Abnormalities of Dynamic Ventricular Shape Change in Patients With Aortic and Mitral Valvular Regurgitation: Assessment by Fourier Shape Analysis and Global Geometric Indexes

David A. Kass, Thomas A. Traill, Mark Keating, Pablo I. Altieri, and W. Lowell Maughan

The normal cardiac cycle is associated with dynamic changes in left ventricular shape, which can be disturbed in disease states. To assess the influences of diastolic volume, percent ejected volume, and abnormalities of acute or chronic systolic loading on general and detailed chamber geometry, we studied dynamic shape change recorded by x-ray contrast ventriculography in both normal patients and those with aortic (AR) or mitral (MR) valve regurgitation. While both lesions increased diastolic volume, the character of load throughout ejection differed markedly. Detailed cavity geometry was assessed by a Fourier analysis technique and general shape by eccentricity and circularity indexes. Normal hearts showed increased systolic elongation by all indexes. AR patients displayed a similar rise in eccentricity during ejection; however, the extent of shape change when measured by Fourier and circular indexes was reduced. In contrast, MR patients displayed enhanced systolic shape change, particularly in chamber elongation. Neither simple eccentricity or circular indexes adequately differentiated these shape abnormalities, whereas detailed Fourier geometric analysis precisely characterized the abnormalities of shape change in these two diseases. Relations between the extent of shape change and ejected volume for each patient group revealed significantly more systolic deformation with a different shape versus volume relation for the MR hearts as compared with AR and controls. Thus, while dynamic left ventricular shape is certainly influenced by the extent of volume change, it also varies independently from volume related to the specific nature of loading during ejection. (Circulation Research 1988;62:127-138)

William Harvey observed that the left ventricle became "narrow, relatively longer, and more drawn together" during ejection while resuming a more spherical configuration in diastole. Such geometric changes influence myocardial wall stress and pump efficiency and are thus integral to normal cardiac function. Studies of several forms of myocardial and valvular disease have revealed abnormalities of dynamic shape deformation. These and other data have shown that the larger the ventricular chamber volume the rounder the shape and that when the percent of volume ejected is reduced, dynamic shape change is similarly decreased. The data, however, have not demonstrated that dynamic shape change abnormalities are in any sense separable from volume change, nor have they been consistent about the nature of these abnormalities. Differences and lack of precision among shape characterization techniques may have contributed to these discrepancies.

Ventricular geometry has been studied using dimensional measurements, planar projections from contrast ventriculograms, echocardiograms, and anatomic studies. Eccentricity, a commonly used index, is based on an ellipsoidal model of the heart. In 1975, D.G. Gibson introduced an alternative index that compared the relative circumference/area ratio of a ventricular silhouette with that of a circle. Both these general indexes defined shape relative to a geometric model (ellipse or circle), but they did not characterize the precise deformation from the model shape. In addition, they displayed relatively little change within the operating range of normal ventricular deformation.

A more comprehensive shape description was proposed by Ehrlich and Weinberg in a study of sand grains utilizing a Fourier analysis technique. Contour coordinates, translated into polar form, were represented by a Fourier series. Individual series components corresponded to specific shapes, and the entire contour could be accurately defined by the sum of these shapes. Initial observations suggested that this approach more completely described ventricular shape changes during the cardiac cycle. Variations on this approach have been used to examine right and left ventricular shape.

The purpose of the present study was to examine the relation between diastolic volume, ejected volume, and dynamic left ventricular geometry in man and to determine whether other factors could also influence dynamic shape change. To compare ventricles with similar end-diastolic volumes and stroke volumes but
with different systolic valve, we examined patients with aortic and mitral valve regurgitation. Two global geometric indexes (eccentricity and the Gibson index) and the detailed Fourier technique were used to characterize shape as recorded by single-plane x-ray contrast ventriculography. We compared these different methods of quantifying left ventricular shape change to examine the extent to which shape characterization is model dependent and to help clarify disparities in the reported literature.

Patients and Methods

Patient Selection

Ventriculograms from 30 patients were retrospectively and randomly selected from routine cardiac catheterization studies performed between 1982 and 1986 at the Johns Hopkins Medical Institutions and the Centro Medico, University of Puerto Rico. Exclusion criteria were poor contrast opacification and excessive ventricular ectopy. Ten patients were chosen in each of three groups.

1) Normal subjects. These patients had a history of chest pain, but hemodynamics, coronary angiography, and left ventriculography were all normal. None of the patients had significant hypertension or left ventricular hypertrophy.

2) Aortic regurgitation (AR). Patients had both acute and chronic aortic regurgitation. Rheumatic disease was responsible for nearly all the chronic AR, while bacterial endocarditis caused most of the acute AR. Coronary arteriograms were normal, and no patient had aortic stenosis.

3) Mitral regurgitation (MR). These patients all had chronic mitral regurgitation. Rheumatic heart disease, severe mitral valve prolapse, and endocarditis comprised the etiologies for valve dysfunction in this group, and no patients had coronary artery disease. All of the patients had 3–4 valvular regurgitation subjectively defined by complete opacification of the chamber into which regurgitant flow was directed within 1–3 beats following contrast injection. Thus, for the AR group, this was assessed by the aortic root angiogram, while for the MR patients, the left ventriculogram was used.

Catheterization Procedure

Patients were premedicated with 5–10 mg diazepam and 25–50 mg diphenhydramine orally 30 minutes before study. Left ventriculography was performed in the right anterior oblique (RAO) projection. Renografin-76 (diatrizoate meglumine and diatrizoate sodium) was injected at a flow rate of 11–15 ml/sec through a pigtail catheter. Cine film was exposed at a rate of 30 frames/sec. Postextrasystolic beats were excluded from analysis. Only well-opacified ventriculograms were used. Calibration was performed using landmarks on the pigtail catheter itself or via a lattice grid exposed at midchest level. Since the shape indexes were dimensionless, calibration was required only for absolute volume estimations.

Digitization of Cineangiograms

Successful frames of the study beat, starting at the frame of maximal area (end diastole), were viewed on a cine projector (XR-35 Vanguard). The contrast silhouette for each frame was then manually digitized using a light pen (Graf/Pen 6P-3, SAC, Southport, Conn.). The outer margin defined by radiographic contrast between trabeculations was used. The perimeter of the contour was traced clockwise starting at the intersection point of the aortic valve with the anterobasal wall. Approximately 80–100 points were generated for each cine frame, and together with calibration data, the results were stored via computer (DG-130, Data General, Westboro, Mass.) on magnetic tape for further analysis.

Shape Analysis

Circular (Gibson) shape index. The circumference-to-area ratio for any planar contour is smallest for a perfect circle. Thus, a measure of the circularity of any shape is the ratio of its area to that of a circle with the same circumference.

If \( A = \text{contour area} \) and \( C = \text{contour circumference} \), then the area of a circle with circumference \( C \) is:

\[
\pi (C/2\pi)^2 = \frac{C^2}{4\pi}
\]

This dimensionless ratio ranges from 1.0 for a circle to zero if the shape is essentially a straight line. The index is independent of long and short axis measurements or cavity orientation.

Eccentricity. Eccentricity is defined using an elliptical model in which \( L \) represents the long or major axis, and \( D \) represents the short or minor axis. Then eccentricity is defined as:

\[
e = \sqrt{L^2 - D^2} \frac{L}{L}
\]

This dimensionless index ranges from 0 for a circle, in which \( L = D \), to 1 for a line, in which \( D = 0 \).

Fourier shape analysis and the shape-power index. To perform Fourier shape analysis of the ventricular contour, the digitized \((x,y)\) coordinates are first transformed into polar form (Figure 1). The center moment of the digitized contour is calculated, and using this as the origin, radii are drawn to each of the digitized points on the perimeter of the contour (lower left panel). The length of each radius \( L \) and the angle relative to a given orientation \( \theta \) are measured, and an \( r(\theta) \) function is generated (lower right panel). We chose the first digitized point (aortic valve–anterobasal wall intersection) as the 0° position and continued counterclockwise from that location to generate the polar representation.
Once in polar form, a standard Fourier series analysis is applied to the \( r(\theta) \) function:

\[
r(\theta) = A_0 + A_1 \sin(\theta) + B_1 \cos(\theta) + A_2 \sin(2\theta) + B_2 \cos(2\theta) + A_3 \sin(3\theta) + B_3 \cos(3\theta) + A_4 \sin(4\theta) + B_4 \cos(4\theta) + \ldots
\]

The successive components of this Fourier series have distinct shape analogs (Figure 2). The zero-order term, \( A_0 \), represents the best fit circle to the shape \( (r=\text{constant}) \), and its power provides cavity size information. The first-order term \( (r = a \sin \theta) \) represents the extent to which the origin chosen for conversion from Cartesian to polar coordinates is the true center moment for the shape. Since the mathematically derived center moment was used for the origin, little power was present in this term reflecting small numerical error, and the lack of perfectly evenly distributed points about the circumference.

Starting with the second-order term, the series components represent shapes made up of increasing numbers of balloon-like lobes. As shown in Figure 2, the \( \sin(2\theta) \) term represents a bilobed “dumbbell” shape and is an index of elongation; the \( \sin(3\theta) \) term represents a trilobed shape and thus indexes triangular shape characteristics; the \( \sin(4\theta) \) a four-lobed shape and thus a “squareness” index, and so on.

The series representations demonstrated rapid convergence in that the power in higher order terms quickly diminished, with less than 2% of the total spectral power contributed by the 8th term. Therefore, we examined only the first eight series components for the present study. Figure 3 shows reconstructions of an original ventricular contour using the first 4, 6, 8, and 12 series components, respectively. There was only a minimal amount of additional shape information gained by the use of 12 as compared to 8 components.

The sine and cosine terms of the Fourier analysis were combined into a single sine term with amplitude \( (C_n) \) and phase \( (P_n) \): 

\[
C_n \sin(n + P_n)
\]

where 

\[
C_n^2 = A_n^2 + B_n^2
\]

and 

\[
P_n = \arctan(A_n/B_n)
\]
plotted amplitudes. To eliminate this contribution of ventricular size, each term was normalized to the zero-order term, \( A_0 \). In this way the absolute value of the modulus reflected a pure shape index not affected by the size of the silhouette.

Two methods were used to examine dynamic shape change as characterized by the Fourier technique. A Fourier shape-power index (FSPI) was generated as the sum of the power in the 2nd through 8th Fourier components, normalized to the zero-order term (Equation 6). This provided a measure of net contour deviation from a circle. A second method plotted the full frequency spectra for each frame over time, generating a three-dimensional dynamic shape surface. This representation had the advantage of simultaneously displaying all of the component amplitude data throughout the cardiac cycle.

### Data Analysis

Digitized coordinates were analyzed using a computer (IBM-PC). The circumference was calculated by integrating the segment lengths between digitized points of the contours. The area was calculated using Green's theorem. The center of the aortic root was estimated, and the farthest distance between this point and any other point along the perimeter was defined as the long axis, \( L \). The short axis, \( D \), was calculated from:

\[
D = 4A\pi/L
\]

Eccentricity and circular shape indexes were calculated by Equations 3 and 2, respectively. Cavity volume was estimated using the area-length method of Dodge et al, as modified by Kennedy et al for single plane RAO projections.

The time series for each shape index and Fourier power amplitude throughout the cardiac cycle was smoothed by a weighted three point running mean. The values of each index determined at the frame of maximal and minimal area were used for end diastole and end systole, respectively.

Statistical testing of differences between means was performed using nonpaired \( t \) tests. Shape change versus percent ejected volume relations were fit to a monoeponential in the form of \( y = A + e^{(t-n-c)\cdot\text{Exponential}} \) using the Marquardt algorithm for nonlinear regression. Significance levels are at the \( p<0.05 \) level unless otherwise indicated.

### Results

**Shape Deformation in Normal Ventricles**

Normal ventricular ejection was associated with significant change in chamber geometry. The ventric-

### Table 1. Ventriculographic and Shape-Change Data for Normal Controls

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<tr>
<th>Patient</th>
<th>EDV</th>
<th>SV</th>
<th>EF</th>
<th>CSI(es)</th>
<th>CSI(es)</th>
<th>%ΔCSI</th>
<th>E(ed)</th>
<th>E(es)</th>
<th>%ΔE</th>
<th>FSPI(ed)</th>
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Mean 89.3 60.3 67.6 82 58 29.5 78 90 15.5 6.7 22.0 240.1

Std 11.2 9.6 7.3 0.3 0.05 5.9 0.04 0.03 4.4 2.2 6.3 104.2

*\( p<0.001 \)

EDV, end-diastolic volume; SV, stroke volume; EF, ejection fraction; CSI(ed) and CSI(es), circular shape index at end diastole and end systole; %ΔCSI, percent change in CSI; E(ed) and E(es), eccentricity at end diastole and end systole; %ΔE, percent change in eccentricity; FSPI(ed) and FSPI(es), Fourier shape-power index at end diastole and end systole; %ΔFSPI, percent change in FSPI.
FIGURE 4. Eccentricity and circular shape indexes (CSI) determined throughout three consecutive cardiac cycles in a normal ventricle. Estimated ventricular volume is displayed in the upper panel. With ejection, eccentricity increased while the CSI decreased indicating increased chamber elongation and less circularity. Maximal changes in both indexes were synchronous with maximal volume ejection.

ulographic volume and shape index data for normal hearts are provided in Table 1. Mean ejection fraction was 67.6±7.3% (mean±SD) at an estimated end-diastolic volume (EDV) of 89.3±11.2 ml, and end-systolic volume of 29.0±6.9. Values for the CSI, chamber eccentricity (e), and the FSPI are provided at end diastole and end systole, defined by the cine frames of maximal and minimal area, respectively.

During ejection, the CSI decreased from 0.82 ±0.03 to 0.58 ±0.05 with a mean change of $-29.5 \pm 5.9\%$ ($p<0.001$). Cavity eccentricity increased by 15.5±4.4% ($p<0.001$) from an end-diastolic value of 0.78±0.04 to a value of 0.90±0.03 by end ejection. Thus, during normal contraction viewed in the RAO projection, chamber shape became elongated with a reduction in contour circularity. Figure 4 displays an example of the time course of chamber volume, eccentricity, and CSI for three consecutive cardiac cycles. Both the rise in e and the fall in CSI were synchronous with ejection, the peak change occurring at the time of minimal volume. During early diastole, cavity shape returned rapidly to the presystolic configuration, and this was reflected in both shape indexes. Shape changes were very consistent from beat to beat.

An example of the results of Fourier shape analysis (Patient 10, Table 1) applied to the same ventriculographic data is shown in Figure 5. The moduli and phase angles for the 1st through 8th harmonics are displayed, and the volume curves are shown for timing purposes. Nearly all components displayed reproducible cyclical changes with maximal values occurring at peak ejection. The second-order ("eccentricity") component contributed the largest proportion to the Fourier spectrum and increased nearly 100% during systole. The 3rd through 8th components also increased during

FIGURE 5. Fourier shape analysis spectra of the same normal cardiac cycles shown in the previous figure. Both normalized amplitudes (A/A) and phase for the 1st through 8th components are displayed. Estimated ventricular volume is shown for timing purposes. Ventricular ejection was accompanied by an increase in amplitude of each component. While the second-order term contributed the greatest amount to systolic change, other terms (in this example 3 and 5) also displayed substantial increases. The time course of amplitude change was not identical for each component. Several terms increased suddenly near end ejection, returning to baseline early in diastole, while others followed the more gradual time course of chamber volume.
DYNAMIC SHAPE CHANGE SURFACE

NORMAL

AORTIC REGURGITATION

MITRAL REGURGITATION

FIGURE 6. Fourier shape change surfaces. The amplitudes for the 1st through 8th harmonics of the Fourier series are displayed (vertical axis) throughout the cardiac cycle. The time axis starts at end diastole (foreground, lower right-hand corner) and continues for one cycle (into the page). Examples of dynamic shape change surfaces are shown for normal (A), aortic regurgitation (B), and mitral regurgitation (C).

systole, contributing smaller proportions to the endsystolic shape. Both the 3rd and 5th components demonstrated a sharp rise near end ejection and a similar rapid fall early in diastole. Thus, Fourier shape analysis delineated geometric changes that followed the general time course of volume ejection, as well as more rapid deformations within the cardiac cycle. While the specific pattern of higher order terms (≥2) tended to vary among the hearts, the observation that at least several terms showed a significant rise and that the time course of this change varied among components was consistent.

The phase angle of the components reflected the orientation of each respective shape. The intersection point of the anterobasal wall with the aortic valve had been chosen as the 0° point for Cartesian to polar coordinate conversion (see “Patients and Methods”). Thus, the highly stable phase seen in the 2nd term (Figure 5) reflected a consistent orientation of ventricular elongation relative to the aortic valve. Other components displayed some cyclical variation in phase indicating alterations in orientation.

To show all of the Fourier shape information throughout the cardiac cycle, a shape surface (Figure 6A) was generated displaying each of the component amplitudes. Normalized amplitudes of components 1–8 were plotted along the vertical axis, with the time course and component frequency plotted on the two other axes. In this way, the relative contributions of the individual components were visualized. As shown in Figure 6A, the largest contribution was in the 2nd order term. In this example, the 5th and 7th terms also demonstrated a significant rise by end ejection.

The FSPI was generated by summing the power of each normalized component and is shown in Figure 7 from the same data displayed in Figure 5. FSPI data (reported × 100) for the 10 control patients is given in Table 1. The end-diastolic value was 6.7 ± 2.2, and this rose by a mean of 240% by the time of end ejection. Values of the FSPI showed a greater variability than the eccentricity or CSI indexes, primarily due to the greater sensitivity of the power index to small changes in the ventricular architecture. The geometric indexes relate to smoothed global geometries and therefore showed less variability but also a smaller operating range. Thus, while one advantage of the FSPI was its greater sensitivity and wider operating range, a drawback was somewhat greater intersubject variability.

Shape Deformation in Aortic Regurgitation

The ventriculographic and shape analysis data for

NORMAL CONTROL

FOURIER SHAPE POWER INDEX

FIGURE 7. Fourier shape-power index (unsmoothed) for three consecutive beats in a normal ventricle. The FSPI displays a much greater range of change throughout the normal cycle than either eccentricity or CSIs (compare with Figure 4). The extent of change was very reproducible from beat to beat, although there was somewhat greater noise than seen in the other general geometric indexes.
Aortic regurgitation

VOLUME

SHAPE INDICES

FOURIER SHAPE POWER INDEX

TIME (msec*30)

patients with aortic regurgitation are provided in Table 2. Mean end-diastolic volume was 243 ± 58.5 ml, with 50.3 ± 8.2% ejected volume. These values were both significantly different from the control group. The CSI fell by 10.7 ± 6.1% during ejection, representing a reduction of nearly one third the change observed in the control group. The source of this reduction was found in the systolic configuration, which was more circular for the AR group (0.78 ± 0.07) compared with the control group (0.58 ± 0.05) (p<0.001). In contrast, the percent change in eccentricity during ejection was similar to that of controls at 13.9 ± 8.8%. Thus, in this group of patients with aortic regurgitation, significant abnormalities in dynamic geometry were documented by the CSI but not the e index. Figure 8 displays an example of shape index data (Patient 3, Table 2). While CSI displayed a smaller extent of dynamic change throughout the cardiac cycle, the change in eccentricity was similar to control. This apparent paradox of maintained chamber elongation despite a fall in the systolic deviation from end-diastolic "circular" geometry is explained by the Fourier shape analysis. FSPI rose from an end-diastolic mean value of 4.6 ± 1.7 to 10.9 ± 5.4 at end systole. This mean increase of 142.5 ± 91.3% was significantly reduced compared with controls. Figure 9 shows an example of the shape spectrum and Figure 6B a shape surface from ventricles in this group. The persistent increase in chamber elongation (or eccentricity) was reflected by the rise in the amplitude of the 2nd harmonic during systole. However, nearly all of the higher order terms (3–8) displayed much less dynamic change than in the control group. In some components (i.e., 3rd), there was even a fall during ejection. Thus, a greater proportion of the shape change abnormality in this group was found in the reduced contribution of higher order harmonics to noncircular geometry, with relative preservation of chamber elongation (or eccentricity) at end ejection.

Shape Deformation in Mitral Regurgitation

In contrast to the aortic regurgitation group, patients with mitral regurgitation demonstrated maintained systolic shape change in all three indexes despite increased end-diastolic volume and reduction in the percent of volume ejected compared with controls. In some cases, the extent of deformation at end systole far exceeded control levels. The mean ejection fraction for this group was 58.9 ± 14.6%, lower than the control group but not significantly different from the hearts with aortic regurgitation. The estimated end-diastolic volume for the group was 238 ± 57.6 ml, also similar to the AR group. By end ejection, the CSI had decreased by a mean of 23.9±9.6%, which was slightly less than control change, while eccentricity increased by 23.5 ± 12.5%, or slightly more than control. Neither comparison achieved statistical significance. Data for this group are provided in Table 3. The FSPI increased by 374 ± 270% by end ejection. This change was more than that observed in the AR group (/?<0.02) despite similar end-diastolic area and stroke volume. The major source for this increase was a significant change in end-systolic shape. Both valvular lesions led to chamber dilation with a small but significant reduction in the end-diastolic FSPI value compared with controls (AR 4.6 ± 1.7, MR 5.3 ± 3.5, controls 6.7 ± 2.2). However, in the case of mitral regurgitation, the end-systolic FSPI was similar to control levels, while it was significantly reduced in the AR group. The second-order harmonic (Figure 6C) increased the most, while changes in higher order terms were slightly less than that seen in control hearts.
Table 2. Ventriculographic and Shape-Change Data in Aortic Regurgitation

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<tr>
<th>Patient</th>
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<th>SV</th>
<th>EF</th>
<th>CSI(ed)</th>
<th>CSI(es)</th>
<th>%ΔCSI</th>
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*<p>0.001.

Influence of Systolic Load on Dynamic Shape Change

The valvular lesions of aortic and mitral regurgitation represented two conditions in which ventricles were similarly dilated but operated under different systolic loading conditions. Since both lesions were associated with chamber dilatation and a reduced ejection fraction, abnormalities in systolic shape change might merely relate to the reduced volume change. To determine whether analysis of chamber shape provided information independent of simple cavity size, we compared the effects of AR and MR both at end diastole and throughout ejection. FSPi was determined at end diastole and at 20, 40, 60, 80, and 100 percent (end systole) of the ejected stroke volume. The FSPi was normalized to the value at end diastole, and the results were plotted against simultaneous volume normalized to EDV. Individual patient data were fit to a monoexponential model (A + e<sup>(k<sub>0</sub>T<sub>30</sub>)</sup>). The regression estimates for each parameter were then averaged within each group. This model was selected

AORTIC REGURGITATION

FOURIER SHAPE ANALYSIS

FIGURE 9. Fourier shape spectra from a patient with aortic regurgitation. Data are displayed as in Figure 5. The time axis starts at end diastole. As in normal ventricles, the second harmonic dominates the shape change. However, unlike controls, little contribution is found in higher order terms, and in some cases (3 and 6 in this example), the amplitude of the component decreased with ejection.
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FIGURE 10. A–C, Dynamic shape change during ejection. The change in FSPI normalized to the end-diastolic value in each patient is plotted against the normalized ventricular volume (percent of end-diastolic volume) during ejection. Each solid line represents a different patient. A, Normal hearts; B, aortic regurgitation; C, mitral regurgitation.

because of its ability to fit the data and not on any theoretical basis. Figure 10A–C displays the individual patient shape/volume plots, while Figure 11 shows the mean regression relations for the three groups.

The data were well described by an exponential relation (p<0.01) in all of the 30 studies. Very little shape change was observed during ejection of the initial 40% EDV; however, with further volume ejection, the FSPI increased rapidly. While both normal and aortic regurgitation ventricles were similar, mitral regurgitation produced significantly different curves. Normal hearts (Figure 10A) had a mean value (± SEM) for the B coefficient of $-4.69 \pm 0.33$ and for C of $2.75 \pm 0.35$. Hearts with aortic regurgitation (Figure 10B) had mean values of $-5.03 \pm 0.5$ and $3.2 \pm 0.4$ for B and C, respectively, which were not significantly different from control. Thus, the reduction in the extent of shape change observed with aortic regurgitation (Table 2) was related to the fall in percent ejected volume rather than a different and flatter shape/volume relation. In contrast, mitral regurgitation hearts (Figure 10C) had significantly different mean values for both parameters (B = $-7.8 \pm 1.3$ and C = $4.77 \pm 0.64$), displaying a greater extent of shape change over a similar volume range than either of the two other states (Figure 11). Thus, the extent of systolic shape change was influenced not only by diastolic volume or the percent of volume ejected but also by the specific nature of the valvular disease states.

Discussion

Our study demonstrates marked disturbances in left ventricular dynamic shape change during ejection in the presence of aortic or mitral valve regurgitation. Furthermore, these data indicate that left ventricular geometry and particularly the course of dynamic shape alterations during ejection are influenced not only by the extent of cavity dilation or the percent of volume ejected but also by the nature of loading during systole. The characterization of shape change abnormalities can depend on which of two geometric shape indexes (eccentricity versus circularity) is chosen. In AR, the CSI index revealed reduced systolic shape change, while eccentricity did not. In MR, eccentricity increased proportionately more with ejection than in controls, while little change was present in the CSI. The Fourier shape analysis, however, provides a more complete characterization of cavity geometry and the time course of ventricular deformation and allows better delineation of abnormalities between the two diseases.

Discrepancies in Shape Change Characterization

The observation that the normal cardiac cycle involves a change in ventricular shape from a more circular to more elongated form is not new. Attempts to quantify this shape change have largely relied on indexes tied to particular models of cavity geometry. Chamber eccentricity, long/short axis ratio, or a ratio of major/minor radii of curvature are all related to an ellipsoidal geometry. Chamber circularity characterizes shape relative to circular geometry. Studies
Gibson and Brown using eccentricity and CSI, differed little from the control group. This was similar reduced, yet the extent of dynamic change with ejection diastolic chamber eccentricity was significantly re-
change during ejection enhanced over the control elongation and the tendency of the end-diastolic chamber eccentricity was less but the patients. Others, however, using diameter/length ratios4-20 have shown that the extent of systolic shape change is reduced in diseased hearts with low ejection fractions.8"1020 However, dynamic shape change abnor-
malities between normal hearts and those with aortic or mitral regurgitation in the absence of substantial reductions of ejection fraction have not been consistently reported, so the literature contains no evidence to suggest that ventricular shape is in any way independent of ventricular volume.

In our patients with aortic regurgitation, end-diastolic chamber eccentricity was significantly reduced, yet the extent of dynamic change with ejection differed little from the control group. This was similar to findings of Fischl et al34 in which eccentricity was used to characterize shape abnormalities in AR patients. Others, however, using diameter/length ratios5,6 reported a reduction in systolic shape change with little alteration in end-diastolic shape in a similar patient group. When the ventricular shape in AR patients was analyzed by the circular shape index in our study, there also was little difference at end diastole from controls but a substantial reduction in the extent of shape change by end systole.

Disparities of shape characterization between different indexes were also observed with mitral regurgitation. End-diastolic chamber eccentricity was less but the change during ejection enhanced over the control group. In contrast, the CSI revealed a decreased change during ejection. Previous reports of Vokonas et al4 and Gibson and Brown9 using eccentricity and CSI, respectively, had demonstrated similar disparities. Possible reasons for these discrepancies include differences among patient groups with respect to underlying causes or chronicity of valvular regurgitation or differences in contouring or angiographic techniques. Our findings, however, in which several indexes were directly compared in the same patient group, suggest that the major problem lies in the different methods used to characterize shape.

The Fourier technique by displaying separate shape components allowed us simultaneously to follow “circularness” (CSI) and eccentricity during the cardiac cycle. Chamber eccentricity was largely represented by power in the 2nd component of the Fourier shape spectrum. The CSI, on the other hand, represented deformation from a perfect circle and thus reflected the power in higher order components as well. In aortic regurgitation, there was less power in nearly all of the spectral components; however, the 2nd harmonic remained relatively spared. Thus, the percent systolic change of CSI was reduced, while eccentricity was similar to controls. In mitral regurgitation, an enhanced elongation noted in the large systolic peak in the 2nd harmonic (Figure 6C) was similarly mirrored in a rise in eccentricity, while the lack of overall change in the higher terms meant little change in CSI. An example of how two shapes can display similar eccentricity but different circularity can be appreciated in the following analogy. In aortic regurgitation, imagine the ventricle starting with a globular outline and becoming banana-shaped at end systole, while in mitral regurgitation the same end-diastolic outline changes to more of a light-bulb shape.

Determinants of Dynamic Shape Change

Both aortic and mitral regurgitation states led to large increases in end-diastolic volume and a reduced percent change in volume during systole, yet the character of load throughout ejection differed markedly. If ventricular shape were simply tied to chamber volume, in a manner analogous to an inflatable balloon, then little or no difference in shape dynamics would be expected between the two states. Thus, from any given end-diastolic volume and shape, all left ventricles would follow the same shape/volume relation during ejection. However, the data displayed in Figure 10 demonstrate that while this is true for patients with aortic regurgitation, the relation between shape change and volume change in mitral regurgitation is quite different. The curvilinear relation between volume and FSPI during ejection is identical for normal ventricles and those with aortic regurgitation. In contrast, pa-

<table>
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<th>Table 3. Ventriculographic and Shape-Change Data in Mitral Regurgitation</th>
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*p<0.001; f<0.005.
tients with mitral regurgitation showed not only increased values for end-systolic shape but also attained that shape by a different shape/volume pathway. Thus, shape change cannot be predicted from diastolic and systolic cavity volumes alone but also depends upon the nature of ventricular loading during ejection.

While the larger end-diastolic volumes in both MR and AR were associated with less eccentric and more circular ventricular shapes, the difference from controls was relatively small. This was due to the already quite circular end-diastolic configuration in normal ventricles. The relation between reduced shape change and a decreased percent ejected volume was confirmed in the normal shape/volume relation (Figure 10A). The curvilinearity of this relation indicated that little shape change occurred during ejection of the initial 40% of filling volume, even in “normal” hearts.

Shape Change and Normal Ejection

By changing from a globular to an elongated shape during systole, the left ventricle ejects a greater volume per unit of fiber shortening than would be achieved if the chamber adhered to a constant shape throughout the cardiac cycle. In addition, chamber elongation reduces the midwall radius of curvature and thus decreases systolic wall stress. From its end-systolic configuration, the ventricle can accommodate rapid early diastolic filling by shape change to a more spherical geometry without depending on equally rapid sarcomere elongation. In support of this, we noted that all three of the shape indexes demonstrated early return toward end-diastolic shape at the beginning of ventricular filling, with a more gradual shape change seen thereafter (Figure 4). Failure of this normal dynamic change in geometry thus presents a multiple mechanical disadvantage. Volume ejection is compromised by maintenance of a more spherical shape, wall stress is increased, and filling unaccompanied by shape change requires greater and more rapid wall distension, with eventual consequences for fiber architecture.

Limitations of Shape Characterization Techniques

Assessment of left ventricular shape by analysis of two-dimensional angiographic views has obvious inherent limitations since the solid geometry may be misleadingly represented even by two orthogonal views. The left anterior oblique view generally provides information concerning the two minor axes, which have not been found to differ significantly from one another throughout ejection. Thus, for this purpose, the heart may be viewed as a prolate spheroid in which the major shape deformation can be assessed in a long axis RAO view. The analysis may be extended to three dimensions using spherical harmonics, with the individual terms being the associated Legendre polynomials. Further studies using data from MRI or cine CT scans will provide the three-dimensional coordinates will evaluate the practicality and use of this approach.

The method is also limited by errors inherent in hand-contouring cineangiograms frame by frame. This can be particularly difficult at end-systole and in small hypertrophied hearts. The subjects of this study, however, had normal or increased end-systolic cavity size. The larger cavities in patients with valvular disease helped reduce difficulties with digitization even in the presence of some hypertrophy. We found good agreement between the values obtained by the two authors who performed the contouring.

The two geometric shape indexes were limited most notably in that they led to different conclusions concerning the shape abnormalities in the two valve diseases. In addition, they displayed relatively small operating ranges and could not relay in what manner a shape had deformed but could only define deformation relative to a model geometric shape. Their advantages lie in simplicity, ease of calculation, small variability, and in the case of CSI, conceptual appeal by relating ventricular shape to its capacity for volume containment.

The Fourier analysis technique provided a much more comprehensive quantification of shape. The technique demonstrated abnormalities in both valvular disease states and helped explain discrepancies seen with the geometric indexes. An advantage of a greater range of change was somewhat offset by greater variability due to a heightened sensitivity to small deviations in the contour. Since Fourier series terms are orthogonal, this meant that changes in one shape term did not automatically lead to changes in another. This enabled chamber eccentricity (reflected in the 2nd harmonic) to be examined separately from other shape deformations that could also substantially alter chamber geometry. Each component provided a unique shape description, often with different time courses of amplitude and phase change. The sudden rise and fall in the amplitudes of the 3rd and 5th components near end ejection in the control example (Figure 5) demonstrates how this analysis could better differentiate pure shape change from volume change in the ventricle. The major limitation of this technique is that it is less intuitive than either the eccentricity or CSI indexes, displaces greater variability, and requires three-dimensional graphics to fully display temporal change.

Conclusion

Our study suggests that dynamic ventricular shape change is influenced in specific ways by particular abnormal systolic loading states and is therefore an aspect of left ventricular function that is distinguishable from diastolic volume, stroke volume, and conventional parameters of ventricular “performance.” While the previously described eccentricity and Gibson CSI indexes are attractive by virtue of their intuitive nature and ease of calculation, neither index proved adequate to describe the differences between the two altered load states in this study. The Fourier analysis technique generated a complete architectural description of shape, displayed a wider operating range in normal hearts, and was more specific in defining abnormalities of dynamic geometry.
References


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Keywords: ventricular function • valvular heart disease • ventricular shape • shape indexes • contrast cine ventriculography
Abnormalities of dynamic ventricular shape change in patients with aortic and mitral valvular regurgitation: assessment by Fourier shape analysis and global geometric indexes.

D A Kass, T A Traill, M Keating, P I Altieri and W L Maughan