Quantitative Detection of Regional Left Ventricular Contraction Abnormalities by Two-dimensional Echocardiography

I. Analysis of Methods

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SUMMARY Different approaches to the quantification of regional left ventricular (LV) function from two-dimensional echocardiographic (2-D echo) images were assessed for their ability to optimize interobserver reproducibility in a heterogeneous patient population and to minimize the variability of regional function observed in a homogeneous normal population. Area, hemiaxis and perimeter measurements were examined, as were the effect of the degree of image subdivision into halves, quadrants or octants. Each approach was also tested using both a fixed and a floating frame of reference for the definition of a regional-axis system. The area method was consistently superior to either linear method in optimizing both reproducibility and variability. Reproducibility decreased inversely with the degree of subdivision. The axis-system frame of reference had no effect on reproducibility. The floating-axis system yielded the same variability as the fixed system for short-axis sections at the mitral valve level, but slightly less variability for a papillary muscle level section. We conclude that area-based methods are superior for the evaluation of regional LV function with 2-D echo, but the degree of subdivision of the image and the frame of reference chosen do not greatly affect reproducibility or variability and should be chosen based on their performance in a well-defined clinical population.

MEASURING regional left ventricular (LV) contraction abnormalities — using axis, perimeter or regional area changes — is well-recognized with angiographic techniques.1-3 Although some investigators have used quantitative approaches to regional LV function with two-dimensional echocardiography (2-D echo),4,5 there is no systematic evaluation of the merits and limitations of different methods of measurement.

The regional function of the entire left ventricle can be characterized by integrating information from multiple parasternal short-axis sections supplemented by long-axis evaluations of the cardiac apex. Parasternal short-axis images weigh heavily into consideration of regional LV function because the entire cardiac circumference can be identified both proximally (at the mitral valve) and distally (at the papillary muscles). This study was designed primarily to evaluate the efficacy of several different approaches to quantifying regional LV function from 2-D echo parasternal short-axis images. We analyzed (1) the geometric parameter of contraction, i.e., perimeter shortening, axis shortening and regional area change; (2) the degree of subdivision of the left ventricle into discrete regions, i.e., halves, quadrants and octants; and (3) the orientation of systolic and diastolic outlines with respect to each other, i.e., a fixed external frame of reference or a floating axis system. Our primary goal was to determine which approach yielded the best reproducibility between independent observers in a heterogeneous patient group and the least variability in a homogeneous group of normal volunteers. From the latter group a normal range was established for application in future studies.

Methods

Subjects

Ten two-dimensional echocardiograms that showed a good resolution of endocardial targets were randomly selected from a series of 71 subjects studied by a standard approach (group 1). These 71 studies were derived from 90 persons in whom quantitative 2-D echo studies were attempted. We had a 79% success rate. Short-axis sections at mitral valve and papillary muscle levels and apical two- and four-chamber views were recorded. Qualitatively, these patients showed a spectrum of regional contraction from normal motion to segmental dyskinesis. Endocardial outlines were traced independently by two experienced observers at end-diastole and end-systole.

In addition, two-dimensional echocardiograms were recorded in the same fashion in 10 normal volunteers (group 2). Endocardial outlines of these volunteers were traced jointly by the same two observers, both in end-diastole and end-systole.

Recording the Two-dimensional Echocardiogram

All echocardiographic records were recorded with the Varian V-3000 phased-array ultrasonograph and stored on the reel-to-reel Panasonic NV3160 tape recording system described previously.6 Mitral valve and papillary muscle sections were recorded with the
transducer as perpendicular to the chest as possible to generate short-axis views that were most nearly circular in each individual. As a rule, the mitral valve cross section was recorded parasternally in the left fourth intercostal space and the papillary muscle cross section slightly laterally, either in the same interspace or one space below. Apical views of the left ventricle were recorded on all subjects in the four-chamber and, when obtainable, two-chamber projections from the region of the cardiac maximum impulse. The four-chamber view was directed superiorly to include both atrioventricular valves and atria. The two-chamber view was obtained from this same position by rotating the transducer clockwise $90^\circ$ to eliminate images of the right-sided cardiac chambers and tilting slightly to the left lateral side to image the left atrium, left ventricle, aorta and mitral valves. A simultaneous ECG and superimposed phonocardiogram were also recorded.

Tracing and Digitizing Images

Endocardial outlines were traced without trying to compensate for imperfections of lateral resolution of the imaging system. In all instances, endocardial outlines were confirmed by playing through preceding and succeeding beats using both real-time and slow-motion playback. For the lower cross-section and apical sections, papillary muscles were included within the confines of LV outlines (fig. 1), consistent with prior reports and standard angiographic practice. Endocardial outlines were traced with a light-pen video digitizer (Electronics for Medicine VVF) and analyzed by computer (Digital Equipment Corp., PDP-11/05).

Subdivision of the Short-axis Images

For each subject studied, the midpoint of the interventricular septum on the LV endocardial surface in diastole was indicated by the observer. From this point, an initial axis was constructed by the computer system to the opposite lateral LV wall so as to divide the image into equal anterior and posterior areas (fig. 2). The initial axis was then bisected sequentially at $45^\circ$ angles. Adjacent octants were recombined to provide regional subdivision into quadrants. The ultimate data for each patient included anterior, septal, posterior and lateral quadrants, as well as antero-septal, anterior and anterolateral, and so on, octants. Measurements were made for the perimeter, principal

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Examples of still-frame two-dimensional echocardiographic images, at end-diastole (DIAS) and end-systole (SYS), from a normal subject in short axis at mitral valve (MV) and papillary muscle (PM) levels and in apical four-chamber (Ap) view demonstrating the convention for outlining the left ventricular cavity along the inner edge of endocardial echos. The small gaps between dashed outlines and left ventricular walls, particularly noticeable in apical views, are caused by loss of subtle endocardial targets associated with still frame imaging and photographic reproduction.
hemi-axis and segmental area of each subdivision to analyze changes in hemi-axis or perimeter length and regional area shrinkage or expansion (fig. 3). The apex, considered as the distal third of the ventricle (fig. 2C), was not subdivided (see below).

The axis system was either maintained as a reference fixed in space for analysis of all systolic images or else the systolic outline was moved — i.e., translated and rotated to superimpose axis systems (fig. 4). Regional function was then quantified for each measurement system using three approaches: (1) hemi-axis shortening, measured as \( \left( \text{diastolic hemi-axis length} - \text{systolic hemi-axis length} \right) \div \text{diastolic hemi-axis length} \times 100 \); (2) perimeter contraction measured as \( \left( \text{diastolic segmental perimeter length} - \text{systolic segmental perimeter length} \right) \div \text{diastolic segmental perimeter length} \times 100 \); (3) regional area shrinkage, measured as \( \left( \text{diastolic area} - \text{systolic area} \right) \div \text{diastolic area} \times 100 \).
Evaluation of the Cardiac Apex

The regional function of the LV apex was quantified from the apical echocardiographic views. The diastolic long axis of the left ventricle was defined by the computer from the midpoint of the mitral valve, as indicated by the operator, to the point on the outline of the apex yielding the longest possible length of this axis. Using the fixed-axis system, the long axis of the systolic outline was determined by finding the intersect points of the diastolic long axis with the systolic outline. With the floating-axis system, the long axis was independently defined for the systolic image in the same manner as for the diastolic outline, and the systolic outline then translated and rotated with respect to diastole so as to align the long axes and midpoints of the two outlines.

The diastolic long axis was then trisected and a perpendicular to the long axis drawn so as to define the apical third of the LV outline (fig. 2). The diastolic and systolic areas of this apical region were then measured. The contraction of the apex was quantified as the percentage change in area. Further subdivision of the apex was not considered warranted because it represents a relatively small portion of the entire ventricle.

Analysis of Data

Interobserver variability for the initial diastolic and systolic outlines in group 1 was determined by dividing the difference between observers by the mean of their observations: [(observer 1 − observer 2) ÷ (mean, observer 1 + observer 2)] × 100.

Interobserver variability of regional function, which was secondarily derived from the primary tracings using the segmental shortening formulas above, was determined as the difference in percent contraction for the same segment between observers. This approach was taken so that small differences between observers occurring in segments with little or no contraction would not be inordinately weighted when expressed in percentage form. (For example, a regional hemiaxis shortening of 1% by observer 1 and 3% by observer 2, while representing a large percentage difference between observers, actually indicates excellent agreement in assessment of regional hemiaxis shortening.)

In the population of 10 normal volunteers (group 2), the mean percent contraction (± SD) for each subdivision was calculated. Variability of regional function in this homogeneous population for each method was expressed as the ratio of the standard deviation and the mean (SD/M).

The statistical significance of differences in interobserver reproducibility and population variability between the different methods and approaches was determined by paired t test using a Monroe 325 programmable calculator and standard statistical methods.

Results

Variation Between Observers Studying a Mixed Population

Primary Measurements

Computer regenerations of the traced outlines for each observer in every other subject in group 1 is shown in figure 5. Differences between observers for a

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**Figure 5.** Examples of the corresponding diastolic-systolic outline pairs drawn by each observer for the mitral valve level in every other patient in group 1.
diastolic and systolic major (septolateral) axis, perimeter outlines and area measurements in group 1 at the mitral valve and papillary muscle levels, are listed in table 1. Interobserver variability of linear measurements ranged from 3.3–6.0% and the variability in area measurements ranged from 5.5–9.7%.

**Derived Measurements**

The mean percent difference between observers for group 1 varied with linear or area measurements and with the degree of subdivision of the geometric figure (fig. 6). At the mitral valve level for area measurements, there was a mean difference of 3% in area shrinkage when the entire figure was considered, but this increased to 7.5% when octants were compared. Perimeters showed a mean percent difference between observers of 2.4% for the entire figure and 6.5% when octants were measured. Hemiaxis values could not be calculated for either the primary figure or the figure divided in halves, but the mean percent difference between observers was 5.4% for quadrants and 5.9% for octants.

The mean percent contraction in area of these 10 figures was 43%, but mean hemiaxis shortening was 25.4% and mean perimeter shortening was 24.5%. Thus, the difference between observers as a fraction of overall change in size was less when the area method was used than when either linear method was used (fig. 6, right). This ratio was 0.07 by the area method for the entire figure and 0.17 when the figure was divided into octants at the mitral level. The ratio was significantly lower ($p > 0.02$) by the area method than either linear method. Similar results were found at the papillary muscle level.

Figure 7 shows the distribution of the discrepancy between observers for regional area shrinkage when the mitral valve cross-sectional image in group 1 patients was divided into octants. Both observers agreed within 10% in 61 of 80 instances, within 20% in 75 of 80 instances, and in five of 80 instances the dis-

**Table 1. Reproducibility of Primary Measurements**

<table>
<thead>
<tr>
<th></th>
<th>MV</th>
<th>PM</th>
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<tr>
<td>Area</td>
<td>D</td>
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<tr>
<td></td>
<td>S</td>
<td>6.1%</td>
</tr>
<tr>
<td>Hemiaxis</td>
<td>D</td>
<td>6.0%</td>
</tr>
<tr>
<td></td>
<td>S</td>
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<tr>
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<td>D</td>
<td>4.7%</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>4.2%</td>
</tr>
</tbody>
</table>

Abbreviations: MV = mitral valve level; PM = papillary level, D = diastole; S = systole.

Values are mean difference (%):

\[(\text{observer 1} - \text{observer 2}) \times 100\]

\[\frac{\text{observer 1} + \text{observer 2}}{2}\]

**Figure 7. Distribution of the amount of discrepancy between observers for each octant of the 10 mitral valve level outlines pairs in group 1 by regional area analysis.** The horizontal axis indicates the amount of discrepancy in percent contraction as measured by each observer between corresponding octants. The vertical axis indicates the number of octants (of the 80 in this group) that fell within each range of discrepancy.
crepancy was ≥ 20%. The distribution of interobserver discrepancy for the papillary muscle level sections was essentially identical (NS).

The effect of using a floating-axis system for the analysis of regional function is demonstrated in table 2. No significant differences in agreement between observers occurred at either level regardless of whether a fixed- or floating-reference system was used. As with the fixed system, the floating system also demonstrated a consistent advantage for the area method.

Variation in a Homogeneous Population

Table 3 shows the mean ± sd in 10 normal subjects as traced by consensus of two observers using octant analysis and a fixed-axis system in each of the methods proposed; i.e., hemiaxis shortening, perimeter contraction and regional area shrinkage. Standard deviation for perimeter shrinkage was 9.8%, for hemiaxis shortening 10.7% and for regional area shrinkage 12.8%. However, as a fraction of the mean measurements, the ratio of standard deviation to mean regional contraction, area shrinkage showed less variability than either of the linear measurements (p < 0.001) (fig. 8). The normal range (mean ± 2 sd) for each of these methods at the mitral valve level is plotted for group 2 and the corresponding regional contraction of two patients from group 1, one with an anterior myocardial infarction and one with an inferior myocardial infarction, are shown. The area method has the least variability (sd/M), so the abnormal contraction of both subjects with infarction was most clearly distinguished by this method.

By the method defined, at peak systole apical area shrinkage averaged 41.1% (sd 8.5%, sd/M 0.21). The apex was not further subdivided, and axis/perimeter measurements were not made for this region of the ventricle.

The effect of superimposing diastolic and systolic outlines by using a floating-axis system is demonstrated in figure 9. While this effect was minimal at the mitral valve level, at the papillary muscle level regional contraction is higher in posterior segments than anterior ones when the fixed-axis system is used, reflecting anterior swinging of the heart during systole. The floating-axis system compensates for the swinging of the heart, producing a more uniform distribution of regional contraction.
Figure 8. Plots of the normal octant contraction range (mean ± 2 SD) established in group 2 for the mitral valve level using each of the three methods with the fixed-axis analysis. (top left) Mitral valve level outline pairs from two patients with contraction abnormalities due to remote myocardial infarction, one anterior (AMI) and one inferior (IMI). The regional contraction measured in each outline pair by each approach is plotted on the corresponding graph. The horizontal axis of each plot indicates the anatomic region of each octant. S = septal; PS = posteroseptal; P = posterior; PL = posterolateral; L = lateral; AL = anterolateral; A = anterior; AS = anteroseptal.

Figure 9. The effect of the axis system convention on the normal regional contraction range using the area method. The regional contraction measured by octant analysis at the papillary muscle level in group 2 using fixed- and floating-axis systems is plotted as the mean ± SEM. Abbreviations are as in figure 8.

Table 4 is a summary of the overall variability within the normal population for each approach. The area method consistently involved less variability than either hemiaxis or segmental perimeter shortening methods.

### Discussion

The widespread use of computers for the analysis of LV function, whether the images are generated by angiographic, echocardiographic or radionuclide techniques, holds great potential for enhancing the quantification of regional LV function. The computer can analyze large amounts of data very quickly, subdivide images to any extent desired, measure areas as easily

<table>
<thead>
<tr>
<th>Octant Region</th>
<th>Area</th>
<th>Hemiaxis</th>
<th>Perimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV level</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fixed axis</td>
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<td>0.29</td>
<td>0.29</td>
</tr>
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<td>0.26</td>
<td>0.31</td>
</tr>
<tr>
<td>PM level</td>
<td></td>
<td></td>
<td></td>
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<td>0.34</td>
</tr>
<tr>
<td>Floating axis</td>
<td>0.19*</td>
<td>0.27*</td>
<td>0.34</td>
</tr>
</tbody>
</table>

(SD/M; *p < .005 compared to corresponding fixed-axis value.
Abbreviations: MV = mitral valve; PM = papillary muscle.)
as lengths, manipulate the spatial orientation of images with respect to each other, and perform analyses with excellent reproducibility. Most of the existing work that quantifies regional LV function has dealt with the analysis of angiographic images and has been performed by hand measurement. Therefore, much of this work has dealt with the analysis in relatively simple fashion, such as the measurement of a limited number of chord lengths. With the aid of computers, many alternative approaches become feasible, and recently, reports have appeared comparing the effectiveness of different approaches in the analysis of angiographic images.3-7 Two-dimensional echocardiographic images, although in some ways similar to angiographic images, differ significantly enough to warrant an independent evaluation of the methods used for their analysis.

The most striking of the results herein is the advantage of the area method over the two linear methods, both in optimizing interobserver reproducibility and in minimizing the variation in regional contraction within a homogeneous population. The most likely reason for the superiority of the area method is that it samples a given region more completely than a single chord or perimeter segment and consequently is less susceptible to errors introduced by sampling of minor geometric aberrations. Empirically, because the images are themselves planar, it is logical to use an area-based method for their analysis. This superiority of area-based methods has also been demonstrated in a recent angiographic study.8 When a computer is used to eliminate the difficulties of hand planimetry, regional area change offers clear advantages over linear methods for the quantification of regional function.

The question of the degree of subdivision of an image for analysis of discrete regions has not been extensively explored, but basically involves a compromise between conflicting considerations. Subdivision of the image into many regions offers a potential advantage of increased sensitivity; however, the best reproducibility and least variability are obtained when a non-subdivided image is examined. The interobserver reproducibility of the areas of 2-D echo outlines (7%) is similar to that reported in angiographic studies (5-10% for volumes).9 Reproducibility and variability deteriorate with greater degrees of subdivision; essentially, as the signal-to-noise ratio becomes less favorable. Moreover, as the number of subdivisions becomes very large, they lose anatomic significance. Also, the data become voluminous and difficult to handle. In subdividing a figure, it is difficult to define a cutoff point at which reproducibility becomes unacceptable; however, the difference in reproducibility between the area-quadrant and area-octant methods is not great (0.13 vs 0.17), considering the octant's greater potential sensitivity. An additional advantage offered by the use of octant subdivision is recombination in different ways for regional analysis, such as in groupings which correspond to coronary artery distribution of a given ventricle. Interestingly, the area method retains its advantage in reproducibility over the linear methods regardless of the degree of subdivision (fig. 6) and appears to deteriorate less rapidly than the others as the degree of subdivision is increased, as evidenced by the greater statistical significance of the differences between methods with greater degrees of subdivision. In application, there may be additional sensitivity vs specificity tradeoffs dependent on the degree of image subdivision.

The convention adopted for the frame of reference in which the systolic image is aligned relative to the diastolic image can have considerable influence on the measurement of regional function. Many approaches to the superimposition of a regional-axis system on angiographic images have been proposed.4-11 Most of them involve shifting the systolic and diastolic contours with respect to each other so that their long axes coincide. This approach is an attempt to compensate for systolic swinging of the entire heart toward the chest wall, and is based on the widely accepted premise that the normal heart contracts roughly symmetrically about its long axis. When the geometry of the left ventricle is distorted by aneurysms or other effects of coronary disease, however, this assumption is not valid and such realignment of the systolic and diastolic outlines may produce significant artifact when regional function is quantified. In less extreme cases, the shifting of the systolic outline tends to oppose the effect of whatever asynchrony is present, and subtle wall motion defects may be masked or underestimated. Short-axis 2-D echo images differ importantly from angiographic images when an axis system is defined because the 2-D echo outline is nearly circular and lacks an obvious major axis. The septolateral axis was chosen as the "major" axis because the septal midpoint was an anatomic location on the LV endocardial perimeter definable in both mitral valve and papillary muscle sections. The computer algorithm which bisects the short-axis image outline area with the septolateral axis and subsequently identifies its midpoint thus defines the center of mass of the figure. This was chosen as the most logical point to superimpose diastolic and systolic images in a floating-axis system, given the geometric configuration of the image. Whether this optimally compensates for the complex net motion of the entire heart during the cardiac cycle is not certain. With the floating-axis system, none of the regional area contraction ranges in the normal subjects differ from each other statistically; however, by the fixed-axis method, the normal range of regional area contraction measured in posterior and anterior segments are significantly different (p < 0.05). This difference in the normal range as defined by the fixed-axis method actually includes the swinging of the heart. However, the regional function of patients can be evaluated relative to the range established on normals using the same convention. If the net systolic motion of the entire heart is comparable in both groups, the effect of swinging will be minimized. The differences in reproducibility and variability between the fixed and floating systems are small, and their relative performance in a well-defined patient population is needed.
to establish whether one approach is preferable.

Ideally, a short-axis image of the cardiac apex would extend the systematic analyses made at the higher levels to this segment. However, the lack of adequate landmarks that will define a reproducible short-axis section precludes this approach. The regional function of the apex is frequently abnormal in coronary disease, so we have included an alternative approach for completeness.

The results for variability in the apical segment are consistent with those of the short-axis section. Reproducibility was not assessed because the apex was neither subdivided nor measured by multiple approaches. We did not attempt to subdivide the apex because it already represents a small portion or the total ventricle and because other investigators have also dealt with it as a unit. The data cited in the results are from the four-chamber view, which was adequate in all subjects studied; the two-chamber section was more difficult to obtain consistently, but the algorithm used is equally applicable for this approach.

In conclusion, quantitative approaches to 2-D echo images can be used to define regional LV wall motion within acceptable limits of interobserver reproducibility and population variability. When a quantitative approach is adopted, measurements of regional area change are superior to linear-based methods for image analysis. Neither the selection of a fixed- or floating-axis system or the division of images into quadrants or octants have a great effect on reproducibility or variability.

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