Quantitative Left Ventricular Wall Motion Analysis: A Comparison of Area, Chord and Radial Methods

HARRIS J. GELBERG, M.D., BRUCE H. BRUNDAGE, M.D., STANTON GLANTZ, PH.D. AND WILLIAM W. PARMLEY, M.D.

SUMMARY We were interested in devising a relatively simple quantitative technique that could be used on a routine clinical basis for wall motion analysis. Three quantitative methods of left ventricular (LV) regional analysis were compared in the 30° right anterior oblique and 60° left anterior oblique projections. The control group consisted of 17 patients with qualitatively normal LV wall motion; the abnormal group comprised 17 patients with at least one region of severe, qualitative wall motion abnormality. Normal regional values were determined for area, chord and radial methods by applying the techniques to the ventriculograms of the control group. Each technique was then applied to the abnormal group's ventriculograms to determine the percentage of qualitatively abnormal regions not detected by each method. The area method had the lowest failure rate (p < 0.001) and the best separation of measured normal and abnormal regions' ejection changes (p < 0.001), and best reflected symmetric uniform motion of the ventricular silhouette. We conclude that the area method, of the techniques examined, was best for the quantitative analysis of LV wall motion abnormalities.

LEFT VENTRICULAR contractile abnormalities can be an important manifestation of coronary artery disease. These wall motion changes may represent ischemia or infarction of myocardium.1-3 Quantifying the extent of regional wall motion abnormality may aid in determining the myocardial effects of coronary artery disease. It would also simplify analysis of wall motion changes after diagnostic and therapeutic interventions and would permit comparison of different imaging techniques to assess their diagnostic accuracy. Often, wall motion evaluation is done on a subjective basis; however, subjective, qualitative analysis has a substantial error rate. An objective, quantitative system is required for accurate regional evaluation.4 No quantitative technique is universally accepted, many of the more recent methods require sophisticated computer facilities,5 and normal segmental wall motion values have not been established for simultaneous 30° right anterior oblique (RAO) and 60° left anterior oblique (LAO) views. We evaluated three commonly used quantitative methods (chord, radial and area) of wall motion analysis to determine which technique best detects abnormal function. The methods chosen are relatively simple and therefore suitable for routine clinical use. The study was performed by analyzing simultaneous 30° RAO and 60° LAO projections of contrast left ventriculograms by each method.

METHODS

Technically adequate cineventriculograms of patients evaluated for possible coronary artery disease were included in this investigation. Ventriculograms were performed using a General Electric 16 mm cinégraphic biplane system at 60 frames/sec with alternate firing of the cameras. The patient was positioned in the 30° RAO to the anterior-posterior tube and 60° LAO to the lateral tube. We performed left ventriculography using 0.8 ml/kg of Renografin-76 to a maximum dose of 60 ml injected in 4 seconds. After ventriculography, each patient had selective coronary angiography by the Judkins technique.

References


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Before drawing the ventricular outlines, two cardiologists simultaneously evaluated the films subjectively according to the American Heart Association system for segmental left ventricular wall motion assessment. Each of seven anatomical regions was scored as normal, mildly, moderately or severely hypokinetic, akinetic, aneurysmal, or dyskinetic (fig. 1). Cineventriculograms of poor quality leading to unknown function of a region were excluded from this study. Ventriculograms of sinus beats were traced at end-systole and end-diastole. Premature and post-premature beats were not used in this study. The ventricular silhouette with the largest total area immediately before mitral valve closure was traced for end-diastole. The end-systolic silhouette was defined as that which had the smallest area before mitral valve opening. These maximum and minimum areas were determined by visual inspection. The traced silhouette was then compared with several preceding and following cine frames to ensure proper selection. The same contraction was used to trace the RAO and LAO views. Several beats were evaluated in both views to ensure that the selected silhouettes were representative of the end-systole and end-diastole in each patient. All ventriculograms were performed with the patients holding their breath at end-inspiration to minimize cardiac rotation about the long axis. No patient in the study demonstrated diaphragmatic motion between diastole and systole.

Two groups were studied. The control group comprised 17 patients with qualitatively normal LV wall motion. These patients had normal coronary arteries or only minor luminal irregularities on selective angiography, as well as normal hemodynamics, end-diastolic and end-systolic LV volumes and normal ejection fractions. All control patients had normal chest x-rays and ECGs. None of these patients had stenotic or incompetent valvular lesions. This control group was considered to represent a normal population. The abnormal group consisted of 17 patients with at least one region of severe, qualitative wall motion abnormality. To minimize the problems inherent in this subjective selection process, only segments classified as severely hypokinetic, akinetic, aneurysmal or dyskinetic were analyzed by the quantitative methods. The patients chosen for the abnormal group also had one or more of the following: 1) a documented myocardial infarction; 2) Q-wave infarct pattern on the ECG; or 3) >90% occlusion of the coronary artery supplying the region of severe, qualitative wall motion abnormality. Thirteen patients had all three associated findings. One had an infarct history and a critical coronary lesion, but no electrocardiographic pattern. One patient had infarction by ECG and a coronary occlusive lesion, but no history of infarction. In two patients with severe qualitative regional abnormalities there was no history of infarction or abnormal Q waves on the ECG, but there was >90% occlusive coronary lesions.

We considered three methods for evaluating regional wall motion. Each system defined the major axis in the RAO view as the line from the apex to the midpoint of the aortic valve plane; in the LAO view the major axis for each technique was a line from the aortic-mitral valve junction to the apex. The apical region furthest away from the aortic valve plane midpoint (RAO) and aortic-mitral valve junction (LAO) was taken as the apex point. All reference systems were applied to the end-systole and end-diastole silhouettes independently, and were thus corrected for any motion of the heart in space except rotation. Figure 2 shows the format for each system. In the

![Diagram of the American Heart Association qualitative reporting system for the left ventriculogram](http://circ.ahajournals.org/)

**Figure 1.** American Heart Association qualitative reporting system for wall motion assessment: $N =$ normal; $HYP =$ hypokinetic; $AK =$ akinetic; $DYS =$ dyskinetic; $A =$ aneurysmal; $U =$ unknown. Hypokinetic regions were further characterized in this study as mild, moderate or severe. By permission of the American Heart Association, Inc. and the authors.
radial system (fig. 2A) lines are drawn from the midpoint of the major axis in the RAO and LAO views to the ventricular outline at 45° intervals. For the rectilinear chord system (fig. 2B) in the RAO view, perpendiculars are drawn from the points that divide the major axis into thirds to the points of intersection of the ventricular outline. In the LAO view, perpendiculars are drawn from the midpoint of the major axis.

In the area method (fig. 2C) we constructed planimetered regions by drawing perpendiculars from points that divide the major axis into thirds in the RAO view. The two apical areas were combined and treated as one region. In the LAO view, a perpendicular was drawn from the midpoint of the long axis to the posterolateral wall, dividing the ventricular silhouette into three areas. The chord and radial tech-

**Figure 2.** Formats for techniques examined: A) radial system with 14 radial line measurements; B) chord system with eight rectilinear line measurements; C) area system with eight area measurements. For each technique, measurements were taken at end-diastole and end-systole, and the percent change was then calculated.
In normal patients, different chords (C), areas (A) or radial (R) measurements changed differently with ejection. We were interested in separating normal segments from abnormal segments by comparing different methods and different segments within a method. This comparison requires that values be comparable. Therefore, we normalized all measurements according to the following scheme:

1) Compute the mean percent ejection change (M) for the 17 normal patients for each region (1, 2, 3 . . . ) by each method (R, C, A): \( M_{R1}, M_{R2}, M_{R3}, \ldots, M_{R14}; M_{C1}, M_{C2}, M_{C3}, \ldots, M_{C6}; M_{A1}, M_{A2}, M_{A3}, \ldots, M_{A8}. \)

2) Compute the standard deviation, \( s \), for the ejection changes for the 17 normal patients for each region by each method: \( s_{R1}, s_{R2}, s_{R3}, \ldots, s_{R14}; s_{C1}, s_{C2}, s_{C3}, \ldots, s_{C6}; s_{A1}, s_{A2}, s_{A3}, \ldots, s_{A8}. \)

3) Normalize the regional ejection change, obtained with \( m \) in region \( r \),  \( X_{mr} \), according to

\[
Z_{mr} = \frac{X_{mr} - M_{mr}}{s_{mr}}
\]  

In other words, \( Z_{mr} \) represents the number of normal

\[
*The cutoff point for the 95% confidence interval is \( -1.75 [p < 0.05 (17)]\).

standard deviations by which the measurement \( X \) varies above or below the mean of the 17 normal patients; \( Z \) is dimensionless.

For example, a) normal: if the anterolateral region by the area technique has a mean ejection change of \( 57.2 \pm 13.5\% \) (SD) and one illustrative normal patient has an area ejection change in this region of 69%, then

\[
Z = \frac{69\% - 57.2\%}{13.5\%} = +0.87
\]

b) abnormal: in a patient with qualitatively abnormal anterolateral wall motion, an area ejection change was 11%, so

\[
Z = \frac{11\% - 57.2\%}{13.5\%} = -3.4
\]

In other words, the more negative \( Z \), the worse the regional function. The lower limit of normal was defined as two standard deviations below the normal mean (i.e., \( Z \leq -2 \)).

Each method was applied to 46 severely abnormal regions defined on qualitative analysis. We questioned if any method produced significantly more negative \( Z \) numbers than the other methods. This can be tested by the null hypothesis: "The values of \( Z \) in qualitatively abnormal segments are the same in all three methods of quantifying regional wall motions." To test this hypothesis, we used the two-way analysis of variance (method fixed, patient random). After rejecting this null hypothesis, we used the Student-Newman-Keuls multiple range test to define which method produced, on the average, more negative values for \( Z \) in the abnormal regions.

The next question addressed was, "Does any method detect a significantly higher fraction of the markedly abnormal regions?" The null hypothesis is: "All methods are equally likely to detect abnormal regions." To test this hypothesis, we constructed a \( 2 \times 3 \) contingency table. After rejecting this null hypothesis, we subdivided \( \chi^2 \) by first testing the null hypothesis: "The chord and radial methods are equally likely to detect an abnormal region." We did not reject this hypothesis. We then pooled the chord and radial failure rates and tested the null hypothesis: "The chord and radial methods, taken together, are as likely to detect abnormal regions as the area method." We rejected this hypothesis.

To quantify the amount of scatter in values of the different methods used to measure regional ejection changes, we examined the sizes of the standard deviation for the different methods as a fraction of the mean change. This coefficient of variation, defined for each region, is

\[
V_{mr} = \frac{s_{mr}}{M_{mr}}
\]

where \( s_{mr} \) is the standard deviation of a method in a region and \( M_{mr} \) is the mean of the same method in that region. A large number means the spread in
values of the measure of segmental wall motion is large by comparison with the mean value for that region. The smaller the coefficient, the more uniformity among the mean regional ejection changes of a technique. This procedure permits us to compare the different methods even though the intrinsic units are different.

We decided that if a region was quantitatively below 97% of the normal population, we would consider it abnormal. We used this strict confidence level because we tested only severely abnormal regions. According to the one-tail distribution with 16 degrees of freedom, \( Z_{mr} \) for a normal population will be below \(-2\) in <3% of cases. Therefore, we called a segment abnormal when \( Z_{mr} \) was below \(-2\) (i.e., two or more normal group standard deviations below the normal group mean).

### Results

Normal mean regional ejection changes for radial, chord and area techniques are presented in table 1. The lowest mean ejection changes of all systems occurred in regions that incorporated aortic and mitral valve structures. Area 5 had the lowest normal mean area ejection fraction, and much of its perimeter was formed by the posterior mitral valve and aortic valve plane. Chords 3 and 7 terminate at the aortic valve and have the lowest axis shortening by the rectilinear technique. For the radial system, numbers 4, 7 and 14 had the lowest values. Radial 4 incorporated the aortic valve plane, 14 fell on or near the aortic valve plane, and 7 tended to incorporate the posterior mitral valve.

The coefficients of variation listed in table 1 represent the standard deviations relative to the ejection

### Table 1: Comparative Regional Ejection Changes in 17 Normal Patients

<table>
<thead>
<tr>
<th>Method (M)</th>
<th>Region (r)</th>
<th>Ejection change</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (SD)</td>
<td>Lower limit of normal*</td>
</tr>
<tr>
<td>Radial (R)</td>
<td>1. Anterobasal</td>
<td>43.5 (13.5)</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>2. High anterolateral</td>
<td>44.0 (17.1)</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>3. Low anterolateral</td>
<td>38.4 (20.0)</td>
<td>-1.6</td>
</tr>
<tr>
<td></td>
<td>4. Apical</td>
<td>24.1 (7.8)</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>5. Anterior diaphragmatic</td>
<td>39.7 (14.3)</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>6. Mid-diaphragmatic</td>
<td>35.2 (12.5)</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>7. Posterobasal</td>
<td>23.4 (11.9)</td>
<td>-0.4</td>
</tr>
<tr>
<td></td>
<td>8. High posterolateral</td>
<td>33.5 (10.7)</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>9. Mid-posterolateral</td>
<td>30.7 (11.9)</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>10. Low posterolateral</td>
<td>30.7 (10.6)</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>11. Apical/inferior</td>
<td>27.1 (5.7)</td>
<td>15.7</td>
</tr>
<tr>
<td></td>
<td>12. Low septal</td>
<td>38.2 (17.1)</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>13. Mid-septal</td>
<td>29.2 (22.2)</td>
<td>-15.2</td>
</tr>
<tr>
<td></td>
<td>14. High septal</td>
<td>14.8 (20.1)</td>
<td>-25.4</td>
</tr>
<tr>
<td>Chord (C)</td>
<td>1. Anterobasal</td>
<td>46.1 (15.4)</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>2. Anterolateral</td>
<td>43.2 (20.9)</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>3. Apical</td>
<td>24.1 (7.8)</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>4. Diaphragmatic</td>
<td>47.7 (21.1)</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>5. Posterobasal</td>
<td>37.2 (11.6)</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td>6. Posterolateral</td>
<td>30.7 (11.9)</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>7. Apical/inferior</td>
<td>27.1 (5.7)</td>
<td>15.7</td>
</tr>
<tr>
<td></td>
<td>8. Septal</td>
<td>29.2 (22.2)</td>
<td>-15.2</td>
</tr>
<tr>
<td>Area (A)</td>
<td>1. Anterobasal</td>
<td>58.8 (12.2)</td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td>2. Anterolateral</td>
<td>57.2 (13.5)</td>
<td>30.2</td>
</tr>
<tr>
<td></td>
<td>3. Apical</td>
<td>60.1 (12.3)</td>
<td>35.5</td>
</tr>
<tr>
<td></td>
<td>4. Diaphragmatic</td>
<td>54.1 (7.7)</td>
<td>38.7</td>
</tr>
<tr>
<td></td>
<td>5. Posterobasal</td>
<td>39.5 (11.1)</td>
<td>17.3</td>
</tr>
<tr>
<td></td>
<td>6. High posterolateral</td>
<td>55.1 (10.9)</td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td>7. Low posterolateral</td>
<td>51.1 (11.8)</td>
<td>27.5</td>
</tr>
<tr>
<td></td>
<td>8. Septal</td>
<td>49.2 (11.1)</td>
<td>27.0</td>
</tr>
</tbody>
</table>

*At the 97% confidence level by the one-tail t distribution.*
change means ($V_{mr} = s_{mr}/M_{mr}$) for each region by all methods. The area technique, when compared with the other methods, had the smallest coefficients of variation for every region of the ventricle and therefore demonstrated the lowest relative variation about the means in the 17 normal patients.

The area technique had the greatest uniformity among the mean regional ejection changes. The mean regional ejection changes for the different regions were (mean ± SD): radial, 32.32 ± 8.29; chord, 35.66 ± 9.15; area, 53.13 ± 6.62. A one-way analysis of variance, followed by a Student-Newman-Keuls multiple range test, shows that the mean ejection change is greater for the area method than for the radial or chord methods ($p < 0.001$). The coefficients of variation are: radial, 0.26; chord, 0.26; and area, 0.12. Thus, the absolute ejection changes were greatest and the relative variation among the regions of the ventricle were smallest in the area technique.

The average Z for the abnormal regions was most negative for the area method (−3.37), compared with the radial (−2.27) and the chord (−1.95) techniques. The two-way analysis of variance rejected the hypothesis that there was no difference among the Z values computed for the abnormal segments by the various methods ($p < 0.001$). The Student-Newman-Keuls multiple range test showed greatest separation between the normal controls and the qualitatively defined abnormal group by the area technique. The null hypothesis that there was no difference between normal and abnormal Z values by the area vs radial and area vs chord methods was rejected as $p < 0.001$. The multiple range test suggested that the separation between the normal and abnormal was probably better by the radial than by the chord technique ($p = 0.06$).

Each system's failure rate was defined as the percentage of severely abnormal segments not detected. These data are presented in table 2. The area method had the lowest failure rate (11%), compared with the chord (52%), and the radial (46%) techniques. The $\chi^2$ test rejected the hypothesis that there was no difference between these failure rates at $p < 0.001$: however, the $\chi^2$ test showed no significant difference between the failure rate of the radial and chord methods. The radial and chord values were therefore combined in a contingency table and tested against the area failure rate by $\chi^2$. The failure rate for the area method was significantly smaller ($p < 0.001$). In the anterobasilar region there was only one severely abnormal example tested and each system detected that abnormality. In six of six other anatomical regions, the area method had a lower failure rate than either the chord or radial methods. In every case where the area method failed to detect an abnormality, the chord and radial methods also failed.

**Discussion**

The relationship between ischemic heart disease and the potential for left ventricular regional wall abnormalities has been firmly established since the classic experiments of Tennant and Wiggers. A measurement of the myocardial effect of coronary artery disease can be obtained by studying regional function. Other etiologies of segmental wall motion abnormalities have been discussed, such as abnormal ventricular activation due to conduction defects and disproportionate hypertrophy. Wall motion analysis in these settings may also prove clinically relevant. Unfortunately, no quantitative method for regional analysis has been universally accepted.

Recently, clinical interventions have been advocated to determine the potential for regional wall motion change. With these interventions, quantitation of segmental function has taken on new importance. Potentially ischemic regions of apparently normally contracting myocardium may demonstrate functional deterioration with stress, such as pacing and exercise. Conversely, it has been reported that abnormal regions may improve with nitroglycerin, postextrasystolic potentiation, inotropes and coronary artery bypass grafting. A quantitative system able to define normal segmental function may assist in determining clinically relevant regional change occurring with interventions. Techniques such as two-dimensional echocardiography and nuclear angiography are being used to assess left ventricular regional function. Analyzing the reliability of these methods is made more difficult by the lack of an accepted quantitative system for cineventriculogram regional evaluation.

Any acceptable wall motion analysis must account for several factors. In the 30° RAO view the analytical system should compensate for lifting of the apex caused by systolic rotation. Artifacts of thoracic, diaphragmatic or camera motion must also be considered. Since ischemic heart disease is a major cause of regional abnormalities, an analytical system might do best to measure segmental ejection change of

### Table 2. Qualitatively Abnormal Regions not Detected by Each Quantitative System

<table>
<thead>
<tr>
<th>Anterobasal</th>
<th>Anterolateral</th>
<th>Apical</th>
<th>Diaphragmatic</th>
<th>Postero-basal</th>
<th>Postero-lateral</th>
<th>Septal</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND %</td>
<td>ND %</td>
<td>ND %</td>
<td>ND %</td>
<td>ND %</td>
<td>ND %</td>
<td>ND %</td>
</tr>
<tr>
<td>Radial</td>
<td>0</td>
<td>3</td>
<td>43</td>
<td>3</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>Chord</td>
<td>0</td>
<td>4</td>
<td>57</td>
<td>3</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>Area</td>
<td>0</td>
<td>1</td>
<td>14</td>
<td>1</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

**Total Abn. R = 46.**

**Abbreviations:** Abn. R = number of qualitatively abnormal regions tested; ND = not detected.
regions supplied by major coronary branches. Reported techniques which bisect the apical region do not consider the usual left anterior descending coronary artery distribution. Finally, any method constructed should examine the entire left ventricle by two simultaneous orthogonal views.

We examined the rectilinear chord, radial and area ejection methods to determine which technique best quantitates left ventricular regional wall motion. Each compensated for systolic apical rotation and aortic motion by in effect overlapping the long axis of diastole and systole. Diaphragm motion was excluded by comparing the diaphragm level in diastole and systole. Although the internal reference technique used makes diaphragm motion less important, rotation about the long axis with cardiac descent may introduce error by changing the portion of the ventricle seen in profile. Each method examines regions of the ventricle that approximate the distribution of major coronary branches. All techniques used biplane simultaneous orthogonal views.

The systems differ in several important ways. The rectilinear chord method measures wall motion as a change occurring perpendicular to the long axis of the ventricle. However, shortening may occur from the base toward the apex in all regions outlined in the 30° RAO projection. The chord method detects all base-to-apex change essentially as one aortic valve plane-to-apex measurement. All area measurements and some radial line measurements take base-to-apex change into account. The area method includes a long perimeter of the ventricular silhouette for each segment, while the chord and radial methods depend on change of one ventricular perimeter point toward one reference point on the long axis. The assumption is made in the chord and radial methods that the point on the perimeter located in diastole is approximately the same point measured in systole. This may often be an invalid assumption and sometimes is clearly not the case. For example, a radial line in the high septum in diastole may be seen in systole to intersect the aortic valve plane. Since a large perimeter, rather than a single silhouette point, determines change in the area method, this technique is more likely to have anatomically coinciding systolic and diastolic regions.

Choosing a standard for comparing the three methods posed a problem because only subjective assessment of wall motion was available. The problem of observer variability with subjective analysis is well recognized. Therefore, we attempted to minimize this variability by analyzing only the regions with marked dyssnergy. The subjective selection process appears reasonable, because the areas chosen were always in the distribution of a coronary artery with at least 90% diameter narrowing, often correlated anatomically with a Q-wave infarct pattern on the ECG (14 of 17 patients), and usually were associated with a history of clinical infarction (14 of 17 patients).

Our criteria for selecting one of the three methods for clinical assessment of regional wall motion are: 1) the method should best illustrate the normally uni-

form symmetric nature of ventricular function on examination of a normal control population, and 2) the method should best detect the selected, markedly abnormal regions. The area method meets these criteria, and demonstrated the best uniformity of the mean regional changes with a coefficient of variation 0.12 vs 0.26 for the other methods. Only the posterobasilar area 5 was low, probably because much of this region consists of noncontractile posterior mitral valve and aortic valve structures. The data in table 2 substantiate that the area method detected abnormality best, independent of which ventricular segment was involved. It also had a significantly lower overall failure rate than the other methods.

The ventriculogram shown in figure 3 was subjectively judged to have severe wall motion abnormalities of four regions in the RAO view. These regions and the Z values for each method are listed in the accompanying chart. Three of four abnormal regions were not detected (i.e., \( Z > -2 \)) by the chord and radial methods. All four abnormal segments in the area method had \( Z \leq -2 \).

Figure 4 shows Z values computed for each qualitatively, severely abnormal region examined. The area method separates the normal and abnormal groups significantly better than the other two methods. The dashed line in this diagram represents the lower limit of normal defined at the 97% confidence level by the one-tail distribution. For our population this represents 2 standard deviations from the mean. Ninety-seven percent of the normal population would fall above this dotted line. The overlap between abnormal and normal is apparent for the radial and chord methods, as demonstrated by the distribution of the Z values for the qualitatively abnormal regions. Three of five abnormal regions not detected by the area method were near the lower limits of normal and exceed the 95% confidence limits. The mean changes and the lower limits of normal for each region by each system are illustrated in figure 5. It is important to note how large the normal limits are in many regions of the radial and chord techniques. The lower limits of normal in some regions fall near or below the zero change line. Lower normal limits are well above the zero line in the area method. Area 5, the region of smallest percent regional change, encompasses mitral and aortic valve structures in the RAO view. It might therefore be expected to have less change than purely myocardial regions of the ventricular silhouette.

In each case where the area method failed to detect abnormality, the chord and radial methods also failed. Five qualitatively abnormal segments were not detected by any method. Four of five of these regions were supplied by critically occluded coronary arteries in patients with infarction by history and current ECG. One region of the five was supplied by a completely occluded coronary artery in a patient with a history of infarct, but the ECG was essentially normal. There were three apparent reasons why qualitatively abnormal segments were not detected by the methods studied: 1) there were two instances of
VALUES OF Z

<table>
<thead>
<tr>
<th>REGIONS</th>
<th>METHODS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RADIAL</td>
</tr>
<tr>
<td>ANTEROLATERAL</td>
<td>-2.59</td>
</tr>
<tr>
<td>APICAL</td>
<td>-1.13</td>
</tr>
<tr>
<td>DIAPHRAGMATIC</td>
<td>-1.15</td>
</tr>
<tr>
<td>POSTEROBASAL</td>
<td>-0.08</td>
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</tbody>
</table>

Figure 3. An example of wall motion analysis by the three techniques. This RAO silhouette was considered by subjective analysis to have four regions of severe abnormality. The solid line indicates end-diastole, the dashed line end-systole. The accompanying chart lists the Z values for each subjectively defined, severely abnormal region by the three methods. A Z value ≤ -2 meets the criteria for detection of abnormality.

QUANTITATIVE EVALUATION OF 46 QUALITATIVELY ABNORMAL REGIONS

Figure 4. The distribution of Z values of qualitatively defined severe abnormalities in each technique. Dashed line represents lower limits of normal at the 97% confidence level by the one-tail t distribution. This is 2 SD below the normal mean in our population (i.e., Z = -2). If the 95% confidence limit is used, all but two of the qualitatively abnormal areas are detected by the area method.
small discrete wall motion abnormalities where the remainder of the region appeared qualitatively normal; 2) in one case the region of abnormality not detected was small and contiguous with an abnormal segment detected by all methods, and the abnormal portion of the region not detected was small in relation to the normal-appearing remainder of the segment; and 3) in retrospect, we may have qualitatively overestimated the degree of abnormality in two segments. Moreover, if the confidence limits for normality were reduced to 95%, all but these two of the 46 qualitatively abnormal regions would have been detected by the area method (see fig. 4). Any quantitative wall motion analysis is likely to miss some subtle subregional abnormalities, and since this technique only measures shortening at end-systole, abnormalities during early ejection (tardokinesis) may not be detected. Even so, objective methods are necessary to assess the effects of therapy and permit comparison of nuclear, echo and catheterization studies.

Our goal was to evaluate methods that could be easily automated with relatively inexpensive equipment. Clearly, a large number of measured radial or chord lines may adequately characterize regional wall motion,20,21 and averaging techniques for multiple radial and chord lines may add to the sensitivity of these methods. However, complex methods are difficult to implement for general clinical use. The area method appears to be the best of the simple quantitative wall motion techniques we analyzed.

References
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