonic beam, i.e., parallel to the direction of the ultrasonic beam. The thorax was opened on the left side, opposite the transducer (fig. 1B). The anterior LV surface was exposed with the right ventricle cranial to and beneath the left ventricle. In each dog, two needles were passed through the right thoracic wall and through the heart at approximately the same incidence of transection as by the ultrasonic beam for short-axis recording at the high papillary muscle level. The needles penetrated first the right ventricle and then successively the interventricular septum, left ventricular cavity, and the anterolateral surface of the left ventricle (fig. 1B). After the dog was sacrificed, the heart was removed with the needles intact and sectioned in long- or short-axis planes parallel to the plane of penetration of the needles. These sections were examined and compared with the two-dimensional echocardiographic images. Figure 1C is a photograph of a short-axis section at the papillary muscle level. The orientation of this short-axis section is the same as projected echocardiographic images (figs. 2 and 3), with the transducer pointing downward from above.

Figure 2 shows (on the bottom left) a diagrammatic sketch of a short-axis section of the left ventricle at the papillary muscle level, as it appears on the video screen, with the transducer location at the apex of the sector arc. This sketch corresponds to the representative echocardiographic image at the top left of figure 2. Short-axis sections obtained with the phased-array sector scanner usually show the entire circumference of the left ventricle within the 84° sector arc. In the top middle section of figure 2 is a representative echocardiographic image of the left ventricle at a level below the papillary muscles. Although both endocardial and epicardial images of figure 2 are generally distinct, discontinuities do exist in these images. Many of these discontinuities may be corrected by viewing the dynamic motion during videotape replay; this is discussed in more detail later.

By rotating the transducer 90°, a long-axis section of the left ventricle is obtained. In many dogs that...
weigh less than 30 kg, the entire longitudinal cardiac silhouette can be visualized within the 84° sector. To obtain sections that most closely approximate the true longitudinal plane, the transducer is rotated until the view obtained gives the longest diameter and simultaneous visualization of the aortic root and mitral leaflets. Figure 2 shows (on the bottom right) a diagrammatic sketch of a long-axis section at end-diastole.

Echocardiographic LV Mass

Using cross-sectional echocardiographic images from the dog, we tested the same models by comparing calculated LV mass with anatomic mass. For each model, LV volume was calculated for both endocardium (LVVn) and epicardium (LVVP); then LV mass (LVM) was calculated by subtracting LVVn from LVVP and multiplying the difference by the density of myocardium: LVM = 1.055 (LVVP - LVVn). In five postmortem canine left ventricles, the apical wall thickness was measured and the mean was determined to be 0.4 ± 0.03 cm (± SEM). The mean apical wall thickness was arbitrarily added to the echocardiographic left ventricular length (Ln) to obtain an epicardial length (Lp): Lp = Ln + 0.4. Thus, with models using ventricular length to calculate ventricular volume, Lp was used to determine epicardial volume and Ln was used to determine endocardial volume.

Endocardial and epicardial outlines at end-diastole were traced from projections of short-axis and long-axis cross sections during videotape stop-motion replay. Linear measurements were obtained from the cross-sectional outlines and areas enclosed within the outlines were obtained by planimetry. Because an outline that is continuous during systole may become discontinuous during diastole (fig. 3), discontinuities are handled by analyzing the dynamic motion of ventricular images during videotape replay. In this way, approximate location of many discontinuous ventricular images may be estimated. A further consideration in accounting for image discontinuities is the general curvature of the existing ventricular outline. These techniques are obviously useful only with discontinuities of small proportion, and when large portions of the ventricular image were missing, the image was rejected as unsatisfactory.

Echocardiographic short-axis images are characterized by strong circumferential echoes at both endocardial and epicardial interfaces (fig. 2). The simplified procedure of tracing the inner echo borders was adopted in the present study because of the smaller potential observer errors involved in delineating the inner border of each echo. By tracing at the inner border of circumferential echoes, the thickness of the epicardial echo is excluded from epicardial area. LV diameters and long-axis areas were also measured from the inner borders of both endocardial and epicardial echoes taken at appropriate left ventricular locations. Thus, LV wall thickness by this procedure includes the thickness of the endocardial echo but excludes the thickness of the epicardial echo.

Recently, the American Society of Echocardiography recommended a leading edge method for standardizing M-mode echocardiographic measurements. This method avoids the errors due to the gain dependence of the trailing edge position, and differs from current conventions for LV wall thickness measurements in that either endocardial or epicardial echo thickness, but not both, is included in wall thickness. In contrast, the standard convention11,12 includes the thickness of both echoes, and the Penn convention excludes the thickness of both echoes.13 The technique in the present study of cross-sectional

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**FIGURE 3.** Echocardiographic short-axis section of the left ventricle at the papillary muscle level at both end-diastolic and end-systolic phases of the cardiac cycle. The continuity of endocardial and epicardial outlines at end-systole is diminished at end-diastole.
echocardiography uses a leading edge method for the anterolateral LV wall and a trailing edge method for the posteroseptal wall.

Length of the ventricle was measured in the long-axis section as the distance from apex to the mitral-aortic valve junction at the base. When the apex was not fully visualized, the length used was that measured from the mitral-aortic junction to the farthest endocardial point on the anterior wall of the left ventricle.

Calibration of cross-sectional echocardiographic measurements was performed from the calibration scales along the horizontal and vertical axes. These calibration scales were predetermined by Varian Inc. from precise fixed-distance points image with the echocardiographic system. The calibration was subsequently checked in our laboratory and found to be accurate. In practice, the calibration scale was measured for each echocardiographic measurement,

because some variation may occur with changes in gain settings. Also, each calibration scale was measured over the range of the screen. Calibrations were measured during videotape motion replay to allow better visualization of the scale. Correction factors were determined and applied to each volume calculation.

Mathematic Models

Model 1 (figs. 4 and 5A)

Length (L) was divided by the number of short-axis sections to obtain the arbitrary height (h) of each short-axis section. LV volume was then calculated by a short-axis reconstruction procedure using Simpson's rule with short-axis areas (A) and heights. Volume for the apical section is calculated by the formula for an ellipsoidal volume segment, shown as the last two terms in the ventricular formula (fig. 4). The predetermined value for apical wall thickness, 0.4 cm, was added to the height of the apical section in calculating the epicardial volume for the apical section (h = h + 0.4). Volumes for each remaining short-axis section were calculated simply by multiplying the respective area (A) of the section by the height (h). Ventricular volume (V), either endocardial or epicardial, is then obtained by summation of the section volumes

\[
V = (A_1 + A_2 + A_3)h + \frac{A_4h}{2} + \frac{\pi h^3}{6}
\]

Model 2 (fig. 5B)

In this case, the volume (V) of a cylinder-like figure is calculated using the area (A) obtained from a single LV short-axis section at the level of the level of the high papillary muscle, and the LV length (L) determined from a long-axis section: \( V = AL \).

Model 3 (fig. 5C)

The volume of an ellipsoid-like figure is also calculated using the area and length. The derivation is
MATHEMATICAL MODEL FOR QUANTIFYING LV MASS/Wyatt et al.

\[ LVV = (A_1 + A_2 + A_3) h + A_4 + I h^3 \]

(Simpson's Rule)

A, A_2, A_3

\[ n = 0.94x + 5.4 \]

\[ r = 0.946 \]

\[ \text{SEE} = 9.0 \]

\[ y = 0.81x - 1.1 \]

\[ r = 0.938 \]

\[ \text{SEE} = 8.8 \]

\[ y = 0.67x + 5.9 \]

\[ r = 0.890 \]

\[ \text{SEE} = 9.0 \]

\[ y = 0.81x + 4.7 \]

\[ r = 0.744 \]

\[ \text{SEE} = 20.8 \]
as follows: \( V = \frac{4}{3} \pi r_1 r_2 r_3 \) for an ellipsoid, where \( r_1, r_2 \) and \( r_3 \) are the different radii. If \( A = \pi r_1 \times r_2 \) and \( L = 2r_3 \), are substituted into the formula, the result is: \( V = \frac{2}{3} AL \). Thus, the only difference between the volume formulas for the ellipsoid-like and cylinder-like models is a constant \( 2/3 \).

**Model 4** (fig. 5D)

Since the left ventricle may be better represented by a figure that is ellipsoidal toward the apex and cylindrical toward the base, model 2 may be altered to that shown in figure 5D. Such a volume formula might be approximated by averaging the constants for the ellipsoid-like and cylinder-like models: \( V = 5/6 AL \).

**Model 5** (fig. 5E)

The volume of an ellipsoidal figure is calculated here using the LV length and both minor-axis diameters determined from a short-axis section at the high papillary muscle level, where \( D_1 \) is the anterosepetal to posterolateral diameter and \( D_2 \) is anterolateral to posteroseptal diameter. The formula for the volume of an ellipsoid is \( V = \frac{4}{3} \pi r_1 r_2 r_3 \). If \( D_1 = r_2 \) and \( L = 2r_3 \), then \( V = \frac{\pi}{6} D_1 D_2 L \). This is a standard ellipsoidal formula that has been used for calculating LV volume by cineangiography.

**Model 6** (fig. 5F)

Volume of an ellipsoidal figure is calculated with the cube-method formula, developed specifically for M-mode echocardiography, based on the anterospetal to posterolateral diameter (D) of the left ventricle measured at the high papillary muscle level, just below the mitral valve. If \( V = \frac{4}{3} \pi r_1 r_2 r_3 \), and \( r_1 = r_2 = D/2 \), and \( r_3 = D \), then \( V = D^3 \). LV diameters for both models 5 and 6 were obtained from a ventricular location similar to that in patients with M-mode echocardiography, that is, at the base of the left ventricle just below the mitral valve tip. In the dog, however, the papillary muscles extend farther toward the base of the ventricle than in the human being. This LV diameter at the high papillary muscle level was approximately the same as that measured slightly higher on the base of the ventricle at the mitral valve level.

**Model 7** (fig. 5G)

Volume of an ellipsoidal figure is calculated by the standard angiographic area-length formula using both the area \( (A_{ij}) \) and the length \( (L) \) from a long-axis section of the left ventricle. \( V = \frac{4}{3} \pi r_1 r_2 r_3 \), where \( r_1 = r_2, r_3 = L/2 \) and \( A_{ij} = \pi r_i (L/2) \). Then, \( r_1 = r_2 = 2A_{ij}/\pi L \) and \( V = \frac{4}{3} \pi (2A_{ij}/\pi L)^2 (L/2) = 0.85 A_{ij}^2/L \). The echocardiographic long-axis section of the left ventricle has a different orientation than the angiographic right or left anterior oblique sections. Thus, the measured area and length of each echocardiographic section may differ from those of an angiographic section.

**Data Analysis**

In 21 dogs, LV mass, calculated by the above seven models, was compared with true anatomic LV weight using linear regression analysis. Standard error of estimate was calculated. Regression equations were determined for each of the seven models and all values for LV mass were corrected by recalculating with the appropriate regression equation; for each corrected value, the percent error from the true value was determined by:

\[
\frac{\text{corrected calculated LV mass} - \text{true LV mass}}{\text{true LV mass}} \times 100
\]

For each model, calculated LV mass was plotted against true LV mass, percent errors were plotted, and mean percent error was calculated as an average of absolute percent errors for all 21 dogs. Reproducibility of LV short-axis area and LV long-axis length measurements at end-diastole was assessed in 20 dogs by determining percent error from the average of duplicate measurements by the same observer (intraobserver), by two observers (interobserver) or by one observer from two beats (beat-to-beat). Mean percent error was calculated for the 20 dogs.

After each echocardiographic study, the dog was killed with an overdose of sodium pentobarbital and the heart removed and rinsed free of blood. The left ventricle was separated by a method similar to the methods of previous studies. The atria and pulmonary artery were removed at the level of the aortic and pulmonary valves. The right ventricle was removed at its junction with the interventricular septum and the right ventricular side of the septum was trimmed of large trabeculae. The left ventricle was weighed to the nearest gram.

**Results**

Typical echocardiographic short-axis and long-axis images from the dog are shown in figure 2. The left ventricular apex was present in echocardiographic long-axis cross-sections from 10 of the 21 dogs in this study.

The seven formulas and geometric models used to calculate LV volume and mass are given in figure 4 and figures 5A–G. Linear regression analysis was performed for calculated LV mass vs anatomic LV weight for each model. Each point was plotted and the identity line drawn in for comparison. The LV mass in this study of 21 dogs was 78–211 grams. To indicate the scatter for each model, individual percent errors are plotted to the right of the regression plot.

The models with highest correlation coefficients (models 1–4) all used short-axis area analysis. Model 1, the Simpson's rule short-axis area reconstruction procedure (fig. 5A), yielded an excellent correlation coefficient \( r = 0.948 \), with a distribution of points on either side of the identity line. The mean error was
6.3%. Models 2–4, with formulas that use only one short-axis area, resulted in a correlation coefficient (0.938) not significantly lower than that for model 1, which used multiple short-axis areas. Model 2 (cylindrical geometry, fig. 5B) consistently overestimated LV mass; model 3 (ellipsoidal geometry, fig. 5C) consistently underestimated LV mass; model 4 (cylindrical-ellipsoidal geometry, fig. 5D) resulted in a distribution of points on either side of the identity line. The mean error for models 2–4 was approximately 7%.

Correlation coefficients were significantly lower for models 5–7 then for models 1–4. A good correlation coefficient ($r = 0.890$) was obtained with LV volume model 5 (fig. 5E), which uses two short-axis diameters and a long-axis length ($\frac{\pi}{6}D_1D_2L$) rather than area measurements. The mean error was 8.6%. Model 5, a formula derived from an ellipsoidal geometry, consistently underestimated LV mass. A significantly lower correlation coefficient (0.828) but similar mean error (8.8%) resulted from use of the cube method of model 6 (fig. 5F), which uses only a single short-axis diameter measurement ($D^9$). Model 6 consistently overestimated LV mass.

Use of the area-length method of model 7 (fig. 5G), which uses the long-axis area (A) and length (L) for LV volume computation (0.85 A²/L), resulted in a poor correlation coefficient (0.744) and a mean error of 10.0%. In the majority of cases, LV mass was underestimated with model 7.

Reproducibility of LV short-axis area and long-axis length measurements at the end-diastolic phase of the cardiac cycle was assessed in 20 dogs by determining the percent error from the average of duplicate measurements by the same observer (intraobserver), by two observers (interobserver), or by one observer from two beats (beat-to-beat). The mean errors for endocardial and epicardial areas were 3.5–5%, and those for estimated endocardial length were 1–4%.

**Discussion**

The unique feature of cross-sectional echocardiography is its ability to view the heart tomographically in virtually any plane. In practice, the planes that are useful for quantifying LV volume and mass are those in which the spatial orientation of the planes relative to the LV cavity can be definitely identified, i.e., the short and long-axis views. The specific goal of this study was to develop and test mathematic models for computing LV mass using the data available from these ultrasonic views. The results show that LV mass can be accurately quantified in the closed-chest dog using cross-sectional echocardiography.

**Geometrical Considerations**

Seven mathematic models were used to compute LV volumes for quantifying LV mass. Four (models 1–4) used LV short-axis area and long-axis length and were developed specifically for cross-sectional echocardiography. The other three, which used LV short-axis diameters, long-axis length and long-axis area, have been used in M-mode echocardiography (model 6) or cineangiography (models 5 and 7).

We expected that model 1 would produce the best estimate of LV mass because the model is not based on assumptions regarding the geometric shape of the LV cavity. By serial measurement of a number of short-axis areas, regional asymmetries in LV shape are accounted for, and, consequently, the sum of the volumes of serial slices along the length of the left ventricle closely approximates the true LV volume. Although the present study was performed in dogs without regional asymmetry such as might be generated with myocardial ischemia, in a preliminary in vitro study of asymmetric dog hearts, we showed that the best echocardiographic quantification of LV volume was obtained with model 1.16 Thus, for measuring LV mass, this model has the advantages of accuracy as well as applicability in hearts with extensive regional asymmetry. The disadvantage of model 1, however, is that the method is tedious and may not be useful in the clinical setting, where the number of adequate short-axis views is usually less than in dogs.

Models 2–7 were developed to simplify computation of LV mass compared with the Simpson's rule procedure. Preliminary studies with cross-sectional echocardiography have investigated the use of these and other mathematic models for volume determination in the in vitro canine left ventricle.17,18 In evaluating the results obtained with these simplified geometric formulas, we paid special attention to the following considerations: 1) use of models that provide a valid description of LV shape; 2) inclusion of short-axis area, a measurement unique to cross-sectional echocardiography, and 3) assessment of the importance of LV long-axis length and area.

Although models 2–4 were developed from different geometric configurations, the only difference between the three formulas is the constant. Thus, the identical correlation coefficient ($r = 0.938$) obtained with these models was predictable. However, model 4 (half-cylinder, half-ellipsoid) provides the closest estimation of LV mass, as judged by the scatter of values around the identity line (fig. 5D). This finding is not unexpected, because the shape of the left ventricle resembles a cylinder at the base and a half-ellipsoid at the apex. Likewise, Geiser and Bove,14 using post-mortem measurements of the left ventricle, showed that accurate calculation of LV mass was best performed by use of a truncated ellipsoid model, which is strikingly similar to model 4 of the present study, and that the formula for a normal ellipsoid was unsuitable. Although the correlation coefficient is slightly lower for model 4 than for model 1, the difference is not statistically significant. Because only one short-axis section is required and calculations are greatly simplified, model 4 is preferable to Simpson's rule in many investigations, especially in the clinical setting.
In our study, inclusion of the LV short-axis area consistently improved quantification of LV mass with cross-sectional echocardiography. Thus, models 1–4, in which one or more short-axis areas were used, had higher correlation coefficients than models 5–7, in which this measurement was not used. A probable explanation for these observations is that only short-axis, cross-sectional area adequately accounts for irregularities of the endocardial outline, especially the presence of the papillary muscles. These findings seem to contrast with those of two clinical studies in which excellent correlations were obtained between true LV mass by weight and estimated LV mass by M-mode echocardiography and cineangiography. The large range of LV mass in the clinical studies (100–500 g) compared with that in our study (78–211 g) was probably an important factor contributing to high correlation coefficients. On the other hand, the clinical studies included ventricles with shape abnormalities, the lack of which in the present study might mask a limitation of the mathematic models. Thus, for several reasons, it is difficult to compare the present study with previous studies.

Sources of Error

Potential errors with our method of LV mass calculation fall into two categories: 1) errors in the measurements of LV short- or long-axis dimensions due to deficiencies inherent in cross-sectional echocardiography, and 2) errors that may arise from certain assumptions used in the mathematic models.

In the first category, difficulty may arise with the measurement of LV long-axis length and area because the cardiac apex is not always well visualized in the long-axis view. Despite this, our preliminary studies (unpublished observations) have shown that, at least in diastole, the LV long-axis length measured by cross-sectional echocardiography was a good approximation of that measured by cineangiography. For 12 measurements in 10 dogs, the average length was only 6.5% shorter for echocardiography than for angiography. Furthermore, the measurement of the LV long-axis length by echocardiography was highly reproducible. Inclusion of length (L) in the mathematic models is more appropriate than simply assuming, as in the D3 method, that length is twice the short-axis diameter; thus, both model 5 (π/6 D,D,L) and a simplified version of model 5 (π/6 D3,L) improved the estimation of LV mass by model 6 (D3,L). Likewise, Machii et al. comparing cineangiography and M-mode echocardiography, showed that better LV volume correlations were obtained with an echocardiographic model using long-axis length (π/6 D3,L) than with short-axis (D3) alone.

Another potential error is in the measurement of LV short-axis areas and diameters from the inner circumferential borders of both epicardial and endocardial echoes. By this method, the posterior and posteroseptal walls are traced by the "trailing edge" method, which may result in a potential error related to the gain setting. Although a gain change may introduce an error with area or diameter measurement, this error cancels out in the determination of wall thickness and LV mass.

Finally, with ventricles that are severely asymmetric due to myocardial ischemia, infarction or aneurysm, problems may arise with application of techniques for recording echocardiographic short-axis cross sections. Specifically, a perpendicular intersection of the left ventricle by the ultrasonic beam may be difficult to determine, as in the present study, by circular configuration of the short-axis image. In this case, since asymmetry is often present only during systole, the diastolic period of the cardiac cycle may be used to determine short-axis configuration.

Problems that may arise from assumptions used in the mathematic models include first, the arbitrary use of equal heights for each short-axis section in the Simpson's rule procedure (model 1). Although the sections were probably not obtained at exactly equal distances along the left ventricle, this assumption would not be expected to introduce a significant error in the estimation of LV mass, because short-axis areas did not vary greatly except near the apex. With models 2–7 based on measurements from only one or two cross sections, errors may arise in the estimation of LV mass from the assumption of geometric models for the left ventricle. Devereux et al. pointed out that mean myocardial wall thickness cannot be accurately estimated, as in the D3 method, by averaging posterior and septal wall thickness, because this varies considerably from base to apex. In the present study, to partially account for thinning of the LV wall toward the apex, an apical wall thickness of 0.4 cm (average postmortem measurement) was used in the geometric models. Thus, the problem of a variable wall thickness was minimized in this study of normal ventricles; however, in severely and asymmetrically enlarged hearts, significant errors might be encountered with estimation of LV mass, especially when the assumed apical wall thickness is based, as in the present study, on measurements taken from normal ventricles.

In conclusion, the present study describes a technique for performing cross-sectional echocardiography in dogs. Using both LV short- and long-axis images, LV mass is calculated according to seven mathematic models. The best estimates result when both short-axis areas and long-axis length are included in the calculation. It may be possible to estimate LV mass simply and noninvasively with cross-sectional echocardiography.

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References
1. Davila JC, Sanmarco ME: An analysis of the fit of mathematical models applicable to the measurement of left ventricular volume. Am J Cardiol 18: 31, 1966
2. Wyatt HL, Heng MK, Meerbaum S, Davidson R, Lee SS, Cor-
day E: Quantitative left ventricular analysis in dogs with the phased array sector scan. (abstr) Circulation 56 (suppl III): III-152, 1977


8. Schiller N, Botvinick E, Cogan J, Greenberg B, Acquatella H, Glantz S: Noninvasive methods are reliable predictors of contrast angiographic left ventricular volumes. (abstr) Circulation 56 (suppl III): III-221, 1977


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