Quantitation of Human Left Ventricular Mass and Volume by Two-dimensional Echocardiography: In Vitro Anatomic Validation

JOSEPH W. HELAK, M.D., AND NATHANIEL REICHEL, M.D.

SUMMARY The reliability of two-dimensional echocardiographic (2-DE) quantitation of left ventricular (LV) section area, volume and myocardial mass was assessed in vitro in 13 postmortem human hearts (LV weight 115–454 g). The pathologic diagnoses included: two normal, five coronary artery disease with infarction and/or aneurysm, three valvular heart disease, two cardiomyopathy and one left ventricular hypertrophy. Hearts were divided into six to 24 short-axis slices (n = 123), imaged in a tank filled with mineral oil and the images planimetered. Calibrated photographs and actual LV weight served as reference standards. Estimates of section LV cavity volume and myocardial volume were derived by multiplying the appropriate area by section thickness. Section LV mass was obtained by multiplying the myocardial volume by myocardial density. Total LV cavity volume and myocardial mass were derived using Simpson's rule and a short axis area–apical length method. In absolute terms, 2-DE underestimated LV cavity area but accurately estimated LV myocardial area. Excellent correlations were obtained between 2-DE and photographic standards for section cavity area (r = 0.95) and volume (r = 0.90). Simpson's rule (r = 0.97) and area–length (r = 0.82, r = 0.90, excluding one heart with a bizarre shaped LV cavity secondary to extensive mural thrombus) estimates of total LV cavity volume also correlated well with reference standards. Similarly, section LV myocardial area correlated well with photographic myocardial area (r = 0.89) and 2-DE and photographic estimates of section LV mass correlated well with actual LV weight (r = 0.92 and 0.96). Consequently, total LV mass obtained with Simpson's rule or the area–length method was highly reliable (r = 0.93 and 0.92, respectively). We conclude that 2-DE can provide reliable estimates of LV volume and mass using the short-axis Simpson's rule or area–length methods and appropriate regression corrections. The area–length method is simple enough to permit clinical application.

TWO-DIMENSIONAL ECHOCARDIOGRAPHY (2-DE) is a potentially valuable noninvasive tool for the quantitative assessment of left ventricular (LV) volume and myocardial mass in man. Validation studies of 2-DE in several laboratories have demonstrated the accuracy of in vitro canine LV volume and mass in symmetric and asymmetric ventricles.1–3 LV volume determination in a beating dog heart preparation,4, 5 in vivo canine LV volume and mass,6–10 and in vitro human LV cast volume.11 Moderately good correlation of human in vivo 2-DE LV volume and ejection fraction with angiographic and/or radionuclide methods has also been reported.8, 12–18 However, 2-DE assessments of LV volume and mass have not been validated directly with quantitative anatomy in man. The present study was designed to test the accuracy of 2-DE imaging of individual cardiac sections and of derived estimates of total LV volume and mass in the postmortem human heart.

Methods

Specimen Collection

Thirteen postmortem human hearts, 300–1100 g, with a wide range of pathologic diagnoses (table 1) were obtained from the necropsy service. Nine were...
formalin-fixed for 24 hours and hand-sectioned in the short-axis plane into six to 11 sections (0.5–3 cm thick) as part of the routine autopsy examination. Four were specially prepared after formalin fixation, being embedded in a gelatinous base and sectioned in the short-axis plane using a motorized slicer set at 0.5 cm thickness producing from 13–24 uniform sections per heart.

The thickness of each short-axis section was directly measured at three to five sites with a millimeter rule and the mean thickness recorded. Because the sections could not be directly planimetered, the superior and inferior surfaces of each section were photographed with a calibration scale on a Xerox copier, model 4000 (fig. 1). Each section was then suspended on an 18-gauge needle and a specially designed stand placed in a glass tank filled with mineral oil. Two-dimensional echocardiographic images were recorded of each section in a short-axis orientation using a Varian VR 3000 phased-array sector scanner with a 2.25-MHz transducer. The transducer was handheld, 8–10 cm from the section. Gain, reject, damping and compression controls were adjusted to produce as complete an image as possible with the least gain. In general, overall gain and compression were high, regional (slide-bar) amplification, contrast and damping low.

To obtain adequate images in some instances, two adjacent 0.5-cm sections were sutured together with 3–0 silk suture. To obtain slice thickness by 2-DE, sections were stacked up from base to apex and images recorded in a projection analogous to the in vivo apical view. Strong interfaces were generated between slices and 50% of each interface thickness was included in each slice thickness, which was traced onto clear plastic and measured on a digitizer. The thickness of the most superior section of each left ventricle could not be isolated in this view because of the attached great vessels and atria. Therefore, these 2-DE thicknesses were interpolated using a regression analysis and measured LV section thickness. The 2-DE images were recorded on a Sanyo ½-inch videotape recorder.

With the corresponding anatomic specimen as a reference, LV epicardium and endocardium were highlighted on each of the photographic images (fig. 2A). Four or five representative, calibrated 2-DE images of each section were traced from videotape onto clear plastic with a fine-tip pen using real-time, slow-motion and stop-frame analysis and a 12-inch television screen. The LV cavity area excluded all endocardial echoes while the thickness of the finest outer line of epicardial echoes seen anywhere on the section

<table>
<thead>
<tr>
<th>Pt</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Pathologic diagnosis</th>
<th>Total heart weight (g)</th>
<th>LV weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>69</td>
<td>Rheumatic heart disease involving mitral valve; prostatic aortic valve; biventricular hypertrophy; coronary artery disease with old anteroseptal myocardial infarction.</td>
<td>1000</td>
<td>290</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>74</td>
<td>Coronary artery disease with old anteroseptal and inferior wall infarctions, apical aneurysm.</td>
<td>450</td>
<td>171</td>
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<tr>
<td>3</td>
<td>F</td>
<td>56</td>
<td>Concenctric left ventricular hypertrophy; coronary artery disease without infarction.</td>
<td>351</td>
<td>149</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>58</td>
<td>Coronary artery disease with old nontransmural arterolateral and inferior wall infarctions.</td>
<td>700</td>
<td>202</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>60</td>
<td>Normal</td>
<td>400</td>
<td>159</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>54</td>
<td>Severe three-vessel coronary artery disease with multiple old transmural and nontransmural infarctions and an apical aneurysm; right ventricular hypertrophy.</td>
<td>720</td>
<td>223</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>32</td>
<td>Mitral regurgitation due to myxomatous mitral valve s/p porcine valve replacement; infarcted posterolateral and posteroseptal regions of left ventricle due to coronary embolus; large left ventricular mural thrombus.</td>
<td>1010</td>
<td>454</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>72</td>
<td>Coronary artery disease with old infarction posterior left ventricle and possible acute anteroseptal infarction.</td>
<td>300</td>
<td>116</td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>63</td>
<td>Restrictive cardiomyopathy—primary amyloidosis</td>
<td>—</td>
<td>202</td>
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<tr>
<td>10</td>
<td>M</td>
<td>43</td>
<td>Congestive cardiomyopathy</td>
<td>850</td>
<td>293</td>
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<tr>
<td>11</td>
<td>M</td>
<td>37</td>
<td>Aortic stenosis, biventricular hypertrophy</td>
<td>1100</td>
<td>377</td>
</tr>
<tr>
<td>12</td>
<td>M</td>
<td>66</td>
<td>Normal</td>
<td>350</td>
<td>115</td>
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<tr>
<td>13</td>
<td>—</td>
<td>—</td>
<td>Concentric left ventricular hypertrophy</td>
<td>—</td>
<td>254</td>
</tr>
</tbody>
</table>

**Table 1. Age, Sex, Pathologic Diagnosis and Heart Weight**
perimeter was excluded from total LV area throughout the image (fig. 2B). When, occasionally, image dropout occurred on the lateral margin of the section, the boundary was extrapolated. The 2-DE images were traced by blinded observers without knowledge of other data. Total LV area and LV cavity area were measured on each photographic and 2-DE image using a planimetry program validated by comparison to manual planimetry on irregular test images of known area and by comparison to calculated area of circular and rectangular test images of known radius or linear dimension. Program results were essentially identical with those of geometric calculation and manual planimetry. Images were digitized, calculations performed and statistical analysis was made on a Hewlett-Packard 9025A programmable calculator equipped with a high-resolution digitizing board (0.001 mm) and high-speed plotter.

**Figure 1.** Representative short-axis heart section (left) with corresponding calibrated photograph (center) and two-dimensional echocardiographic image (right).

**Figure 2.** (A) Photographic image shown in figure 1 with endocardium and epicardium of the surface nearest to the camera outlined. (B) Two-dimensional echocardiographic image shown in figure 1, with total left ventricular (LV) area and LV cavity area outlined. LV cavity area excludes endocardial echoes, while the thickness of the finest outer line of epicardial echoes seen anywhere on the section perimeter is excluded from total LV area throughout the image. The finest line of epicardial echoes is identified by the arrow.
For photographic images, the mean of the superior and inferior surface areas was used to represent the mean area of each section. For 2-DE images, the mean of at least four images was used to represent the section area. Both photographic and 2-DE LV myocardial areas were determined by subtraction of LV cavity area from total LV area.

Videotapes of 69 2-DE sections were traced independently by two observers to determine inter-observer variation.

Geometric Models

Photographic and 2-DE volumes were determined for each nonapical section by multiplying the appropriate area (A) (LV myocardium or LV cavity) by section thickness (T) (fig. 3). The directly measured section thickness was used to calculate the photographic volume. Apical section volume was determined using the formula for an ellipsoidal volume segment:

\[
\frac{AT}{2} + \frac{\pi T^3}{6}.
\]

LV section mass was obtained by multiplying the LV myocardial volume by the accepted value for density of myocardium (1.055 g/ml).

Total LV muscle volume and LV cavity volume for each heart were derived from the 2-DE and photographic images using Simpson’s rule. We also tested an area-length method reported by Wyatt and co-workers to provide accurate LV volume and mass in the canine left ventricle.\(^7\) Simpson’s rule merely added the volume of all sections together (fig. 4), while the area-length volume was calculated as \(\frac{5}{6} (A_{\text{pap}}) L\), where \(A_{\text{pap}}\) = area at high papillary muscle level and \(L = \) LV length (fig. 4).

LV Weight

After the photographic and 2-DE images were obtained, the sections were blotted dry, dissected with removal of the right ventricle, atria, great vessels and epicardial fat and the LV sections weighed on a triple-beam balance. All section weights were added to determine total LV weight per specimen.

The specific gravity of portions of four left ventricles weighing 43–79 g was determined by volume displacement using a 250-ml beaker and 100-ml graduated cylinder.

Statistics

The 2-DE data, photographic data and LV weights were compared by standard least-squares linear regression analysis.

The regression line for each relationship examined was compared with the line of identity for that variable using a standard statistical method for comparison of slopes.\(^9\) The regression equations for Simpson’s rule approximations and area-length approximations of the same variable were compared in a similar manner.

Results

Individual Cardiac Sections

One hundred twenty-three cardiac sections were studied anatomically, photographically and with 2-DE to determine LV cavity area and volume and LV myocardial area and mass as described above.

Section Area and Thickness

The 2-DE LV cavity area showed a close linear correlation with photographic LV cavity area \((r = 0.95)\) over the range 0–31.5 cm\(^2\) (fig. 5A). The least-squares linear regression equation relating 2-DE LV cavity area to photographically measured LV cavity area was \(A_{2-DE} = 0.76 A_{\text{photo}} - 0.1\) (SEE = 1.8 cm\(^2\)). Thus, in absolute terms, 2-DE markedly underestimated photographic cavity area.

The 2-DE total LV area also correlated well with photographic total LV area \((r = 0.94)\) over the range 6.4–85.8 cm\(^2\) (fig. 5B). The regression equation relating 2-DE total LV area to photographic total LV area was \(A_{2-DE} = 0.96 A_{\text{photo}} - 0.21\) (SEE = 6.8 cm\(^2\)).

The 2-DE LV myocardial area correlated slightly less well with photographic LV myocardial area \((r = 0.89)\) (fig. 5C). The regression equation relating 2-DE LV myocardial area to photographic LV myocardial area was myocardial \(A_{2-DE} = 0.97\) myocardial \(A_{\text{photo}} + 0.98\) (SEE = 6.9 cm\(^2\), range 6.1–65.4 cm\(^2\)).

The 2-DE LV section thickness showed a close linear correlation with actual thickness \((r = 0.88)\) over
a narrow range (0.3–1.6 cm, fig. 5D). The regression equation relating 2-DE section thickness to directly measured thickness was $T_{DE} = 0.85 T$ actual ± 0.13 (SEE = 0.14 cm).

Section Volume and Mass

The 2-DE section LV cavity volume correlated well with photographic section LV cavity volume ($r = 0.90$) over the range 0–63.8 ml. The regression equation relating 2-DE section LV cavity volume to photographic section LV cavity volume was $V_{DE} = 0.65 V_{photo} + 0.56$ (SEE = 3.2 ml).

While 2-DE LV section mass correlated well with actual section LV weight ($r = 0.92$) over the range 0.3–84 g (fig. 6A), the regression equation relating 2-DE section LV mass to directly measured LV weight was $M_{DE} = 1.42$ weight $-1.8$ (SEE = 9.9 g). Thus, in absolute terms, 2-DE markedly overestimated LV weight.

Similarly, photographic section LV mass showed a close correlation ($r = 0.96$) with actual section LV weight over the range 0.3–84 g (fig. 6B), but the regression equation relating photographic section LV mass to directly measured LV section weight was $M_{photo} = 1.3$ weight $+0.19$ (SEE = 6.1 g). Thus, the photographic method also overestimated LV section weight. The relationships of 2-DE section LV mass and photographic section LV mass to actual section LV weight were not statistically different.

Total LV Mass and Volume

The 2-DE total LV mass and volume correlated extremely well with total LV weight and photographic reference standards.
Area-length Method

Area-length estimates of total LV mass and volume correlated well with reference standards in the 13 study hearts but not as well as Simpson’s rule estimates. The 2-DE total LV cavity volume was related to photographically determined total LV cavity volume by the equation $V_{2-DE} = 0.77 \, V_{photo} + 1.8$ ($r = 0.82$, SEE = 38.4 ml). This relationship was markedly distorted by one heart (patient 7; table 1) that contained a large, markedly irregular thrombus that occupied more than 50% of the LV cavity and produced a bizarre cavity shape. With this heart excluded, the equation relating area-length 2-DE total LV cavity volume to photographically determined total LV cavity volume was $V_{2-DE} = 1.07 \, V_{photo} - 11.76$ ($r = 0.90$, SEE = 29.0, range 12.4–183.1 ml) (fig. 8A). The regression equation relating area-length 2-DE total LV mass to photographic total LV mass was $M_{2-DE} = 1.21 \, M_{photo} - 4.61$ ($r = 0.93$, SEE = 71.1 g, range = 146.5–612.6 g) (fig. 8B). This slope did not differ significantly from unity. In contrast, the equation relating area-length 2-DE total LV mass to actual total LV weight had a slope much greater than unity: $M_{2-DE} = 1.66$ weight $- 23.83$ ($r = 0.92$, SEE = 74.7 g) (fig. 8C). Photographically determined area-length total LV mass showed a similar relationship to actual total LV weight: $M_{photo} = 1.67$ weight $- 35.86$ ($r = 0.99$, SEE = 29.4 g).

Specific Gravity

The specific gravity of the LV myocardium from hearts in this study determined by volume displacement was 0.964 g/ml.

Interobserver Variation

Videotapes of 69 2-DE sections from seven hearts were reviewed and traced independently by two observers to determine interobserver variation in area measurement from the same recording. Excellent linear correlation was obtained for 2-DE section total LV area (slope = 0.99 $r = 0.97$, SEE = 4.9 cm²). Likewise, 2-DE section LV cavity area showed close linear correlation between observers (slope = 0.90 $r = 0.91$, SEE = 2.1 cm²). The 2-DE section thickness also correlated well between observers ($r = 0.96$, slope = 0.91, SEE = 0.1 cm). Interobserver variation in performing the recordings was not assessed.

Discussion

The accuracy of 2-DE assessment of LV volume and mass has been validated in canine models in vivo7–10 and in vitro.11–14 Numerous studies11–18 have also examined the validity of 2-DE quantitative assessment of LV volume, LV mass and ejection fraction in man by comparing 2-DE with angiographic and/or radionuclide methods. Overall, comparing 2-DE to angiography, LV end-systolic volume has been more reliable ($r = 0.86–0.96$) than either ejection fraction ($r = 0.73–0.94$) or LV end-diastolic volume ($r = 0.92–0.96$).

Simpson’s Rule

Thirteen human left ventricles weighing 115–454 g had photographically determined LV cavity volumes of 12.4–217.9 ml. The regression equation relating total 2-DE LV cavity volume to photographically determined total LV cavity volume was $V_{2-DE} = 0.75 \, V_{photo} - 2$ ($r = 0.97$, SEE = 13.9 ml) (fig. 7A). The regression equation relating 2-DE total LV mass to photographically determined total LV mass was $M_{2-DE} = 1.05 \, M_{photo} - 6.1$ ($r = 0.94$, SEE range 180–613 g) (fig. 7B). The regression equation relating 2-DE total LV mass to actual total LV weight was $M_{2-DE} = 1.43$ weight $- 21.8$ ($r = 0.93$, SEE = 59.5 g) (fig. 7C). As expected, photographically determined total LV mass also correlated well with actual total LV weight ($r = 0.98$). The regression equation relating photographic total LV mass to actual total LV weight was $M_{2-DE} = 1.36$ weight $- 13.3$ (SEE = 26.5 g).

FIGURE 6. (A) Comparison of two-dimensional echocardiographic section measurement of left ventricular (LV) mass (vertical axis) and actual section LV weight (horizontal axis). (B) Comparison of photographic section LV mass and actual section LV weight.
When 2-DE was compared only to biplane angiography, the apparent reliability of ejection fraction increased ($r = 0.84-0.94$) but the reliability of LV volume estimates was not significantly altered. In a comparison of 2-DE and radionuclide studies to biplane angiography, one study showed no major difference in reliability between 2-DE and radionuclide estimates of end-diastolic volume index, end-systolic volume index or ejection fraction. However, others have observed a poorer correlation between radionuclide ejection fraction and angiographic ejection fraction than between 2-DE and angiographic ejection fraction (2-DE vs angio, $r = 0.94$; radionuclide vs angio, $r = 0.80$). Comparisons of 2-DE and radionuclide ejection fractions have shown correlation coefficients of 0.75 and 0.92. Excellent results have been obtained in canine studies of in vitro and in vivo 2-DE LV mass compared to actual LV weight ($r = 0.86-0.97$). However, comparison of human 2-DE in vivo LV mass estimates to those of biplane angiography has given less satisfactory results ($r = 0.80$).

Most investigators have concluded that 2-DE ejection fraction has a close enough correlation with angiography to allow meaningful clinical application. However, volume measurements by 2-DE in four studies have underestimated angiographic LV volume with a large standard error, which limits clinical applicability. In contrast, one study indicates that 2-DE can accurately predict angiographic LV volume. The 2-DE estimation of LV mass has appeared to have limited clinical applicability.

This inconsistency in conclusions is not surprising, given the many variables that must influence the results reported. A fundamental problem is the inherent limitation of 2-DE image resolution, which is accentuated by the need to trace images using stop-frame analysis, and results in limited accuracy of boundary identification of endocardium and epicardium. A second problem relates to the many different geometric formulas for estimating LV volume used in different studies (table 2). However, using biplane angiographic and radionuclide methods to validate quantitative 2-DE can be misleading because these methods also indirectly estimate quantitative anatomy. This was demonstrated by Bommer et al. in a recent study comparing angiographic and 2-DE estimates of LV volume to direct measurements of LV casts and working LV models in vitro. When compared to this independent reference system, angiography appeared no more accurate than 2-DE. A previous report from our laboratory comparing M-mode echocardiographic LV mass estimates to anatomic weight also showed the importance of using an anatomic reference rather than angiography for
validation whenever possible. In that study, several echo LV mass methods validated previously by angiography correlated relatively poorly with actual LV weight, while the optimal method obtained by direct comparison to LV weight was far more reliable.

To better define the limitations of the 2-DE method itself in man, we chose to assess the quantitative accuracy of 2-DE imaging of the area of individual cardiac short-axis sections obtained from postmortem human hearts. Short-axis sections were selected because they generally provide optimal endocardial imaging, and thus, should have the greatest potential for accurate quantitation. The 2-DE data were compared to two direct anatomic reference standards: an in vitro photographic method for sectional LV area and volume and the actual LV section weight. Derived estimates of total LV cavity volume and mass obtained using Simpson’s rule and an area-length method shown7 to be potentially clinically applicable were also compared with the photographic and LV weight standards. Direct comparison of photographic and 2-DE image areas permitted assessment of the impact of image properties per se on quantitation. Conversely, use of the Simpson’s rule and area-length approximation for both 2-DE and photographic methods made it possible to assess the impact of the geometric method independent of a particular image type. A wide range of pathologic findings, including myocardial infarction, LV aneurysm and severe LV dilation, was present in this series.

Our results show that, in this in vitro system, excellent correlations are obtained between 2-DE and photographic standards for section LV cavity area and volume. Thus, Simpson’s rule estimates of total LV cavity volume are also reliable. Area-length estimates of total LV cavity volume also correlate well with our reference standard when cavity shape is not bizarrely distorted. In one heart, a huge irregular thrombus did markedly affect the area-length volume estimate, but a second heart (no. 10) with an ordinary apical thrombus was accurately assessed. Moreover, myocardial infarction (five hearts), LV dilatation (five hearts) or LV aneurysm (two hearts) did not invalidate the area-length volume estimate. Therefore, this simple area-length method may give reliable results in the common types of LV shape distortion that are clinically encountered. Volume and mass estimates based on long-axis, four-chamber and two-chamber views, which include more of the LV perimeter, would probably deal more effectively with abnormalities of LV shape than a short-axis area-length method. However, endocardial identification may not be as reliable as in short axis. Unfortunately, in the present study, the sectioning method, which permitted direct comparison of echo image with original target, also precluded evaluation of other 2-DE views. The reliability of 2-DE volume estimates obtained using

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**Figure 8.** (A) Comparison of area-length total left ventricular (LV) cavity volume by two-dimensional echocardiography (2-DE) (vertical axis) and by calibrated photograph (horizontal axis). One heart with a large irregular thrombus occupying greater than 50% of the LV cavity was excluded from this analysis (see Results). (B) Comparison of area-length total LV mass by 2-DE and by calibrated photograph. (C) Comparison of area-length 2-DE total LV mass and actual total LV weight.
either method we tested appears to be comparable statistically to that reported for angiographic methods in vitro. However, in absolute terms, 2-DE underestimates LV cavity volume as compared to Simpson's rule photographic estimates. This suggests that underestimation is related to the properties of the echo image. The relatively thick endocardial echo display probably encroaches on the cavity area. This problem is compounded in heavily trabeculated areas or those containing papillary muscle, where fine extensions of LV cavity may actually be obliterated by thick endocardial echoes. Echo line thickness is gain-dependent, but images used in this study were all done at the lowest gain that provided a complete image. Also, problems of this type may be heavily dependent on the 2-DE instrument used. Validation of quantitation obtained with one type of 2-DE system may not therefore be applicable to others.

Using Simpson's rule, 2-DE reliably predicts actual LV weight (r = 0.93). Results are similar using the area-length method (r = 0.92). The reliability of the 2-DE estimates of LV mass in this in vitro system is similar to that noted in a canine in vitro study. However, 2-DE LV mass appears to be less accurate than biplane angiographic LV mass has been reported to be when compared to LV weight in vitro. In absolute terms, 2-DE systematically overestimates LV weight (slope = 1.43 for Simpson's rule, 1.66 for area-length). Similar overestimation occurs when photographic images are used to estimate LV mass with either Simpson's rule or area-length geometry, so the major problem is not due to 2-DE imaging. One component of the overestimate is the unexpectedly low specific gravity of our formalin-fixed, oil-immersed sections. However, the reduction in specific gravity accounted for only 22% of the mean overestimate of LV weight. We conclude that most of the LV mass overestimate results from the geometric methods used. The Simpson's rule approximation, the best available geometric method, ignores the irregularity of the trabeculated endocardial surface, which can be marked in hearts which are fixed at small cavity volume, and can vary throughout the thickness of even a thin section of LV. Inclusion of small recesses of the LV cavity in LV mass probably results. Because post-mortem LV volume is often smaller than in vivo end-diastolic volume, this problem may be less important in vivo. In any event, use of a regression relationship compensates for the problem.

Because of the many differences between in vitro and in vivo 2-DE, estimates of in vivo human LV mass must also be compared to anatomic LV weight, as has been done with M-mode echocardiography and biplane angiography. The 2-DE LV volume methods evaluated in this study must also be compared with in vivo angiographic volumes. Moreover, further evalua-

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### Table 2. Summary of Geometric Formulas, Two-dimensional Echocardiographic Projections and Reference Methods Used in Different Studies to Approximate Left Ventricular Volume

<table>
<thead>
<tr>
<th>Authors</th>
<th>2-DE projections</th>
<th>Geometric formulas</th>
<th>Reference method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bommer et al.</td>
<td>Biplane, apical</td>
<td>Simpson's rule</td>
<td>Biplane angiography</td>
</tr>
<tr>
<td>Starling et al.</td>
<td>Biplane, apical</td>
<td>Simpson's rule</td>
<td>Biplane angiography and radionuclide method</td>
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<tr>
<td>Carr et al.</td>
<td>Long axis, short axis Axial (RAO equivalent)</td>
<td>V = \frac{\pi L1 L2 L3}{6} L1 from image with longest apparent long axis</td>
<td>Biplane angiography and single-plane angiography</td>
</tr>
<tr>
<td>Schiller et al.</td>
<td>Short axis, mitral leaflet tips (equivalent to LAO)</td>
<td>Simpson's rule</td>
<td>Biplane angiography</td>
</tr>
<tr>
<td>Folland et al.</td>
<td>Short axis, mitral leaflet tips Short axis, base of papillary muscle Apical view (4-chamber)</td>
<td>Modified Simpson's rule Ellipsoid using biplane data Ellipsoid using single-plane data Hemisphere-cylinder model Modified ellipsoid model</td>
<td>Biplane angiography, radionuclide ventriculograms</td>
</tr>
<tr>
<td>Chaudry et al.</td>
<td>Short axis, mitral valve tip apical view (RAO equivalent)</td>
<td>V = \frac{4}{3} \pi L1/2 D_1/2 D_2/2</td>
<td>Single-plane angiography</td>
</tr>
<tr>
<td>Quinones et al.</td>
<td>Measure short axis at base, mid-LV and distal LV in apical 4-chamber view and apical RAO equivalent view Measure short axis at base and mid-LV in long axis Estimate fractional shortening of LV long axis from apical contraction</td>
<td>EF = \frac{Dd1 - Dd2}{Dd2} + Dd2 / Dd1 \cdot \Delta L</td>
<td>Single-plane angiography, Gated blood pool imaging</td>
</tr>
</tbody>
</table>

Abbreviations: RAO = right anterior oblique; LAO = left anterior oblique; LV = left ventricular.
tion in vitro and in vivo of other geometric approaches is clearly necessary. However, this quantitative in vitro study provides a useful basis for such efforts, demonstrates the limitations of quantitative 2-DE imaging with present instrumentation, and shows the potential clinical applicability of a simple short-axis area-length method to the human left ventricle for quantitation of both mass and volume.

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