A comparison of traditional wall motion assessment and quantitative shape analysis: A new method for characterizing left ventricular function in humans

To forego the need to arbitrarily choose coordinate, reference, and indexing systems and to make other assumptions mandated by traditional methods of measuring wall motion, a technique of regional function analysis based on shape characteristics and pattern recognition was developed. The method is based on curvature analysis, a fundamental shape parameter, and is adaptive to the complex geometry of cineangiographic ventricular images. Quantitative shape parameters were compared to a standard method of regional function analysis (center-line method) in 130 patients. Quantitative shape and wall motion indexes showed a positive correlation over a broad range of normal and abnormal function ($r = 0.748$, $p < 0.001$). Overall sensitivity and specificity for categorization of regional function were not statistically different for either technique. Within regions, however, shape criteria were more specific in categorizing inferior zones than anterior zones and were more often abnormal in the presence of mild regional abnormalities that were not located in the apical region. In conclusion, shape analysis and pattern recognition techniques can be used to forego dependence on the numerous assumptions and approximations required by traditional wall motion techniques, while providing performance characteristics that are similar to, and in some instances better than, traditional approaches. Incorporation of shape information in assessments of regional function provides a more comprehensive evaluation that includes the important visual cues used by experienced observers or "experts." (AM HEART J 1987;114:1183.)

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The concepts embodied in the fields of artificial intelligence, computer vision, and robotics are very likely to become as widely applied in medicine as they are in industry.[1] Subsets of these fields are those of pattern recognition and shape analysis, which have not yet been extensively applied in cardiology.[2] These fields provide new approaches for assessing complex information and are designed to mimic more closely the performance of well-trained observers or "experts." Ventricular images convey complex information about motion and the coordination of motion and shape. The integration of these features by the clinician likely accounts for the fact

that no single method of regional function analysis has been universally adopted or reflects the performance of a true expert, particularly in detection of subtle abnormalities. However, because of the known variability of this subjective process,[3] quantitative methods that comprehensively analyze this information in a reproducible manner would be of both theoretic and practical value. Although numerous studies have investigated the contribution of motion[4,5] and temporal characteristics[6] to the clinical assessment of ventricular function, few studies have assessed the value of shape characteristics for this purpose.[7-12]

Traditional wall motion analyses are dependent on numerous assumptions about the coordinate, reference, and indexing systems that are required to deal with three-dimensional rotational and translational motion as projected onto the imaging plane.[13] Presumptions about the geometry of the ventricle and the uniformity and direction of its contraction pattern also influence the choice of specific meth-
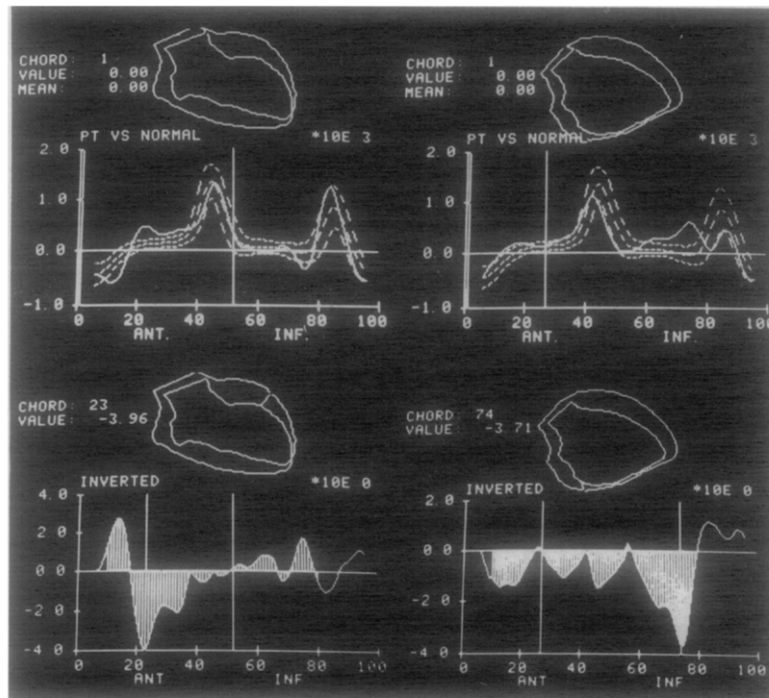
Fig. 1. Examples from patients with abnormalities of anterior *(left)* and inferior *(right)* zones. *Upper graphs* show end-systolic curvature signatures for patients *(solid line)* plotted against mean ± 1 SD of the normal group *(dashed lines)*. Ordinate is marked in dimensionless curvature units and abscissa gives percentage of perimeter length progressing in clockwise direction from anterior aspect of aortic valve to junction of mitral and aortic valves. Vertical bars in upper panels mark the end of automatically determined segmentation between anterior and inferior regions. Note crossovers of solid line with normal mean curvature signature resulting in arithmetic, regional heterogeneity in significance of deviations from normal. *Lower panels* show results after inversion process and normalization (see text). In these panels ordinate is in units of standard deviations. Note typical scalloped appearance of this display, which is caused by crossover points and inversion process that rectifies the arithmetic sign. All negative values now represent areas of abnormality. In lower panels of each example, a moveable cursor has been positioned on the graph and on the ventricular silhouettes at the point of greatest abnormality in shape. Display to the left of ventricular silhouettes gives position of this cursor and value (SD) at that location. Quantitative output (not shown) also records points marking beginning and end of each segment, length of each segment, points bordering "apical zone," sum of all positive deviates, sum of all negative deviates, sum of all deviates, standard deviations per point in each region, and standard deviation per point spanning a percentage of each region.

ods.[14, 15] This laboratory has attempted to establish a method of regional function analysis that is not dependent on these assumptions and that is based on shape analysis. Initial observations quantitated the shape characteristics of normal ventricles and established the complex patterns that occur in the presence of wall motion abnormalities.[16, 17] The purpose of this investigation was to establish the regional heterogeneity and observer variability of this form of shape analysis, to develop a clinically oriented and automatic quantitation of regional shape information, and to compare these shape indexes with those determined by a traditional wall motion analysis system. These investigations represent the initial rudimentary steps toward full application of automatic regional ventricular function diagnosis that use the techniques of computer vision and artificial intelligence.

METHODS

Left ventriculograms obtained in the 30-degree right anterior oblique projection were retrospectively analyzed to find patients with studies suitably opacified to allow accurate tracing of the endocardial outline. Postectopic beats were excluded, and patients with significant valvular disease, papillary muscle hypertrophy, or angiographic mitral valve prolapse were excluded. Four groups of patients were established by consensus: (1) patients with normal regional function (N = 30), (2) patients with isolated anterior wall motion abnormalities (N = 35), (3) patients with isolated inferior wall motion abnormalities
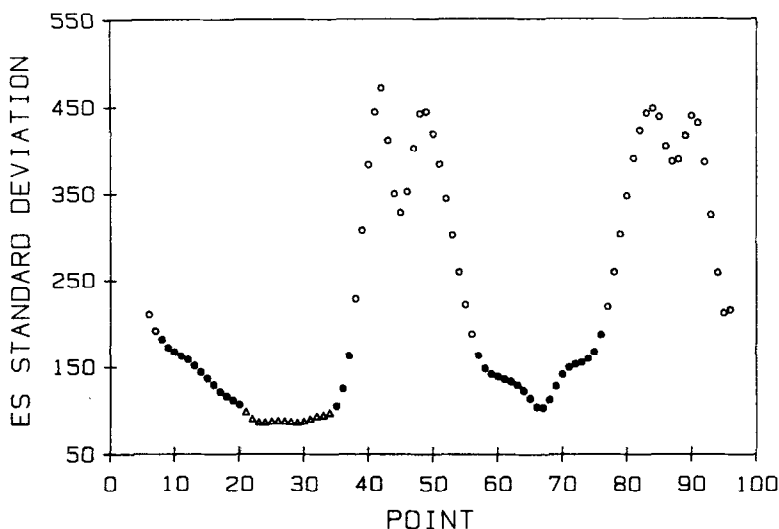
Fig. 2. Results of regional variability analysis of end-systolic shape in 30 normal subjects. Standard deviations of end systole *(ES)* are plotted. Solid circles designate those points at which variability of normal curvature measurements is similar. Points shown as *open circles* have variances that are significantly greater than the rest ($p < 0.05$). These occur in anterobasal, apical, and mitral valve plane regions. Points designated by *open triangles* have variances that are significantly less than the rest ($p < 0.05$). These are seen in points corresponding to anterior zones.

(N = 28), and (4) patients with abnormalities encompassing both the anterior and inferior regions (N = 37). The 30 normal patients had been referred for investigation of chest pain syndromes but were found to have normal hemodynamics, normal coronary angiograms or minor irregularities (five patients), and negative ergonovine challenge test results (21 patients). In the absence of a true gold standard for regional wall motion, the group designations were corroborated by at least three experienced observers and also by retrospective analysis of the catheterization reports to ensure that the original angiographer not involved in the study also gave a similar designation to the location of regional dysfunction. Subjects were selected to show a spectrum of wall motion abnormalities ranging from mild hypokinesis to mild dyskinesis. Ninety of the 130 subjects in this study constitute the study population of a previous report.[17] Careful tracings of the endocardial outlines at end diastole and end systole were made. Papillary muscles were included within the cavity. These tracings were photographed on 35-mm film and projected on a Vanguard viewer, which was interfaced by a video chain to a commercial digital image processing unit (ADAC DPS-4100C, San Jose, Calif.). The tracings were digitized at 256 × 256 resolution and stored. Spatial smoothing of the outlines was employed before curvature calculations were performed to overcome noise introduced by the digital nature of the curves.[16, 17]

Shape was quantitated by calculating regional curvature by a technique developed in this laboratory.[16, 17] Briefly, standard vector differentiation formulas were used to calculate the curvature of ventricular silhouettes

at 100 equidistant points starting from the anterior aspect of the aortic valve plane and proceeding in a clockwise direction to the junction of the mitral and aortic valves. Right-handed curves were assigned positive curvature and left-handed curves were assigned negative curvature values. Curvature, which is the reciprocal of the radius of curvature, has dimensions of length^{-1}; thus all results were made dimensionless by multiplying them by the length of the perimeter of the silhouette, thereby allowing comparisons from region to region and patient to patient. The point-by-point curvature values were subjected to a three-point smoothing process before display. The result is a function that comprises a quantitative signature unique to the shape of the ventricular border (Fig. 1).

Preliminary observations[17] demonstrated the complex patterns of abnormality to be expected in the presence of regional dysfunction, as well as several characteristics of the curvature signatures that precluded simple quantitation of these abnormalities. Software was developed to accommodate these observations and the software development is described in the Appendix.

The curvature signature of an individual-patient was standardized based on the point-by-point mean ± standard deviation of the normal group as follows: Standardized curvature = $(C_i - C_{i,n})/SD_{i,n}$, where C_i is the observed curvature value at point i in an individual patient, $C_{i,n}$ is the mean normal curvature value at point i, and $SD_{i,n}$ is the standard deviation of the normal results at point i.

Fig. 1 shows the final result of the complex, adaptive, shape analysis process for analysis of patients with typical anterior and inferior wall motion abnormalities. The final quantitative output is given in simple units of standard de-
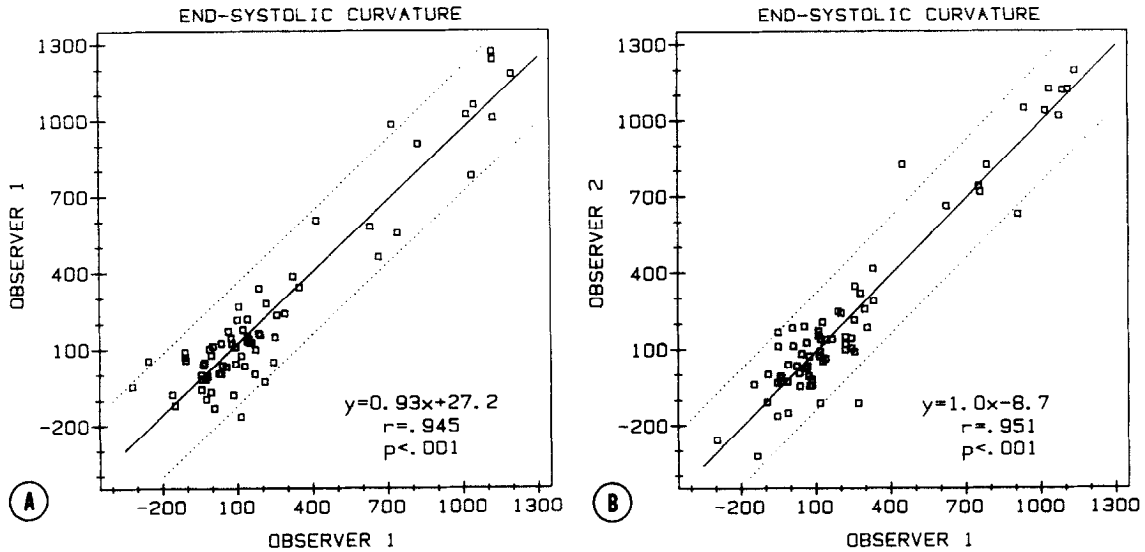
Fig. 3. Intra- and interobserver variability results are shown in *panels A and B,* respectively. *Solid lines* represent regression lines and *dotted lines* represent 95% confidence limits for individual values. Axes are in dimensionless curvature units. Few values occurred outside 95% confidence limits. Moreover, these few discrepancies did not cluster in regions of either positive or negative curvature.
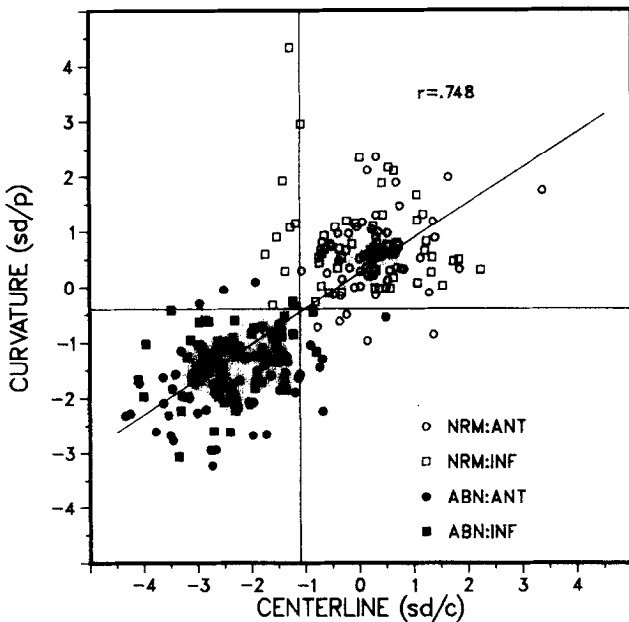
Fig. 4. Quantitative shape and wall motion indexes are plotted in standard deviations per chord or point for each region. Solid vertical and horizontal lines represent critical values that optimized sensitivity and specificity of each method. High correlation between shape and motion indexes is seen ($r = 0.748$, regression shown by *oblique solid line*); however, two populations with discordant results are also evident in *upper left and lower right quadrants. Open circles and squares* represent normal anterior *(Nrm:Ant)* and inferior segments *(Nrm:Inf),* respectively. *Closed circles and squares* represent abnormal anterior *(Abn:Ant)* and inferior segments *(Abn:Inf),* respectively. Curvature and center-line indexes are in units of standard deviations per point *(sd/p)* and standard deviations per chord *(sd/c),* respectively.

viations removed from normal at each position along the ventricular silhouettes. This process establishes a simple quantitative continuum from negative to positive values representing abnormal and normal shapes, respectively.

Wall motion was assessed by the center-line method.[8] Regional shape and wall motion indexes were determined in two ways: (1) the average standard deviation per chord (center-line method) or point (curvature method) over the entire anterior or inferior regions, and (2) the average standard deviation per chord or point in 50% of the region showing the most positive ("best") standardized results in regions believed to be normal or the most negative ("worst") results in regions categorized as abnormal. This latter quantitation is similar to the usual approach used for the center-line method. It was proposed in that setting to avoid regression toward the mean and to allow adaptability in finding the areas of regional abnormality.[18, 19]

Receiver-operator characteristics methods were used to determine the quantitative wall motion and shape indexes that optimized sensitivity and specificity for each technique. Sensitivity was defined as the number of clinically abnormal segments correctly identified by the quantitative programs divided by the total number of clinically abnormal segments. Specificity was defined as the number of clinically normal segments correctly categorized as normal divided by the total number of clinically normal segments. Concordance was defined as the number of correctly defined segments divided by the total number of segments. The predictive accuracy of a positive test was defined as the number of clinically abnormal segments correctly identified divided by the total number of segments identified as abnormal. The predictive accuracy of a negative test was defined as the number of clinically normal segments identified correctly divided by the total number of segments identified as normal.

Table I. Comparison of shape and wall motion analyses by means of different quantitative criteria and critical values

Region	Critical value	Method	Sn	Sp	PA (+)	PA (−)	Con
Best/worst 50%	−0.40 SD/p	Shape	97.1	95.9	96.4	96.7	96.5
	−1.10 SD/c	Motion	94.9	92.7	93.5	94.2	93.9
Entire region	−0.45 SD/p	Shape	81.8	87.0	87.5	81.1	84.2
	−0.95 SD/c	Motion	85.4	86.2	87.3	84.1	85.8

Abbreviations: SD = Standard deviation; p = point; c = chord; Shape = assessment of end-systolic curvature; Motion = assessment of motion by the centerline method; Sn = sensitivity; Sp = specificity; PA (+) = predictive accuracy of a positive (abnormal) test result; PA (−) = predictive accuracy of a negative (normal) test result; Con = concordance with clinical categorization.
All results are given as percentages. See text for definition of regions.

Table II. Performance of shape and motion quantitation in categorizing anterior and inferior regions

Region	N	Method	Sn	Sp	PA (+)	PA (−)	Con
Anterior	130	Shape	95.8	91.4	93.2	94.6	93.9
		Motion	93.1	100*	100†	92.1	96.2
Inferior	130	Shape	98.5	100	100	98.5	99.2
		Motion	96.9	86.2‡	87.5§	96.6	91.5§

Abbreviations as in Table I. Quantitation was based on the "best/worst 50%" approach shown in Table I and described in the text. Results are given as percentages.
*$p < 0.03$.
†$p < 0.04$.
‡$p < 0.002$.
§$p < 0.004$ compared to shape analysis.

Inter- and intraobserver variability was assessed by calculating regional curvature values averaged over 10 contiguous points in 10 randomly selected normal ventricles outlined a second time by the original observer and outlined by a second independent observer.

Regional shape heterogeneity was analyzed in the 30 normal subjects by applying a Bartlett test of homogeneity to the variances of the curvature values at each point.[20] Confidence limits were established for a maximal number of points outside of which regional variability was considered to be either greater or less than in other regions if $p < 0.05$.

Quantitative parameters were compared by standard linear regression analysis. Chi-squared analysis was used to determine differences between methods in the categorization of normal and abnormal regions. Results were considered significant if $p < 0.05$.

RESULTS

Fig. 2 shows the results of tests for regional variability of end-systolic curvature values in the normal subjects. The highest variability was seen in the anterobasal, apical, posterobasal, and mitral valve plane regions. As a consequence, all subsequent quantitation excluded the regions of the mitral valve plane and the anterobasal area (see Appendix). Moreover, by normalizing all results and expressing them in units of standard deviations at each point, the contribution of the variable apical zone to the quantitative parameters was minimized,

because these values were divided by the largest standard deviations.

Fig. 3 shows the results of inter- and intraobserver variability for end-systolic curvature values averaged over 10 contiguous points beginning at point 10 and ending at point 80. Few values were noted to be outside the 95% confidence limits for individual values. These few discrepancies did not cluster in areas of either positive or negative curvature values.

Table I shows the comparative sensitivity, specificity, positive predictive value, negative predictive value, and concordance rates for the different criteria used to categorize normal and abnormal regions. None of the results was significantly different.

Table II demonstrates that although shape and motion analyses showed comparable overall performances, quantitation of anterior and inferior regions showed individual differences. Wall motion analysis of the anterior region was more specific and demonstrated a higher positive predictive value than did shape analysis. In contrast, shape analysis was more specific, more highly concordant, and demonstrated a higher positive predictive value than did wall motion analysis in the categorization of inferior abnormalities.

Fig. 4 shows the relation between wall motion and shape indexes. The indexes plotted are based on the "best/worst 50%" approach described previously
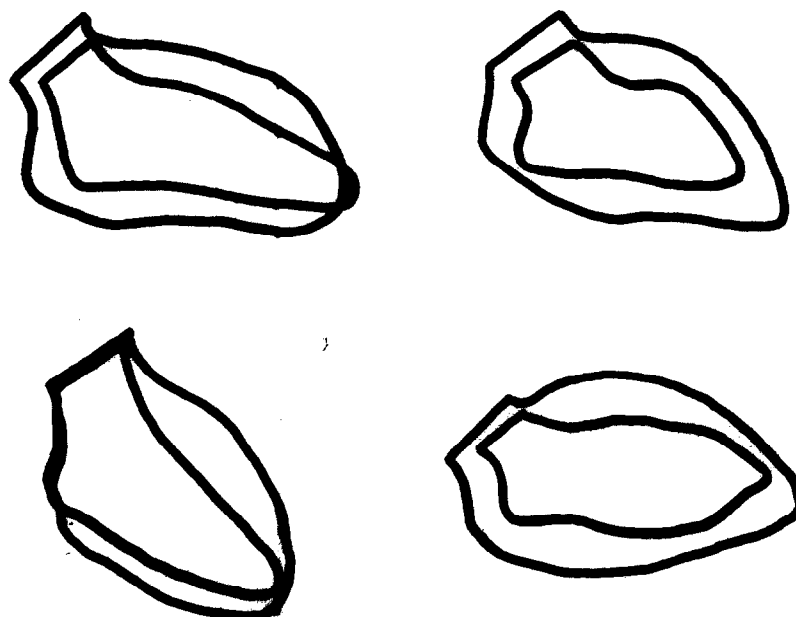
Fig. 5. Examples of ventricular outlines showing normal shape parameters but abnormal function *(left)* and abnormal shape with normal wall motion *(right). Upper right panel,* a subtle anterior abnormality was identified by shape analysis but not by wall motion analysis; *lower right panel,* mild inferior abnormality was identified only by shape analysis. These examples demonstrate the complimentary nature of the two methods and suggest that shape analysis may be most useful in highlighting patients with mild localized dysfunction that is not predominantly in the apical region.

and the critical cutoff values shown are those that optimized sensitivity and specificity for *each* approach. A positive correlation was seen between these two indexes ($r = 0.748$, $p < 0.0001$). Fig. 5 shows typical examples of the types of shape and wall motion conditions accounting for discrepancies between the two quantitative methods. There were four abnormal regions (three anterior and one inferior) that were found to have a normal shape index but an abnormal motion index. These were largely accounted for by abnormalities localized primarily to the apical region. There were seven abnormal segments that were classified as having abnormal shape but normal wall motion. Of these, five showed subtle abnormalities in the anterior wall.

DISCUSSION

While the importance of shape characteristics of ventricular chambers has been appreciated for many centuries, shape parameters have been used rarely to help characterize global ventricular function and even more rarely to characterize regional function.[11, 12] Current developments in computer vision and artificial intelligence have caused an increased interest in exploitation of such methods for medical diagnosis and decision making, which often includes shape analysis.[21, 22] An attraction of these methods is

that they provide alternative approaches that are independent of the numerous assumptions required by all traditional methods of regional wall motion analysis. These include assumptions regarding coordinate, reference, and indexing systems and assumptions about the geometry of the normal ventricle and the uniformity or direction of its contraction.[4, 13, 15] The proposed methodology is immune to variations in wall motion assessment caused by the different methods used to compensate for translational and rotational motion. In addition, the method makes no assumptions about concordance of ventricular segments at end diastole and end systole.

The results of this investigation show that shape quantitation and pattern recognition techniques can be used to characterize regional ventricular function, that this approach closely mimics the regional categorizations made by experienced clinicians, that the performance is similar to that of traditional methods but does not invoke any of the assumptions mandated by those approaches, and that these results can be provided in an automatic, adaptive, and quantitative fashion. The results also demonstrate the complimentary nature of the two techniques analyzed in this study, as shown by detailed analysis of the discrepancies in the regional function designations by the two methods. It was shown that

in several instances, when wall motion was in the low-normal range, shape characteristics were often abnormal. In contrast, small regions of wall motion abnormality localized primarily to the apical region were generally not detected by the shape analysis. This is likely related to the fact that such abnormalities do not greatly distort shape except by lengthening the long axis of the end-systolic outline (Fig. 5). This abnormality of shape does not displace the apical curvature peak of the individual curvature signature relative to that of normal ventricles, and the resultant apical curvature remains high because of the relatively normal inward motion on either side of it. This highlights the fact that although distortion of ventricular shape is a consequence of abnormal function, this relationship is not uniform in different regions of the heart. Thus, the overall significant correlation between shape and function parameters should not obscure the fact that the two approaches provide different information. It should also be emphasized that shape abnormalities may not be solely the result of inadequate contraction. For example, a previous investigation demonstrated shape aberration resulting from contralateral hyperkinesis in patients with anterior abnormalities.[17] Similarly, the ventricular distortion seen in hypertrophic cardiomyopathy is also the result of hyperkinesis.

Few previous investigators have used shape parameters to assess regional function. However, Brower and Meester[11] assessed shape parameters that were calculated by assuming an external reference system and a radial coordinate system with its origin at the center of area of the end-systolic frame. These are arbitrary choices that this laboratory wished to avoid. The method proposed in this study overcomes the drawback of the approach of Greenbaum and Gibson,[12] which provided only a semiquantitative determination of regional curvature. Moreover, this latter study concentrated mainly on end-diastolic shape, which has been shown to provide relatively little diagnostic information compared to end systole in the setting of coronary artery disease.[10, 17]

Several implications of this work are evident. First, an application of a classical approach to pattern recognition and shape quantitation can be used to overcome the need for invoking numerous assumptions required for the clinical measurement of wall motion while still providing performance comparable, and in some cases superior, to traditional methods, particularly in detecting small regional abnormalities that do not involve the apex. Abandonment of the need to invoke specific refer-

ence, coordinate, and indexing systems is a result of the fact that quantitative regional curvature analysis is not affected by translational and rotational motion parallel to the imaging plane and that end-systolic shape provides most, and probably all, of the diagnostic regional information, thus obviating the need to invoke assumptions about concordance of specific sites at end diastole and end systole. The approach allows an assumption-free and clinically applicable assessment of interventions designed to alter ventricular function. Application of other techniques of shape analysis, extension to biplane or three-dimensional quantitation, and assessments of other parameters, such as rates of shape change in the different phases of the cardiac cycle, are likely to further enhance the usefulness of such applications and will help to integrate important temporal features that are known to occur in areas of regional dysfunction.[6] Second, application of expected shape criteria in the setting of coronary artery disease may be useful in developing automated, "expert" methods of ventricular edge detection.[23] Third, application of pattern recognition to cardiac images obtained during an ischemic stress might be automatically analyzed and interpreted to give the probability of finding a functionally significant stenosis in a specific perfusion bed. Last, the method may allow serial assessment of ventricular remodeling after infarction and may reveal specific shape abnormalities associated with poor prognoses.[24] These features, therefore, provide justification for further development and investigation of the use of shape analysis for ventricular quantitation and decision making.

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APPENDIX

Several observations requiring software modifications were identified in preliminary studies.[16, 17] First, it was found that end-diastolic shape characteristics seldom provided significant diagnostic differences between normal and abnormal regions. In contrast, end-systolic shape characteristics provided all of the diagnostic information, and changes in shape from end diastole to end systole (end-diastolic curvature minus end-systolic curvature) did not add substantially to the diagnostic information provided by analysis of end systole alone. Moreover, calculation of the curvature difference had the disadvantage of requiring assumptions regarding concordance of segments at end diastole and end systole that could not be ensured without implanted radiopaque markers. Second, quantitative curvature signatures of abnormal ventricles showed deviations from normal that were of a different arithmetic sign dependent on the region being considered. That is, regional shape aberrations of individuals showed increased curvature values on either side of the expected location of the normal "apical zone" and decreased curvature values in the "apical zone" region (Fig. 1). Despite the differences in arithmetic signs, the abnormalities reflected an increased regional globularity that was secondary to the wall motion abnormality. A means of rectifying this arithmetic discrepancy was required before a single quantitative shape parameter could be derived to reflect the normality or abnormality of a given region. A third aspect of the pattern recognition was required to account for the fact that both isolated anterior and inferior abnormalities often extended around the apex and appeared to involve the contralateral wall. Thus, an adaptive method was required to segment each ventricle into an anterior and an inferior zone that would not erroneously ascribe this "wrap-around" phenomenon to the wrong region.

Software was developed to automatically and adaptively overcome the problems posed by the observations listed previously. To rectify the sign of the curvature values so that negative deviations would represent potential abnormalities and positive deviations would represent absence of an abnormality, an automatic-search algorithm was developed to find the area in the individual ventricle in question to be designated as the "apical zone." This was achieved by first determining the point of maximal apical curvature of the normal group. The algorithm then searched to either side of this point until the first crossover points of the normal mean curvature signature and the curvature signature of the individual being analyzed were found. Based on numerous observations, this search was constrained within a region spanning 30% to 55% of the perimeter length, which corresponded to the base of the apical peak in the normal mean curvature signature. If a crossover did not occur within these bounds then the algorithm determined the points within the bounds that most closely approached the normal mean results. This zone was then designated as the

"apical zone" within which curvature values of less than normal were considered to constitute a potential abnormality. Curvature values on either side of this zone were inverted (multiplied by −1), thereby rectifying the arithmetic sign of any deviations from normal. In so doing, normal and abnormal shape parameters could be quantitated on a continuous scale ranging from positive to negative, respectively.

The problem of segmenting the curvature results into anterior and inferior zones was approached by assigning the beginning of the anterior segment at point 10, because of the variability of the shape results in the anterobasal area (see above). An automatic-search program then determined the point of highest curvature in the normal mean curvature signature corresponding to the junction of the mitral valve plane and the posterobasal wall. A search was then made leftward along the curvature signature to determine the first crossover point occurring at a point value of 80% or more of the perimeter length. If no crossover was found then the search was ended at point 80. This marked the end of the inferior segment and effectively excluded the highly variable shape data of the mitral valve plane. When the anterior and inferior zones were either both normal or both abnormal, then the "apical zone," determined as described previously, was simply divided in half so that quantitative results from point 10 to the middle of the "apical zone" were assigned to the anterior wall, and results from this latter point to point 80 or the last crossover point were assigned to the inferior wall. However, a more complex and adaptive approach was required in the presence of isolated regional abnormalities that involved the anatomic apex and a portion of the contralateral wall. Accordingly, the software was further developed to automatically determine the extent of involvement of the contralateral wall, so that this small region would be correctly included in the description of isolated anterior or inferior regional abnormalities. This phenomenon was found to be readily and automatically identified by searching leftward from the previously designated left-hand "apical zone" boundary and rightward from the right-hand "apical zone" boundary for the next crossover point of the individual curvature signature and that of the normal mean curvature signature. These searches were constrained between 20% of the perimeter length and the left-hand "apical zone" border for inferior abnormalities and from the right-hand "apical zone" border to 70% of the perimeter length for anterior abnormalities. These heuristic limits were based on numerous observations of mild-to-severe wall motion abnormalities and their quantitative shape characteristics. If a crossover did not occur within these limits then the point that most closely approached the normal mean curvature value was used as the boundary between anterior and inferior regions. It is noteworthy that this form of segmentation is analogous, but more adaptive, to the actual shape of the ventricle than the approach proposed for the center-line method of regional function analysis.[18] The entire process was performed automatically.