Three-dimensional Echocardiography

Advances for Measurement of Ventricular Volume and Mass

Donald L. King, Aasha S. Gopal, Andrew M. Keller, Peter M. Sapin, Klaus M. Schröder

Abstract
There is a need for more accurate and reproducible serial measurement of left ventricular volume and mass in individual subjects by echocardiography. Conventional echocardiography has significant measurement variability because of its use of geometric assumptions and image plane positioning errors. Guided three-dimensional echocardiography eliminates geometric assumptions and reduces image plane positioning errors by using a "line of intersection" display. Use of three-dimensional guided imaging for a one-dimensional measurement of the left ventricle resulted in a threefold improvement of interobserver variability over conventional echocardiographic measurements. Computer-aided three-dimensional reconstruction of the ventricle for ventricular volume from a series of 8 to 10 short-axis images also achieved more than a threefold improvement of interobserver variability compared with two-dimensional echocardiography. Three-dimensional echocardiographic computation of ventricular volume and mass in healthy subjects was achieved with an accuracy comparable to magnetic resonance imaging and was superior to two-dimensional echocardiography. Three-dimensional echocardiography promises to be a more accurate method of estimating left ventricular volume and mass and may be suitable for serial study of individual subjects because of its improved accuracy and decreased interobserver variability compared with conventional echocardiographic methods. (Hypertension. 1994;33[Suppl 1]:I-172-I-179.)

Key Words • ultrasonic diagnosis • cardiac volume • ventricular mass • image processing, computer-assisted

Recent advances in technology have made it possible to create a three-dimensional echocardiograph, a scanner that registers image position and orientation in three-dimensional space. This system is able to guide acquisition of images using a "line of intersection" display and to perform three-dimensional reconstructions of the heart in a clinically practical manner. The underlying purpose for creating this system has been to achieve a significant improvement in the accuracy and reliability of quantitative echocardiographic measurements, such as ventricular volume and mass. Conventional echocardiographic estimates of ventricular volume and mass, whether by one- or two-dimensional echocardiography, have significant inherent measurement variability because of their use of geometric assumptions and image plane positioning errors. Conventional echocardiography requires the use of geometric assumptions because the position and orientation of its images are not registered in three-dimensional space and must be assumed. Also, with conventional echocardiography, image plane positioning errors occur because the operator is unable to visualize anatomic landmarks in the nonvisualized dimension orthogonal to the real-time image plane. Visualization of these landmarks is essential for accurate and reproducible positioning of image planes. The effect of these limitations on quantitative estimates by conventional echocardiography may produce a measurement variability in excess of the anticipated biologic changes being sought in the measurement. This necessitates the use of relatively large numbers of patients to detect a therapeutic effect in clinical trials and renders the conventional methods of

little use for reliable assessment of the effects of therapy in individual patients. To overcome these limitations, we have developed a three-dimensional echocardiograph.

Three-dimensional Echocardiography

The three-dimensional echocardiograph is composed of a personal computer, a three-dimensional spatial locater, and a conventional real-time echocardiographic scanner. The personal computer (Gateway 2000/486DX33, Gateway 2000, North Sioux City, SD) is used to control system operation, acquire data, generate the line of intersection display, and perform three-dimensional analysis and reconstruction. An acoustical spatial locater (GP8-3D, Science Accessories, Stratford, Conn) registers the position and orientation of the real-time transducer, and thus its image, in three-dimensional space. The user's real-time echocardiograph (Hewlett-Packard, Andover, Mass) supplies the video image and an R-wave trigger signal to the computer. The spatial locater is composed of a set of three sound emitters rigidly attached to the imaging transducer and a set of four point microphone receivers mounted in an overhead array. The emitters are activated in sequence, generating 60 kHz sound waves that travel to the four microphones. The time of flight is measured, and distances are computed. From these distances, the X, Y, and Z coordinates of the images in a microphone-based coordinate system are computed and associated with each set of 16 images acquired at the same time. These data are then used for concurrent generation of the line of intersection display and subsequent three-dimensional reconstruction.

Line of Intersection Display

The line of intersection display is a unique feature of our three-dimensional echocardiograph. It allows the operator to see the position and orientation of the...
real-time image in relation to anatomic landmarks in its orthogonal, nonvisualized dimension (Fig 1). This capability allows the operator to accurately guide the positioning of these images. To create this display, a left ventricular long-axis image is first acquired and saved as a reference image. Subsequent real-time short-axis images approximately orthogonal to the reference image intersect with it, defining a line common to both image planes, the line of intersection. This line is computed and displayed as a white line in each image—the reference long-axis image and the short-axis real-time image. As the real-time image is moved by the operator, the line of intersection is rapidly recomputed and redisplayed, showing the changing relation of the real-time image to anatomic landmarks in its orthogonal dimension displayed in the reference image. The ability to see this relation is very useful for guiding the positioning of images for linear measurements such as a left ventricular minor (chordal) dimension. It also is useful for accurately positioning end-plane images at the aortic valve and ventricular apex when computing ventricular volumes. In addition, it is useful for adjusting short-axis image position to optimally image endocardial boundaries and wall motion. In addition, the line of intersection may be used to instruct technicians as well as evaluate their performance.

Assessment of Two-dimensional Standardized Imaging

The limitations of two-dimensional echocardiography require the use of standardized images defined by anatomic landmarks and assumptions regarding the orientation of these images when these landmarks are visualized. The structure of the heart, however, is a complex three-dimensional shape. Variations of anatomy and operator technique may invalidate these assumptions, causing variations of image position and orientation. These variations may limit accuracy and reproducibility of measurements recorded from these views. The line of intersection display, when not viewed by the operator, may serve to assess actual image orientation achieved by the operator during standardized two-dimensional imaging. In this study, 340 standard images were assessed for optimal positioning from 85 examinations performed by 11 echocardiographers at three different institutions. The standard images were the parasternal left ventricular long-axis, short-axis at the chordal level, and apical two- and four-chamber views. Twenty-four percent of the conventional two-dimensional unguided images were optimally positioned within ±5 mm and ±15° of the standard. Two thirds of these adequately positioned images were the parasternal long-axis image, but only two thirds of the parasternal long-axis images were optimally positioned. It is evident from these results that two-dimensional echocardiography does not achieve a consistent and reasonable level of optimal image positioning. At one institution a subgroup of three echocardiographers who each examined 10 subjects was subsequently evaluated using the line of intersection display to guide image positioning. They followed the same imaging protocol and were assessed by the same criteria previously established. By guided three-dimensional imaging, 80% of their standard images were optimally positioned for image quality, displacement, and angulation/rotation. This threefold improvement compared with their performance using unguided two-dimensional imaging was highly significant by χ² analysis.

Guided One-dimensional Echocardiography

One third of the parasternal long-axis images obtained in the above assessment study were not optimally positioned. This fact is especially significant because standard one-dimensional measurements of the left ventricle for estimating left ventricular volume and mass are usually obtained from this image. This result suggests that mediolateral variation of the position of the parasternal long-axis image may be a major source of interobserver variability for these measurements. To evaluate this possibility, we compared the interobserver variability of anteroposterior measurements of the left atrium and left ventricle made by conventional unguided two-dimensional imaging with those made by three-dimensional line of intersection-guided imaging. Three pairs of operators at three different institutions performed unguided two-dimensional and guided three-
dimensional examinations on 10 patients each. In each examination, the left atrium was measured in a plane parallel to and through the inferior surface of the aortic cusps, and the left ventricle was measured in a plane perpendicular to its long axis 1 cm below the mitral leaflet tips. For the unguided two-dimensional examination, the measurements were made in the parasternal long-axis image. For the guided three-dimensional examination, a reference long-axis image was used to guide positioning of real-time short-axis images into the atrial and ventricular measurement planes described above. The measurements were then made on the short-axis image through the center of the chamber and thus were correctly positioned not only superoinferiorly but also in the mediolateral direction. These results are shown in Table 1. 

The standard unguided examination was associated with an interobserver variability of 4.1 ± 2.5 mm, 5.6 ± 5.3 mm, and 4.3 ± 4.2 mm for the left atrium, left ventricle, and right ventricle, respectively. Guided three-dimensional echocardiography, however, significantly reduced interobserver variability to 2.2 ± 1.5 mm, 1.1 ± 1.0 mm, and 1.7 ± 1.3 mm, respectively. Thus, for the ventricular measurement, the standard error of the difference between two replicate measurements by independent observers using unguided two-dimensional echocardiography was 4.1 ± 2.5 mm. In other words, in one third of the cases two unguided examiners would be expected to obtain measurements of the same left ventricle that differ from each other by more than 5.6 mm. Guided three-dimensional echocardiography, however, significantly reduced interobserver variability to 2.2 ± 1.5 mm, 1.1 ± 1.0 mm, and 1.7 ± 1.3 mm, respectively, for the same measurements (P < .005 by McNemar’s test).

The standard error for the ventricular measurement by three-dimensional guided measurement was 2.0 mm, a nearly threefold reduction. This reduction was highly significant (P < .005) and independent of differences in operator skill or practices among the three institutional groups. These results thus demonstrate that three-dimensional line of intersection guidance can provide a basis for significantly improved serial evaluation and comparison of left ventricular one-dimensional measurements by different operators.

**Guided Two-dimensional Echocardiography**

In a similar manner, line of intersection guidance can be applied to positioning image planes for determination of left ventricular volume by the apical biplane summation of disks algorithm. The assessment study revealed that only 12% of unguided apical two- and four-chamber views were optimally positioned through the center of the ventricle and at a 90° angle. In addition, it showed that two thirds of the four-chamber views passed through the inferior septum rather than, as expected, through the middle septum. These results demonstrated that significant variability also occurs in placement of the apical views and suggested the possibility that three-dimensional line of intersection–guided positioning and orientation of these views could improve interobserver variability. To evaluate this, we performed a study in 15 healthy subjects comparing repeated determinations of ventricular volume by conventional unguided two-dimensional echocardiography, line of intersection–guided two-dimensional echocardiography, and three-dimensional echocardiography using polyhedral surface reconstruction. Interobserver variability for conventional unguided echocardiography was 8.5%, and for line of intersection–guided two-dimensional echocardiography it was 3.1%. Thus, line of intersection guidance of apical image position and orientation achieved a nearly threefold improvement of reproducibility compared with unguided conventional two-dimensional echocardiography. In a separate study, the accuracy of left ventricular volume computation by unguided apical views was compared with that obtained by guided apical views using cineventriculography as a standard. This study showed that there was no significant improvement of volume determination achieved by use of image guidance. Several reasons for this were apparent. First, guidance was unable to eliminate foreshortening of the ventricular image from the apical window. The ventricular apex in a significant percentage of the patients, probably about 50%, lies underneath a rib, and the transducer cannot be placed directly over it, thus resulting in some foreshortening of the image and reduction in the apparent length of the ventricle and, therefore, the volume. Also for the same reason, attempting to force the image into a correct position resulted in a degradation of image quality because of rib interference. This degradation resulted in greater boundary-tracing errors. Furthermore, it was suggested by the study that the geometric assumptions inherent in the apical biplane summation of disks method are a more significant source of error than image plane positioning. Guided two-dimensional echocardiography therefore can be expected to improve reproducibility if used for measurement of ventricular volume or mass but cannot be expected to improve overall accuracy. However, both of these—reproducibility and accuracy—have been demonstrated to be improved by three-dimensional echocardiography.
Three-dimensional Echocardiography

Registration of all images in a three-dimensional spatial coordinate system makes it possible to measure not only within image planes but also between image planes and, in addition, to perform a three-dimensional reconstruction of the ventricle and compute its volume without the use of geometric assumptions. We achieve reconstruction of the ventricular surface using an algorithm called polyhedral surface reconstruction. In a typical examination, 7 to 10 short-axis cross sections of the ventricle are obtained from the inferior surface of the aortic valve to the apex (Fig 2). These cross sections are neither parallel nor evenly spaced but must not intersect in the region of interest, the ventricle. The line of intersection display is used to guide them to optimal position and orientation to best display the endocardial boundaries and to document the changing curvature of the ventricular wall. The ventricular boundaries in each image are traced manually by the operator. The computer then reconstructs the surface using the polyhedral surface reconstruction algorithm. One hundred eighty points are placed on each traced boundary, and pairs of points on adjacent boundaries are connected by three spans to form two triangles (Fig 3). Thus, 360 triangles reconstruct the ventricular surface between each pair of cross sections. To compute ventricular volume, centroids of each cross section are defined and connected to the 180 boundary points. Each pair of triangles connected to the centroids forms a wedge- or sector-shaped solid that is decomposed into three tetrahedrons (Fig 4). The volumes of the tetrahedrons are computed and summed to obtain ventricular volume. In addition, total endocardial surface area is computed by summing the areas of the surface triangles. And, if appropriate, "infarct" (or wall motion abnormality) surface area and its subtended volume may also be computed by demarcating the abnormal region on the traced boundaries. Of course, myocardial volume and, therefore, ventricular mass are obtained by subtracting endocardial volume from epicardial volume.

Validation of Three-dimensional Echocardiography

In vitro studies using a pin model have been carried out to determine the system measurement accuracy as nearly independent of operator error as possible. In these studies, distances between image planes were measured with a mean error of 0.4% of true value. Distances within image planes, as would be measured by conventional echocardiography, were, in contrast, measured with a mean error of 1.7%. This fourfold increase is the result of the relatively poor lateral resolution of the ultrasound beam. Three-dimensional volumes defined by the pin model were measured with an overall mean error of 1.6%, or 0.64±0.72 mL of true value. From these studies, we concluded that the intrinsic system error was less than 0.4%, that it did not introduce any significant new errors compared with conven-
tional echocardiography, and that the principal source of measurement error is poor lateral resolution resulting from ultrasound beam width. Measurement of the volume of irregular water-filled balloon phantoms was then carried out with an accuracy of 2.27%, an interobserver variability of 4.33%, and an SEE of 2.45 mL.10 Similar determinations of the same balloon phantoms were carried out by magnetic resonance imaging and found not to be significantly different. In another study, distorted and nondistorted water-filled balloon phantoms were measured by three-dimensional echocardiography and cineventriculography, and when compared with true values, the results also were found not to be significantly different. Fixed, trimmed animal hearts were used for validation of measurement of total and infarct surface areas as well as ventricular mass. Accuracies for total and infarct surface areas were 1.61% and 3.48%, and interobserver variability was 1.92% and 2.37%, respectively. Fixed heart myocardial volume and mass were measured with SEE values of 2.72 mL and 2.73 g, respectively.

Comparison With Two-dimensional Echocardiography In Vitro

The superiority of three-dimensional over two-dimensional echocardiography has been demonstrated in vitro. Using distorted and nondistorted water-filled balloons imaged by both methods, it was found that three-dimensional echocardiography had significantly smaller limits of agreement (mean difference, ±2 SD) and higher repeatability than two-dimensional echocardiography.15 With excised porcine left ventricles imaged by two-dimensional echocardiography, three-dimensional echocardiography, and cineventriculography, the measured volumes were compared, and three-dimensional echocardiography was found to have significantly less measurement error than two-dimensional echocardiography and single-plane cineventriculography. Biplane cineventriculography resulted in greater mean error than three-dimensional echocardiography, however, the difference was not significant by statistical test16−17.

Three-dimensional Echocardiography in Humans

In a study of 15 healthy volunteers, three-dimensional echocardiography was compared with magnetic resonance imaging.18 In addition, in 10 of these subjects, two-dimensional echocardiography was also obtained. Three-dimensional (3D) echocardiographic measurement of left ventricular end-diastolic and end-systolic volumes (EDV and ESV) compared favorably with magnetic resonance imaging (MRI): r=.92 and .81; SEE=6.99 and 4.01 mL; regression equations: 3D EDV=0.84 (MRI EDV)+22.0 and 3D ESV=0.51 (MRI ESV)+18.2, respectively (Figs 5 and 6). Two-dimensional echocardiography compared less favorably with magnetic resonance imaging: r=.48 and .70; SEE=20.5 and 5.6 mL, respectively. The end-diastolic volume SEE for two-dimensional echocardiography is threefold that for three-dimensional echocardiography. For total end-diastolic and end-systolic endocardial surface areas, three-dimensional echocardiography correlated very well with magnetic resonance imaging (r=.84 and .84; SEE=8.25 and 4.89 cm²). Interobserver variability for three-dimensional echocardiography ranged from 5% to 8%, and for magnetic resonance imaging from 6% to 9%. In these same 15 subjects, left ventricular mass was computed by three-dimensional echocardiography, and in 10 subjects by two-dimensional echocardiography, and then compared with the mass obtained by magnetic resonance imaging. End-diastolic and end-systolic mass (EDM and ESM) by three-dimensional echocardiography compared favorably with magnetic resonance imaging:
Comparison of left ventricular volume determination by three-dimensional echocardiography and two-dimensional echocardiography with cineventriculography was also carried out in 14 patients undergoing cardiac catheterization. The correlation coefficients were higher and the SEE values lower for three-dimensional echocardiography versus cineventriculography end-diastolic volume, end-systolic volume, and ejection fraction than they were for two-dimensional echocardiography versus cineventriculography. The end-diastolic volume SEE for two-dimensional echocardiography is almost twice that of three-dimensional echocardiography. These results are summarized in Table 3.

Other Investigations of Three-dimensional Echocardiography

Other studies have used a similar approach to trans-thoracic three-dimensional echocardiography. An acoustic spatial locating system has been used in conjunction with a reconstruction algorithm to compute ventricular volume in several in vitro investigations. These studies largely confirm the results reported above. Su and coworkers investigated in an in vivo canine model the minimum number of images necessary to accurately reconstruct the ventricle. They concluded that in a large percentage of cases, left ventricular volume could be accurately quantitated with 8 to 12 images. The same authors have compared three-dimensional echocardiographic volume determinations with two-dimensional determinations in excised left ventricles of normal and abnormal shapes and found that three-dimensional echocardiography had the lowest SEE. In another study, they compared in excised left ventricles three-dimensional echocardiographic volume determination with angiographic volume determination and found the SEE of three-dimensional echocardiography to be approximately half that of biplane angiography. They have also used an in vivo canine preparation in which the left ventricular volume could be varied and continuously measured. Volume computation by three-dimensional echocardiography in this model was also shown to be highly accurate and when compared with conventional two-dimensional echocardiographic methods to be superior with a lower SEE. Jiang and coworkers have shown the usefulness of three-dimensional echocardiography for evaluation of right ventricle volume and mass. Mele and coworkers have shown in beating and excised dog hearts that three-dimensional echocardiography is able to estimate left ventricular mass more accurately than wall thickness methods. Three-dimensional reconstruction of the heart is also being carried out by other investigators using transesophageal echocardiography for image acquisition. However, this approach will be limited to selected patients, is not as widely applicable as trans-thoracic three-dimensional reconstruction, and is not within the scope of this review.

Limitations of Three-dimensional Echocardiography

Three-dimensional echocardiography adds to the information available for analysis by registering all images in a single spatial coordinate system. This enables the line of intersection display to reduce image plane positioning errors, permits measurements between image planes, and eliminates geometric assumptions for volume and mass computation. Nevertheless, the process of three-dimensional data reduction and analysis at the present time requires the ventricular boundaries to be manually traced by the operator, as does two-dimen-
sional echocardiography. This step creates the potential for human error and interobserver variability. A number of approaches to automatic or semiautomatic boundary detection are under development but have not been established as acceptable for general application. Acquistion of a set of images for three-dimensional reconstruction takes only 6 to 8 minutes and may be easily incorporated into the normal examination routine. However, the process of manual boundary tracing adds 1 or 2 minutes to analysis time for each boundary traced, depending on the image quality. For a routine. However, the process of manual boundary tracing adds 1 or 2 minutes to analysis time for each boundary traced, depending on the image quality. For a typical ventricular mass determination using eight images, there would be 16 traced boundaries. Each image sequence is first viewed as a cine loop to display the boundary in motion, and then the selected frame is traced. Experience has shown that accuracy and reproducibility are optimized by tracing on the “white side” of the black-white boundary. The three-dimensional echocardiographic system is available at reasonable cost as an add-on to existing echocardiographs and operates without affecting the host system. Its operation is guided by menus displayed on the computer screen and is easily learned. Use of the line of intersection display requires the operator to learn new eye-hand coordination skills that are generally achieved rather quickly.

**Implications for Quantitative Echocardiography**

Conventional echocardiography has been and remains an examination providing primarily qualitative information despite attempts to introduce standardized quantitation. These attempts have failed because the underlying technology, and therefore the data it produces, was imprecise and poorly reproducible in routine practice. Three-dimensional echocardiography is a technological step forward addressing some of the underlying causes of that imprecision and poor reproducibility, namely, the lack of registration of image position and orientation, the need to use geometric assumptions, and the inability to visualize anatomic landmarks in directions orthogonal to the real-time image. Although these do not account for all variability in conventional echocardiography, they have been major contributors, and investigations using three-dimensional echocardiography have suggested that their elimination leads to substantial improvement in quantitative results. A threefold improvement in interobserver variability for simple measurements and for three-dimensional volume computation has been achieved along with a twofold to threefold improvement of accuracy for volume computation by three-dimensional reconstruction. Comparison with magnetic resonance imaging and cineventriculography suggests that three-dimensional echocardiography provides comparable data noninvasively, repeatedly, and at lower expense with greater patient acceptance. Additional studies will be required for validation, but the available data strongly suggest that

**TABLE 2. Left Ventricular Volume and Mass by Three-dimensional and Two-dimensional Echocardiography Versus Nuclear Magnetic Resonance Imaging**

<table>
<thead>
<tr>
<th></th>
<th>3D vs MRI</th>
<th>2D vs MRI</th>
<th>3D vs CINE</th>
<th>2D vs CINE</th>
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<tr>
<td></td>
<td>EDV</td>
<td>ESV</td>
<td>EDV</td>
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<td>15 Normal subjects</td>
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<tr>
<td>3D vs MRI EDV</td>
<td>.92</td>
<td>6.99 mL</td>
<td>.88</td>
<td>7.0 mL</td>
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<td>3D vs MRI ESV</td>
<td>.81</td>
<td>4.01 mL</td>
<td>.89</td>
<td>10.6 g</td>
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<tr>
<td>3D vs MRI EDM</td>
<td>.89</td>
<td>10.6 g</td>
<td>.92</td>
<td>9.24 g</td>
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<tr>
<td>3D vs MRI ESM</td>
<td>.92</td>
<td>9.24 g</td>
<td></td>
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<td>10 Normal subjects</td>
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<tr>
<td>2D vs MRI EDV</td>
<td>.48</td>
<td>20.5 mL</td>
<td>NS</td>
<td></td>
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<tr>
<td>2D vs MRI ESV</td>
<td>.70</td>
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<td>&lt;.025</td>
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<td>3D vs MRI EDV</td>
<td>.90</td>
<td>7.0 mL</td>
<td>&lt;.001</td>
<td>3D=0.72 (MRI)+29.7</td>
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<tr>
<td>3D vs MRI ESV</td>
<td>.88</td>
<td>3.1 mL</td>
<td>&lt;.001</td>
<td>3D=0.45 (MRI)+20.2</td>
</tr>
<tr>
<td>10 Normal subjects</td>
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<td></td>
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</tr>
<tr>
<td>2D vs MRI EDM</td>
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<td>21.8 g</td>
<td>&lt;.030</td>
<td>2D=0.76 (MRI)+27.7</td>
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<td>2D vs MRI ESM</td>
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<td>23.8 g</td>
<td>&lt;.020</td>
<td>2D=0.91 (MRI)+13.0</td>
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<td>3D vs MRI EDM</td>
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<td>10.4 g</td>
<td>&lt;.001</td>
<td>3D=0.72 (MRI)+32.2</td>
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<td>3D vs MRI ESM</td>
<td>.90</td>
<td>10.8 g</td>
<td>&lt;.001</td>
<td>3D=0.86 (MRI)+13.2</td>
</tr>
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</table>

3D indicates three-dimensional echocardiography; 2D, two-dimensional echocardiography; MRI, nuclear magnetic resonance imaging; EDV, end-diastolic volume; ESV, end-systolic volume; EDM, end-diastolic mass; and ESM, end-systolic mass.

**TABLE 3. Left Ventricular Volume by Three-dimensional and Two-dimensional Echocardiography Versus Cineventriculography**

<table>
<thead>
<tr>
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<th>3D vs CINE</th>
<th>2D vs CINE</th>
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<tbody>
<tr>
<td></td>
<td>r  SEE</td>
<td>r  SEE</td>
</tr>
<tr>
<td>EDV</td>
<td>.88 16 mL</td>
<td>.76 28 mL</td>
</tr>
<tr>
<td>ESV</td>
<td>.96 9 mL</td>
<td>.72 29 mL</td>
</tr>
<tr>
<td>EF</td>
<td>.84 0.07</td>
<td>.55 0.12</td>
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</table>

3D indicates three-dimensional echocardiography; CINE, cineventriculography; 2D, two-dimensional echocardiography; EDV, end-diastolic volume; ESV, end-systolic volume; and EF, ejection fraction.
three-dimensional echocardiography may be sufficiently accurate and reproducible to monitor small biologic changes, such as the regression of left ventricular mass, in individual subjects. We expect that by the year 2000 all echocardiographic imaging will incorporate, where clinically indicated, three-dimensional scanning, image reconstruction, and quantitative analysis. 35

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