Geometric Considerations in Determination of Left Ventricular Mass by Two-Dimensional Echocardiography

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SUMMARY This review describes the technique of and advances in determination of left ventricular mass by two-dimensional echocardiography. Two-dimensional echocardiographic model systems, which require geometric assumptions, may have limited accuracy in mass determination if ventricular shape is deformed or the architecture is irregular, as it may be in various disease states. Recently developed techniques allow free angulation of the echocardiographic transducer with continuous recordings of the three-dimensional coordinates of each image without imposing restraints on transducer orientation. These developments have led to methods for accurate three-dimensional reconstruction of left ventricular mass, even in the presence of severe dilatation or deformity. With the interaction of two-dimensional echocardiography, a coordinate system for locating the transducer in three-dimensional space, and computer-aided echocardiographic contouring, it is possible to obtain left ventricular mass estimates with a high degree of accuracy from randomly oriented views without practical restriction on transducer motion or major geometric assumptions. (Hypertension 9 [Suppl II]: II-85-II-89, 1987)

KEY WORDS • echocardiography • left ventricle • mass

ACURATE, noninvasive determination of left ventricular (LV) volume and mass is important to the evaluation and management of a variety of cardiovascular disorders. The introduction of echocardiography opened the possibility of repeated noninvasive measurements of cardiac volumes and mass.1-4 Although two-dimensional (2D) echocardiography can provide clinically useful estimates of LV ejection fraction compared to cineangiographic and radionuclide determinations, use of 2D echocardiography to predict absolute volume has been hindered by broad variability in results in spite of the good correlation with angiographic volume determinations.5-8

Some errors are inherent in single plane and biplane cineangiographic volume measurements, the standard against which 2D echocardiography has been judged. Cineangiography is a nonanatomic standard requiring major geometric assumptions, and it is a shadow technique, tending to overestimate LV volume because it cannot compensate for the effect of endocardial trabeculations and papillary muscle encroachment.5-7 Minor errors in cineangiographic calibration may result in large discrepancies in cineangiographic volume estimates.8

We have previously used isolated, ejecting dog hearts connected to a volumetric chamber for direct comparison of measured ventricular volume, without reliance on geometric assumptions, with 2D echocardiographic volume obtained by reconstructing multiple cross-sectional images (Simpson’s reconstruction) obtained at 3-mm intervals along the vertical axis of the heart.9 Comparison of simultaneous data obtained throughout the cardiac cycle revealed not only a high correlation of echocardiographic to direct volume but also a high predictive value of direct volume from the echocardiographic determination owing to low variability. These measurements were obtained under highly controlled conditions, and it was not expected that the accuracy of echocardiographic volume determination could be matched in clinical use or in research applications in intact animals. At the very least, one could not obtain the large number of slices used in that study, and we did not assess the accuracy of volume estimates with decreasing numbers of slices.

Using the same preparation in a more recent study but analyzing the data using progressively fewer slices, we found that at least four cross-sectional parallel images of known location were required to predict volume without significant loss in accuracy in the noninfarcted ejecting canine heart.10 The results of that study also suggest that even under highly controlled conditions, accurate 2D echocardiographic volume measurement in this beating heart preparation required at least four cross-sectional short-axis images of known location. This study was intended to define the requirements for accuracy of echocardiographic volume measurements under the most controlled circumstances and did not enable definition of the accuracy of the technique for studies in patients or intact animals, especially those with diseases that alter regional ventricular function and shape.
Two-Dimensional Echocardiography

Important advances in noninvasive determination of LV mass were made several years ago with M-mode echocardiographic techniques. The seminal work of Reichek and Devereux\(^{11,12}\) provided critical methodology for determining LV mass noninvasively (Penn convention) and was found to be relatively accurate in humans when compared to necropsy studies. These and other studies also showed, however, that the geometric assumptions required for M-mode methods introduced the potential for broad variability in mass or volume determinations and the possibility of significant error.

The 2D echocardiographic techniques require fewer geometric assumptions and are potentially more accurate than M-mode techniques.\(^{13}\) Using the above-described, highly controlled, volumetric chamber preparation, we showed that it was possible not only to determine LV cavity volume accurately in the isolated supported heart preparation but also to determine LV mass with nearly similar accuracy. The volumetric chamber apparatus permitted validation of the technique by confirming near constancy of mass throughout the cardiac cycle.

Even in the absence of precise localization of 2D echocardiographic cross-sectional views, several investigators have reported increased accuracy in volume or mass determination using multiple cross-sectional short-axis views\(^{14}\) or a combination of one short axis and one long axis or longitudinal dimension.\(^{15}\) These studies used 2D echocardiographic algorithms for mass calculation based on the subtraction of endocardial cavity volume from total epicardial volume, resulting in a residual myocardial volume. Schiller et al.\(^{13}\) have recently reported a method for accurate estimation of LV mass in dogs using a truncated ellipsoid model and report constancy of mass between end diastole and end systole.

Although these techniques are more accurate than M-mode techniques,\(^{13}\) they may be hampered by even the more limited geometric assumptions employed by 2D methods when ventricular shape is deformed or the architecture is irregular, as it may be in various disease states.

Three-Dimensional Reconstruction

Accurate determination of volume or mass in intact animals or patients by using multiple parallel views would be impractical due to the high probability of being unable to obtain such views. On the other hand, fewer views would impose the requirement of major geometric assumptions for echocardiographic volume determination, most of which would have uncertain validity in dysfunctional or misshaped hearts. In order to determine mass or volume accurately in hearts with regional myocardial dysfunction, especially in intact patients, techniques need to be developed that would allow free angulation of the echocardiographic transducer with continuous recordings of the three-dimensional (3D) coordinates of each image without imposing restraints of transducer orientation.

The next step is accurate volume determination (i.e., allowing free transducer movement) awaited development of a system for locating the position of the echocardiographic transducer, fixing the spatial registration of the echocardiographic image at any instant, and synchronizing the transducer location data with the echocardiographic data stored on videotape. Recent refinements in transducer localization using spark-gap techniques\(^{16}\) and mechanical arms\(^{17}\) have been particularly encouraging as crucial steps in 3D reconstruction. A number of algorithms have recently been developed for this purpose.\(^{18-21}\)

We have developed a transducer locating system for determining LV volume and mass with a high degree of accuracy but few assumptions of geometry.\(^{22}\) This system consists of a series of spark gaps affixed to the echocardiographic transducer, a series of microphones that receive the spark-gap sonic signals from a fixed position, and digital electronics designed to convert the sonic signals into specific range data that give the 3D coordinates, in both position and angle, of the transducer in free 3D space.

A subsystem, added to a standard 2D echocardiographic instrument, provides range data between the three spark-gap sonic transmitters fixed to the transducer and the four sonic receivers (microphones) in an array fixed with respect to the laboratory floor and patient or preparation (Figure 1). The resulting 12 ranges provide accurate and redundant data to determine the position and point direction (three position and three angle coordinates), thereby providing the information necessary to transform to 3D space the individual contours from standard 2D echocardiographic images. Since there are no mechanical linkages between the transducer and the sonic range receiver array and since a complete set of redundant ranges is determined four times per second, there is no practical restriction on the position and angulation of the echocardiographic transducer during echocardiographic data acquisition.

To generate the individual echocardiographic contours for 3D reconstruction, we utilize a computer-aided echocardiographic contouring system developed several years ago in this institu-

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**Figure 1.** Acquisition of a three-dimensional echocardiogram. The three spark-gap sonic transmitters are mounted to the two-dimensional transducer in a fixed manner relative to the transducer head and angle of the fan beam. The four sonic receiver microphones are fixed above the patient, mounted to an X-shaped frame.
FIGURE 2. Nine end-diastolic freeze-frame echocardiographic views used for three-dimensional reconstruction. These nine are part of a set of 19 used for reconstructing the left ventricle. The patient had dilated cardiomyopathy and a large pericardial effusion. The latter facilitated identification of the posterior left ventricular free wall epicardial surface. The top panels and first two middle panels represent a variety of cross-sectional views from the mitral valve tips to the apex. The right middle panel is a long-axis parasternal view of the left ventricle, while the lower panels represent a variety of apical left ventricular orientations.

We are currently validating 3D reconstruction techniques on cardiac transplant patients, from echocardiographic studies taken prior to transplantation in vivo. Preliminary studies suggest that this method is extremely accurate for LV mass determination when compared to directly measured ex vivo LV weight: mean error for 3D echocardiographic LV mass determination is about 2.5 ± 6 (SD) %. Figures 2 and 3 demonstrate the steps in 3D LV reconstruction in a single patient with dilated cardiomyopathy. Figure 2 shows 9 of the 19 original end-diastolic echocardiographic freeze-frames used for 3D reconstruction. The top panels and the first two middle panels represent a variety of cross-sectional views, beginning at the mitral valve tips and ending at the LV apex. This patient had a large pericardial effusion, making identification of the posterior LV surface quite easy. The right middle panel is a long-axis parasternal view, while the bottom three panels represent a variety of apical or semiapical views of the left ventricle.

Figure 3 demonstrates an actual 3D LV reconstruction. The top panel is a wire diagram of the original 2D echocardiographic contours generated by the contouring system and displayed stereoscopically for the purpose of confirming visually that all contours share a common endocardial or epicardial surface. There are usually 15 to 20 such contours obtained in a variety of nonparallel orientations with the hand-held transducer. On the top panel are contours of both the endocardium (left) and the epicardium (right). In order to compute volumes, surface area, or mass in three dimensions from these multiple oblique views, our data are necessarily limited to the wires or contours seen here. One cannot assume, therefore, that the surface between each wire is a straight line or flat surface. There are simply not enough wires to do a straight line interpolation or even an interpolation based on simple global geometric figures, such as an ellipse. Instead, we need a rational method of nonlinear 3D interpolation between the wires or contours. To do this, we fit a curved surface between the contours using a least squares fit when data are sufficiently dense to infer as much of the curved endocardial or epicardial surface as possible; between sparse data points we use a spline fit.

We do the 3D interpolation by transforming the original contours as seen in the top panel into a longitudinal orientation as seen in the lower panel. This represents a system of cylindrical...
coordinates with the long axis of the cylinder equivalent to the long axis of the left ventricle. This yields a series of equally spaced cuts analogous to orange segments (see Figure 3, lower panel). We use this technique because a short-axis radius rotating around the LV long axis is the most nearly constant of the available coordinates, and the best interpolation is possible with the least natural variation in coordinates. What results are 16 segments, 22.5 degrees apart. These segments represent refitted curves of the original 2D echocardiographic contour data. The resultant curves are controlled entirely by the original contours. Most importantly, these curves are generated without using global geometric models.

Conclusion
With the interaction of 2D echocardiography, a transducer-locating system and computer-aided echocardiographic contouring, it is possible to obtain LV mass estimates with a high degree of accuracy from randomly oriented views without practical restriction on transducer motion. One important aspect of our pilot studies is the ability to obtain accurate indices even in the presence of major disturbances in ventricular architecture, such as myocardial infarction or severe cardiomyopathy. If further validation studies on a larger patient population confirm the preliminary accuracy level, the method holds promise for highly accurate, noninvasive estimation of LV mass.

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