Three-Dimensional Echocardiographic Reconstruction of the Mitral Valve, With Implications for the Diagnosis of Mitral Valve Prolapse

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Mitral valve prolapse has been diagnosed by two-dimensional echocardiographic criteria with surprising frequency in the general population, even when preselected normal subjects are examined. In most of these individuals, however, prolapse appears in the apical four-chamber view and is absent in roughly orthogonal long-axis views. Previous studies of in vitro models with nonplanar rings have shown that systolic mitral annular nonplanarity can potentially produce this discrepancy. However, to prove directly that apparent leaflet displacement in a two-dimensional view does not constitute true displacement above the three-dimensional annulus requires reconstruction of the entire mitral valve, including leaflets and annulus. Such reconstruction would also be necessary to explore the complex geometry of the valve and to derive volumetric measures of superior leaflet displacement. A technique was therefore developed and validated in vitro for three-dimensional reconstruction of the entire mitral valve. In this technique, simultaneous real-time acquisition of images and their spatial locations permits reconstruction of a localized structure by minimizing the effects of patient motion and respiration. By applying this method to 15 normal subjects, a coherent mitral valve surface could be reconstructed from intersecting scans. The results confirm mitral annular nonplanarity in systole, with a maximum deviation of 1.4±0.3 cm from planarity. They directly show that leaflets can appear to ascend above the mitral annulus in the apical four-chamber view, as they did in at least one view in all subjects, without actual leaflet displacement above the entire mitral valve in three dimensions, thereby challenging the diagnosis of prolapse by isolated four-chamber view displacement in otherwise normal individuals. This technique allows us to address a uniquely three-dimensional problem with high resolution and provide new information previously unavailable from the two-dimensional images. This new appreciation should enhance our ability to ask appropriate clinical questions relating mitral valve shape and leaflet displacement to clinical and pathologic consequences. (Circulation 1989;80:589–598)

Mitral valve prolapse, initially believed to be uncommon,1 has evolved into a pervasive clinical problem.2,3 Based on a variety of criteria, it can be diagnosed in a disturbingly high proportion of individuals from the general population, many of whom are otherwise normal.2–8

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To resolve this confusion requires a return to basic definitions. Prolapse is the displacement of a bodily part from its normal position or relations.12

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Mitral valve prolapse, then, implies displacement of the mitral leaflets relative to some reference structure, generally taken to be the mitral annulus. Therefore, the practical application of this definition requires a technique that can display leaflet-annular relations accurately.

Two-dimensional echocardiography is ideal for displaying these structures in a single tomographic view and has therefore been widely applied to the evaluation of prolapse. The relations in question, however, are fundamentally three dimensional. Only if the annulus were a plane could different two-dimensional views cutting through that plane be used equivalently to detect leaflet displacement above the annulus, implying prolapse by existing standards. However, we recently presented evidence that the annulus is nonplanar in systole, with its low points (closest to the apex) located medially and laterally and its high points lying anteriorly and posteriorly at the aortic insertion and posterior left ventricular wall. The leaflet surface connects all these points and spans the intervening distance. Therefore, in principle, it is possible for the leaflets to lie above the annular insertion points in mediolateral imaging planes through the low points of the annulus (implying prolapse by current criteria), and to lie below the annular insertions in anteroposterior imaging planes through the high points (implying normality). Clinical studies indicate that this may be the case. There is a higher prevalence of superior leaflet displacement in a mediolateral plane (the apical four-chamber view) than in an anteroposterior plane (the parasternal long-axis view), particularly in otherwise normal individuals. Also, patients with leaflet displacement above the low points but not the high points of the annulus are similar to normal individuals, that is, free of the disease prolapse.

Unfortunately, these initial observations are limited in several respects. First, the studies of annular shape have relied upon geometric assumptions to align the tomographic data, rather than upon a true three-dimensional reconstruction. Second, only the mitral annulus was reconstructed, having a shape that could potentially explain superior displacement in a mediolateral (four-chamber) view by comparison with an in vitro model. The next logical step is to determine whether or not the postulated leaflet-annular relations actually occur, that is, whether or not superior leaflet displacement displayed in a mediolateral view actually lies below the high points of the annulus. To determine this directly requires reconstruction of the entire mitral valve, including leaflets and annulus, which has not yet been performed.

The purpose of this study, therefore, was to develop a practical method for noninvasive three-dimensional reconstruction of the entire mitral valve without geometric assumption and with sufficient resolution to address the question of prolapse. In particular, our hypothesis was that superior leaflet displacement in the four-chamber view can be shown to lie below the highest points of the mitral annulus.

Although other groups have generated three-dimensional reconstructions of ventricular structures, the techniques used have, in general, sequentially acquired individual images and their spatial locations at discrete points in time. Such techniques are therefore subject to potential inaccuracies caused by patient motion and respiration occurring between images. This may be tolerated in examining large structures but may limit the reconstruction of the relatively small mitral valve. Therefore, to address our hypothesis, a technique was first developed that allows simultaneous and continuous real-time acquisition of echocardiographic images and of the information about their location in space necessary to reconstruct them properly in three dimensions. This involved modification of existing technology that uses acoustic markers to locate the transducer in space. Two important advantages of this system are that images can be obtained without limitation of view and that continuous acquisition of multiple views allows the valve to be scanned rapidly to minimize the effects of patient motion and respiration. This technique was then applied to reconstruct the mitral valve in a series of normal subjects.

**Methods**

**Reconstruction Technique.**

To align two-dimensional echocardiographic images properly in space, their relative orientation and positions must be known. Because three points determine a plane, the plane of the ultrasound sector scan can be determined if we know the location of three points that bear a fixed relation to that plane. Therefore, three spark gap locating devices were rigidly placed on a plexiglass sleeve that could be mounted in a reproducible position on an ultrasound transducer (Figure 1A). The spark gaps are located on a plate perpendicular to the long axis of the transducer and form the corners of an equilateral triangle. When current is passed through the two wires of each locator, a spark crosses the intervening gap, generating an audible sound. The location of the spark is determined by an array of microphones that time the arrival of the sound at four known locations (Figure 1B). From the speed of sound in air at that temperature, an attached microprocessor can calculate the distance from the spark gap to each microphone. By triangulation, the position of the spark gap can then be determined in rectangular coordinates, with one corner of the microphone array taken as the origin. The four microphones provide several calculations for internal consistency, to check for such problems as interposed reflectors or air turbulence.
The three spark gaps are fired in rapid succession by a microprocessor (Science Accessories, Southport, Connecticut) that also receives information from the microphones; an attached computer then determines the spark gap locations. Because these locations bear a known relation to the origin and plane of the sector scan, both of these features can be calculated each time the three spark gaps are fired. Because the transducer may move slightly between spark gap firings, their locations are taken as the least squares fit to their known relative positions on the plexiglass plate. As a check of internal consistency, the directly computed distance between spark gaps is checked against known values. Deviations are generally 1 mm or less, with greater deviations, indicating rapid motion or obstruction of a direct path between spark gaps and microphones, leading to exclusion of that data set. Spatial position can be obtained as rapidly as 10 times/sec. Because the spark gaps are mounted on a
plate perpendicular to the axis of the transducer, this system can be used in a wide variety of apical and para-apical views with any degree of rotation, with the patient in a standard left lateral decubitus position, and with the microphone array facing the spark gaps (Figure 1B).

Data Acquisition

The mitral valve or any other cardiac structure can be scanned by this system with continuous acquisition of 1) echocardiographic images and an electrocardiogram on videotape and 2) a sequence of transducer positions in a computer file. A trigger marker is automatically recorded on the videotape at the onset and cessation of spark gap firing so that the two data sets can be coordinated in time.

Reconstruction

Images are selected from the videotape at a consistent time in the cardiac cycle, determined in reference to the electrocardiographic R wave. These images are converted to digital format by a Microsonics videoframe-grabbing system and are transferred to a mainframe VAX computer. Given the coordinated spatial locating information, the computer can correctly position the images in space, with any derived tracings of the leaflet surface (Figure 1B). Because approximately three videoframe images are acquired during each update of localizing information, the location used to reconstruct any given videoframe is derived by interpolation between the recorded spark gap positions that immediately precede and follow the image acquisition time to provide the best estimate of transducer position for that image. For this reason, images are excluded if they are associated with rapid or wide excursion of the transducer as indicated by the spark gap data (>1 mm average excursion between frames).

The resulting reconstruction is displayed on an Evans & Sutherland PS300 Series interactive graphics display device (Salt Lake City, Utah), which allows real-time rotation, translation, and scaling of the image to improve three-dimensional appreciation.

Validation

In addition to the continuous checks described above (consistency of triangulation with four microphones, and checking for accurate reproduction of the distance between spark gaps), the accuracy of this system has been validated by reconstructing a number of objects of known size and shape imaged in a water bath (see "Results").

Patient Studies

This system was applied to reconstruct the mitral valve in a series of 15 normal individuals with structurally normal hearts by two-dimensional and Doppler echocardiography and with no auscultatory findings of note in the supine and sitting positions. Only one subject had been referred for echocardiographic screening; the rest were recruited from laboratory personnel. There were 10 men and five women (mean age, 32 years; range, 18–41 years).

The 3.5-MHz transducer of a Hewlett-Packard phased-array sector scanner was used to optimize imaging resolution in the adult heart. With the subject in the left lateral decubitus position, the transducer was placed near the apex, and during held respiration, two perpendicular series of scans were obtained, the first having a mediolateral orientation similar to the apical four-chamber view and the second having an orientation similar to the long-axis view (Figure 2A). In each series of scans, the basic view was obtained, and then the transducer was angulated in an arc perpendicular to the scan plane to cover the extent of the valve. These two orientations were chosen because they are roughly perpendicular and should provide the most information about annular nonplanarity and spatial differences in leaflet-annular relations based on existing studies.5,13 Videoframes from a fixed point in late systole were then selected and digitized from all these scans. Late systole was chosen because the phenomenon of interest, superior systolic displacement relative to the annulus, is most evident at that time. Because the mitral valve and annulus appear to move rapidly in the one to two videoframes before mitral valve opening, images were chosen three frames before mitral valve opening. This timing was established with respect to the R wave in the four-chamber view and used consistently throughout the scans. RR intervals varied by no more than 3%. Individual images were discarded if the leaflets or their annular hinge points could not be clearly discerned, or if the spark gap information indicated rapid transducer movement, making localization less precise.

The ventricular borders of the mitral leaflets were traced with a bit pad interfaced to the Evans & Sutherland display (Figure 2B). The location of the annular hinge points was determined by real-time review of the videoimages. The traces were then combined with correlated spatial information to produce a three-dimensional sample of the leaflet surface.

Analysis

Surfacing algorithm. Although leaflet shape was evident from the reconstructed tracings, a topographic surfacing algorithm was developed to describe this shape quantitatively (a mathematical method for producing a continuous three-dimensional surface that best represents the discrete samples of that surface represented by the two-dimensional leaflet traces). Similar to altitude mapping in geography, this method resembles laying a sheet over the valve traces and letting it conform to their contours. The leaflet surface in any given region of the valve was determined as a best fit to the leaflet traces in the immediate vicinity (a fit producing the smallest spatial differences between the position of the surface and that of the adjacent...
traces). As part of this process, a smoothed annular border was obtained by spline-fitting the edges of the individual traces. This process fits a continuous curve to the annular endpoints of the traces. Each point on the curve is determined as a best approximation to the neighboring endpoints, weighted by their proximity to the point in question.\(^{34}\)

**Reference plane.** From the annular border, a plane of least squares fit was derived (a plane chosen to minimize the deviation of annular points from it). This provides an objective reference plane for orienting the entire structure in space.

**Annular nonplanarity.** The height of the annulus above or below the plane of least squares fit could then be plotted around the circumference of the valve, as a function of angle around the centroid, or geometric center of mass of the annulus. If this curve showed two high points and two low points, roughly equidistant, it would confirm the saddle shape of the annulus.

**Leaflet annular relations.** Leaflet-annular relations were then examined in the reconstructions to determine whether or not superior leaflet displacement was evident in any of the scans and to determine the relation of such displacement to overall valve shape and, in particular, to the boundaries defined by the mitral annulus.
To determine the variability in leaflet tracing, two independent observers traced the leaflet borders in 10 systolic images, and the average difference between points on their respective traces was calculated. One observer subsequently repeated the tracings to determine intraobserver variability.

**Results**

**Validation**

The reconstruction technique faithfully reproduced objects of known size and shape. 1) A planar surface with a small central elevation was imaged. The planar border was reproduced with less than 1.0-mm standard deviation from planarity (individual traces also deviated 1.0 mm or less from the plane), and the central elevation, which was 3 mm high, could be clearly resolved. 2) A hollow rubber hemisphere 3 cm in diameter (similar in size to the mitral valve) was imaged in intersecting views. Traces of the surface from the ultrasound images reproduced a coherent hemispherical shape, which could best be appreciated by rotating the reconstruction on the graphics screen.

**Valve Reconstruction**

In all 15 subjects, the three-dimensional shape of the valve was similar to that shown in Figure 3, in which the heart is viewed from two perpendicular perspectives. On the left, the viewer is looking at the apical four-chamber view; traces of the closed valve and its annular border are depicted in orange. On the right, the heart is viewed from the long-axis perspective. The overall leaflet surface is convex upward toward the left atrium on the left, whereas it is convex downward toward the left ventricle on the right. (The leaflets, of course, are individually concave toward the ventricle by virtue of its distending pressure; the two closed leaflets, however, descend from the high points of the annulus, constituting convexity toward the ventricle.) This opposite convexity in perpendicular views defines a saddle shape. The smoothed leaflet surface from another subject has a similar shape as shown in Figure 4.

**Annular Configuration**

In all cases, plotting annular height above the least squares plane confirmed annular nonplanarity (Figure 5), with anterior and posterior high points and medial and lateral low points. The maximum deviation from planarity was calculated for each subject; this value was, on the average, 1.4±0.3 cm. This was derived from the smoothed annular border, which would, if anything, underestimate the degree of nonplanarity.

**Leaflet-Annular Relations**

In all subjects, superior systolic leaflet displacement could be identified in at least one view in the
four-chamber series, as shown in Figure 6, without superior displacement in any of the long-axis views. From the two-dimensional images alone, the relative location of these two leaflet traces in three dimensions cannot be determined, and if the prior assumption of a planar annulus were made, one would have to conclude that the leaflets prolapse above the annulus. The reconstructions provide the three-dimensional relations that are otherwise not evident: they show that the atrial displacement in the four-chamber view always lies below the high points of the valve (Figures 3, 6).

Observer Variability

The average variability for leaflet tracing was 0.5 mm (interobserver and intraobserver variability; the maximum difference between individual points was ≤1.2 mm).

Discussion

Previous methods of three-dimensional echocardiographic reconstruction, designed to assess ventricular size and function, have not yet attracted widespread use, given the availability of geometric assessments combining two-dimensional images and the limitations of existing technology. On the other hand, studying mitral leaflet-annular relations in the hope of refining the diagnosis of mitral valve prolapse presents a uniquely three-dimensional problem requiring information previously unavailable from cross-sectional echocardiography and also requires a degree of precision greater than that previously required to examine larger structures. In this study, therefore, the spark gap acoustic method for transducer location was modified, and a technique was developed that can reconstruct three-dimensional structures accurately as shown by examining objects of known size and shape. Geometric analysis of the reconstructed valve surfaces confirms mitral annular nonplanarity and further directly shows that leaflets can appear to ascend above the mitral annulus in the four-chamber view without actual leaflet displacement above the high points of the annulus contained in the long-axis view. Moreover, these results are observed consistently in the normal subjects studied, unselected for the presence of displacement. They therefore challenge the diagnosis of prolapse on the basis of displacement limited to the four-chamber view in otherwise normal individuals as do other clinical correlative studies.

Why can superior leaflet displacement in a four-chamber view be found uniformly in this study compared with only 13% of the 193 normal children or 34% of the normal 10–18-year-old individuals previously reported? The answer lies in the nature of this study, in which the mitral valve was exten-
sively scanned to reconstruct a broad sample of its surface. In contrast, the normal children were studied in routine views to determine normal echocardiographic dimensions, and the prolapse findings were only subsequently noted. It is not surprising, therefore, that the four-chamber view obtained in any given child might not have shown superior leaflet displacement that would have become evident in a more complete scan. Reviewing the reconstructed valves confirms this reasoning: superior leaflet displacement is, in general, evident only in a narrow angular range of views around the circumference of the valve; this range might not be intersected by any given, routinely obtained view. In addition, however, this confirms our clinical impression that the frequency of prolapse in the four-chamber view is, to a large extent, a function of the diligence for which it is searched.

Three-Dimensional Technique

Although the basic method used to locate images is not unique,26,29 this study applies this approach to a uniquely three-dimensional problem that cannot be solved with two-dimensional views alone. The spark gap method has the advantage of allowing view and window to be varied to optimize imaging quality: views are not restricted to conform to a predetermined geometry of reconstruction (parallel or rotational).27,30-32 The modifications introduced in this study have several additional advantages. 1) Rapid acquisition of multiple views permits the mitral valve to be scanned rapidly, minimizing problems of patient motion and respiration. 2) Displaying both images and traced borders in three dimensions helps guide the tracing process. 3) The ability to rotate and translate the reconstruction rapidly on the graphics display device is invaluable in achieving three-dimensional appreciation. 4) The geometry of the spark gap attachment (Figure 1A) is well suited to an in-line transducer as opposed to the angled transducer used by Moritz et al.26

There are several sources of variability in the reconstruction: 1) the resolution of spark gap location (≤1 mm by selection of data sets, with error further reduced by fitting the calculated spark gap positions to their known locations at the corners of an equilateral triangle); 2) imaging resolution (because annular nonplanarity is parallel to the ultrasound beam in apical views, only the axial resolution of ≤1 mm can affect its assessment); 3) the temporal averaging used to assign a transducer position to each videoframe acquired during a cycle of spark gap firing (≤1 mm; see "Methods"); 4) the uncertainty created by the finite spacing of raster lines on the video image (digital scan conversion; approximately 1 mm in this setting); and 5) observer variability in tracing leaflet borders (<1 mm). In this study, imaging was practiced until views could be acquired during one held respiration. When more views are required, respiratory variability will also need to be considered and possibly minimized by respiratory gating.33 The average variability created by these independent factors (the root mean square variability) is 2.2 mm or less, which is small compared with the vertical (height) and horizontal (diameter) dimensions of the annulus (in the centimeter range), and cannot account for the consistent finding of nonplanarity.

It is anticipated that this method can provide us with a three-dimensional measure of leaflet displacement beyond the "bounds" defined by the mitral annulus, for example, displacement above the highest points of the annulus (see Figure 6) or above a convex-hull surface that connects all the annular points to each other.39 Several alternative measures can then be compared to determine which measure correlates best with clinical and echocardiographic measures of valve disease. In addition, a fuller appreciation of three-dimensional relations should, in turn, allow a more informed interpretation of two-dimensional views and findings, such as the significance of minor degrees of displacement in long-axis views. The spatial insights obtained could have more universal applications to other techniques as well, such as angiography and magnetic resonance imaging.

Currently, the technique requires several levels of time-consuming computational involvement as a research tool (acquiring spark gap locations, digitizing images, and reconstructing). Work is underway to combine these elements into a unified workstation to make the technique more routinely available for the assessment of ventricular structure and function as well as mitral valve prolapse. The availability of transducers providing two simultaneous orthogonal views of the heart should also facilitate this process.40

Significance of This Shape

The anterior high point is reasonable because the anterior mitral leaflet extends superiorly in the region of the fibrous trigone41 and is attached to the aortic root, which moves anteriorly during systole. The rest of the configuration must ultimately be determined by the architecture and contraction pattern of the cardiac muscle bundles.

Whatever its cause, the saddle-shaped configuration can be rationalized in two ways. First, annular nonplanarity is reasonable because the circumference of the base of the left ventricle decreases in systole,18,24 whereas the length of leaflet attached to the ventricle does not decrease (the leaflet does not contract). The only way to accommodate this constant length within a smaller circumference is to make it nonplanar in some fashion. A simple calculation based on actual circumferences, for example, 8–10.5 cm in diastole and 7–9 cm in systole,24 and a range of saddle-like configurations implies the potential range of nonplanarity on this basis is 0.3–1.4 cm, which is similar to that observed. Second, the saddle shape of the entire valve in systole may provide a configuration more capable of withstand-
The stresses imposed by left ventricular pressure, recalling, for example, the shape of the Saddledome Olympic stadium in Calgary, Alberta, designed to support weight over a wide area.

In summary, this technique directly shows that leaflets can appear to ascend above the mitral annulus in the apical four-chamber view without leaflet distortion or actual displacement above the entire mitral valve. This three-dimensional technique should enhance our ability to ask appropriate clinical questions and develop new criteria that better associate mitral valve shape with clinical and pathologic consequences.

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