The relationship of mitral annular shape to the diagnosis of mitral valve prolapse

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ABSTRACT The geometric or anatomic diagnosis of mitral valve prolapse, as opposed to the pathologic diagnosis of myxomatous valve disease, is based on the relationship of the mitral leaflets to the surrounding anulus. Current echocardiographic criteria for this diagnosis include leaflet displacement above the annular hinge points in any two-dimensional view; implicit in this equivalent use of intersecting views is the assumption that the mitral anulus is a euclidean plane. Prolapse by these criteria is found in a surprisingly large proportion of the general population. In most of these individuals, however, prolapse is present in the apical four-chamber view and absent in roughly orthogonal long-axis views of the left ventricle. This frequently observed discrepancy between leaflet-annular relationships in intersecting views suggests an underlying geometric property of the mitral apparatus that would produce the appearance of prolapse in one view without actual leaflet distortion. To address this possibility, a model of the mitral valve and anulus was constructed. When the model anulus was given a nonplanar, saddle-shaped configuration, the clinical observations were reproduced: the leaflets appeared to lie above the low points of the anulus in one plane, and below its high points in a perpendicular plane. Therefore, the appearance of mitral valve prolapse can occur without actual leaflet displacement above the most superior points of the mitral anulus if the anulus is nonplanar. To determine whether this pattern is reflected in the human mitral anulus, two-dimensional echocardiographic views of the mitral apparatus were obtained by rotation about the cardiac apex in 20 patients without evident annular or rheumatic valvular disease. In all cases the mitral anulus, as reconstructed from these views, had a nonplanar systolic configuration, with high points located anteriorly and posteriorly. This is consistent with the findings of other groups in animals, and would favor the appearance of prolapse in the four-chamber view and its absence in long-axis views that are oriented anteroposteriorly. This model can therefore explain the frequently observed discrepancy between leaflet-annular relationships in roughly orthogonal views. It challenges the assumption that the mitral anulus is planar as well as the diagnosis of prolapse in many otherwise normal individuals based on that assumption.


PROLAPSE is defined as the displacement of a bodily part from its normal position or relationship. The term mitral valve prolapse, therefore, implies that the mitral leaflets are displaced relative to some reference structure, generally taken to be the mitral anulus. Since two-dimensional echocardiography is ideally suited to define these structures and their spatial relationships, it has become the procedure of choice for the diagnosis of mitral valve prolapse.

The original two-dimensional echocardiographic studies showed that normal mitral leaflets coapted below (on the ventricular side of) a line connecting the annular hinge points in the parasternal long-axis view of the left ventricle, which is oriented anteroposteriorly; leaflet displacement above this line correlated with angiographic prolapse. Subsequently, the criteria for prolapse were extended to include superior leaflet displacement in the apical four-chamber view as well; this view is oriented to intersect the medial and lateral margins of the anulus, and is roughly orthogonal to the parasternal long-axis view. This extension

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was readily accepted because of the greater ease with which leaflet-annular relationships could be determined in the four-chamber view, which displays the hinge points in a horizontal orientation. Although unstated, extending the criteria to include both views implies the assumption that the mitral anulus must be a euclidean plane, so that leaflet-annular relationships would be comparable in the two views.

The introduction of this assumption has led to two observations that raise questions as to its validity. First, prolapse by these criteria has been found in 11% to 13% or more of the general population, including individuals preselected to be normal, suggesting that these criteria may be too sensitive for abnormality. Second, when prolapse is diagnosed in the apical four-chamber view, it is frequently absent in the long-axis view, which is unexpected if the mitral anulus is truly a plane.

The frequent presence of prolapse in one view and its absence in an intersecting view suggest the following hypothesis: that the appearance of prolapse in such instances can reflect the nonplanarity of the mitral anulus as opposed to any localized leaflet distortion above a planar anulus. Further, the basic geometric nature of such a nonplanar anulus is suggested by the pattern of observed leaflet-annular relationships in the long-axis and four-chamber views. Specifically, a discrepancy in these relationships would result if the leaflet-annular structure were concave downward in one plane and upward in a perpendicular plane. In a section through the first plane, the leaflets would appear to lie above the edges of the structure; in the second plane, this relationship would be reversed, with the leaflets appearing to lie below the edges of the structure.

These geometric requirements suggested by the echocardiographic patterns are satisfied by a structure that has the general shape of a hyperbolic paraboloid or saddle surface (figure 1). Therefore, our hypothesis can be restated as follows: if the mitral leaflets and anulus comprise an elliptical portion of a saddle-shaped surface located about its center, the observed discrepancy in leaflet-annular relationships will result.

To test this hypothesis, a model of the mitral leaflets and anulus was constructed. First the model was used to determine whether the clinical observations described could be reproduced in a truly planar anulus. It was then restructured to study the effects of a nonplanar, saddle-shaped anulus on leaflet-annular relationships in intersecting views. Finally, to determine the clinical correlate of the proposed annular shape, the human mitral anulus was reconstructed from echocardiographic views obtained at various degrees of rotation about the cardiac apex in a series of patients.

Methods

Model studies. To simulate the mitral anulus, a model was constructed from an elliptical metal ring that was initially flat. Rubber leaflets were attached to this ring around its circumference and shaped to curve downward toward the region of coaptation, as shown in figure 2, top left. The model was placed in a water bath, and cross-sectional images were obtained at various increments of transducer rotation about an axis passing through the center of the ring, and with varying degrees of transducer tilt or angulation. A commercially available sector scanner was used at 3.5 MHz, and images were recorded on 1/2 inch VHS tape.

The model mitral valve was then restructured into the shape of a hyperbolic paraboloid or saddle surface (figure 2, top right). The highest or most superior points of the anulus were considered to be located anteriorly and posteriorly, consistent with the findings of Tsakiris et al. and Pomar et al. in dogs. The model was then placed in a water bath, and echocardiographic views were obtained in the long-axis anteroposterior plane through the annular high points and in the four-chamber plane oriented approximately 15 degrees off the mediolateral line and passing anteriorly to it on the right so as to intersect the center of the tricuspid valve in an actual heart.

![Figure 1](http://circ.ahajournals.org/)

**FIGURE 1.** The mitral anulus as a central, elliptical portion of a hyperbolic paraboloid or saddle-shaped surface, which is concave downward in one direction (parallel to the yz plane) and upward in a perpendicular direction (parallel to the xz plane). a, b, and c are constants that determine the shape of the structure.
This model, however, does not adequately represent the systolic configuration of the mitral leaflets, which are concave toward the left ventricle by virtue of its distending pressure. The model was therefore restructured more realistically: the anulus remained saddle-shaped, but the leaflets were made individually concave toward the left ventricle (figure 2, bottom). Echocardiographic views were then obtained.

To compare the three-dimensional configuration of this model anulus to that seen in man, the anulus was imaged echocardiographically at 30 degree rotational intervals, starting with a mediolateral orientation at 0 degrees, with the central ray of the beam directed through the center of the anulus (figure 3, left). In each view, the distance z of the anulus from the transducer along the axis of rotation was calculated by the method described below, and plotted against the angle theta of rotation (figure 3, right).

**Human Studies.** The purpose of these studies was to determine whether the model configuration has a clinical counterpart — in other words, whether it occurs in people. The mitral anulus was therefore studied in 20 ambulatory patients referred for echocardiographic examination who did not have rheumatic or infective mitral valve disease, calcified or thickened mitral anulus, or left ventricular dysfunction with the potential for annular dilatation. After exclusion criteria were applied, patients were selected only on the basis of having high-quality apical images of the heart from which quantitative measurements could be made and the availability of personnel to perform the annular reconstruction described below. They therefore represent the population seen in the echocardiographic laboratory without the abnormalities listed above.

The patients were 13 to 79 years old (mean age 33 years); there were 10 male and 10 female patients. They had been referred for a variety of exclusionary questions, to exclude (or determine) the presence of mitral valve prolapse, atrial septal defect, cardiomyopathy, hypertrophic disease, a cause of atrial arrhythmia, and a cardiac cause of syncope.

Patients were studied in the left lateral decubitus position with a Hewlett-Packard phased-array sector scanner operating at 3.5 MHz. Mitral regurgitation was searched for with a 2.5 MHz transducer with the Doppler sample volume on the atrial side of the closed mitral leaflets. The sample volume was scanned in an expanding radial arc in the apical four-chamber, apical long-axis, and parasternal long-axis views. Twelve of the 20 patients had no significant superior systolic displacement of either leaflet above the annular hinge points in either the long-axis or four-chamber views, while four had superior systolic displacement of the anterior mitral leaflet in the four-chamber view only; none of these 16 patients had pulsed Doppler evidence of mitral regurgitation. The remaining four patients had superior systolic displacement of both mitral leaflets above the hinge points in both long-axis and four-chamber views; three of these patients had pulsed Doppler evidence of mitral regurgitation.

The mitral anulus in these patients was studied in a series of views obtained by rotation about the cardiac apex in a manner similar to that described by Ormiston et al. This procedure was used because the three-dimensional configuration of the mitral

**FIGURE 2.** Top left, Diagram of the model in vitro with a planar anulus and leaflets curving downward toward the zone of coaptation. Adjacent cardiac structures are also diagrammed. Ant. = anterior; Ao = aorta; LA = left atrium; LV = left ventricle; Post. = posterior. Top right, Diagram of the model in vitro with the leaflets and anulus shaped to lie on a saddle surface. Bottom, The model restructured with leaflets concave toward the left ventricle, reflecting its systolic pressure, but not protruding above the anterior and posterior high points of the saddle-shaped anulus.
anulus cannot be discerned in any single tomographic view available with conventional scanning techniques. The mitral valve was initially examined in the apical four-chamber view, which includes the apex and displays a full excursion of both the mitral and tricuspid leaflets. Images were recorded on ½ inch VHS tape during 10 cardiac cycles obtained at mid expiration. The position of the transducer was marked on the chest wall and was not varied during the rest of the procedure. Subsequent views were obtained by rotating the transducer around the cardiac apex in 30 degree increments, as determined by an inclinometer (a fluid-filled cylinder containing an air bubble) attached to the transducer. At each stage of rotation, the transducer was angulated slightly in an arc perpendicular to the scan plane to maximize the diameter of the mitral orifice; images were then recorded at mid expiration. This procedure was repeated for each of the six rotational increments.

The geometry of the mitral anulus was reconstructed from these rotational views (figure 4). The anulus was considered to be elliptical or nearly so based on anatomic and physiologic information, so the maximal diameters measured at various degrees of rotation will bisect each other at the center of the anulus. Therefore, the anulus could be reconstructed around an axis of rotation identifiable in each view and formed by a line connecting two points: the apex of the sector scan, which was fixed on the chest wall, and the midpoint of the annular diameter in each view. Once this axis of reconstruction was established,
the distance or height of each annular point from the transducer along this axis could be determined and compared to assess annular shape.

**Measurements and calculations.** For each rotational stage, measurements were made as indicated in figure 4, in which point A represents the center of rotation (the head of the transducer and apex of the sector scan). Points B and C represent the points of the mitral anulus intersected by the plane of view, where the mitral anulus is defined as the leaflet hinge points determined by real-time review of the images. The dimensions measured were \( r_1, r_2, \) and \( D; r_1 \) and \( r_2 \) are the distances from point A to each of the annular hinge points and \( D \) is the separation of the hinge points in a given view.

Each of these measurements was made with a Microsonics Easy-View II off-line analysis system in three end-systolic videoframes and the results were averaged for each rotational stage. End-systolic measurements were taken in the frame showing the smallest left ventricular cavity size. \( z_1 \) and \( z_2 \) were then calculated, where each \( z \) value represents the vertical distance or height of its corresponding annular hinge point from the center of rotation (point A) along the axis of reconstruction. This axis, represented by line \( AX \) in figure 4, passes through the apex of the sector scan, point A, and bisects the annular diameter, BC. \( z_1 \) and \( z_2 \) are, then, the projections of \( r_1 \) and \( r_2 \) onto this axis. These values were calculated by the following formulas, derived as shown in the Appendix:

\[
z_1 = \frac{(3r_1^2 + r_2^2 - D^2)}{E}
\]

and

\[
z_2 = \frac{(r_1^2 + 3r_2^2 - D^2)}{E}
\]

where \( E = 2\sqrt{2(r_1^2 + r_2^2 - D^2)} \).

**Statistical analysis.** The effect of rotational angle on annular height \( z \) was evaluated by analysis of variance, with angle as a fixed factor and subject as a random factor (RS1 package, Bolt, Beranek and Newman, Inc., Cambridge, MA, 1985). Individual pairs of rotational stages were compared with two-way contrasts by the same routine, with correction for multiple comparisons.

Two independent observers measured the sets of rotational views in two patients to determine interobserver variability. The ray length \( r \) and diameter \( D \) values for the observers were then separately evaluated by analysis of variance to obtain variability due to observer as opposed to patient or angle measured (BMDP8V statistical program, UCLA, 1982). One of these observers repeated the same sets of measurements 1 month later to determine intraobserver variability by the same method.

**Results**

**Model studies.** With a flat mitral anulus and leaflets curving downward toward the region of coaptation (as in figure 2, top left), the appearance of leaflet displacement above the anulus could not be created in any echocardiographic view. A long-axis view oriented anteroposteriorly, as indicated by the dotted line in figure 5, top left, produced the appearance seen in the top right panel, with the leaflets lying below the anulus. The bottom panels of figure 5 show that a similar relationship was evident in a plane oriented more nearly mediolaterally to resemble the four-chamber view. Therefore, if the mitral anulus is planar, the clinical observations of consistently different leaflet-annular relationships in these two views cannot be reproduced with undistorted leaflets.

Figure 6 shows the results of shaping the mitral apparatus into an elliptical portion of a saddle surface. In the long-axis plane, the leaflets appeared to lie below the annular high points, while in the four-chamber plane the appearance of superior leaflet displacement was created.

Maintaining the saddle shape of the anulus and restructuring the leaflets more realistically to be individually concave toward the left ventricle gave the results shown in figure 7. In the long-axis plane, the leaflets appeared to lie entirely below the intersections of the anulus with this plane. In a four-chamber view, however, the leaflets appeared to rise above the intersections of the anulus with the plane of view in a manner similar to that seen clinically.

**Vertical distance vs rotational angle plots: model anulus.** To compare the model and human mitral anulus, the vertical distance \( z \) of the anulus from the transducer along the axis of rotation was plotted in each case against the angle theta of rotation by the method illustrated in figures 3 and 4. For a planar model anulus oriented perpendicular to the axis of rotation, this plot was a straight line with a slope of zero. This procedure was repeated with the anulus tilted at an angle other than 90 degrees to the axis of rotation, because this angle is not known a priori in man. For a planar anulus, the resulting plot of \( z \) vs theta was a sinusoidal curve with only one maximum as theta varied from 0 to 360 degrees.

The saddle-shaped anulus, on the other hand, produced a curve with two peaks corresponding to the high points of the anulus (figure 3, right). The reconstruction technique accurately reproduced the configuration and vertical extent of the model anulus. Tiling the structure so that it would be oriented obliquely to the axis of rotation altered the relative height of the peaks, as shown by the dotted curve in figure 3, left, but the bimodal shape was preserved.

**Vertical distance vs rotational angle plots: human anulus.** In all 20 patients studied, the plots of annular height versus the angle of rotation were bimodal, predicting a nonplanar configuration. Figure 8, top, shows four representative curves, with high points (farthest from the apex) located near the aortic root and the posterior wall of the left ventricle (in the vicinity of 90 and 270 degrees), and low points located medially and laterally (in the vicinity of 0 and 180 degrees). The difference in vertical height \( z \) from the most apical to
PLANNED ANNULUS

LONG-AXIS VIEW

![Diagram of planar annulus in long-axis view]

FOUR-CHAMBER VIEW

![Diagram of planar annulus in four-chamber view]

Figure 5. Two-dimensional echocardiographic views of the model in vitro with a planar mitral anulus. The heavy interrupted lines on the left indicate the plane of view. On the right, echocardiographic images of the model are shown along with diagrams of the surrounding structures. The dotted lines in the echocardiographic images demarcate an apparent annular plane in each view; they were manually placed with the aid of the echocardiographic instrument. In both views, the leaflets lie below the edges of the anulus. RA = right atrium; RV = right ventricle; other abbreviations are as in figure 2.

the most basal point of the anulus in each patient ranged from 0.8 to 1.9 cm, with a mean of 1.3 cm.

Figure 8, bottom, shows the mean and standard deviation of annular configuration for all patients studied. To compare annular shape in the different patients whose anuli were located at varying distances from the chest wall, each patient’s curve was first normalized as follows: the annular height or z values for each patient were divided by the mean z value for that patient. These normalized curves, representing the systolic shape of the anulus, were then averaged. The resulting average configuration is given by the interrupted curve in figure 8, bottom. To express this configuration in terms of actual distances as opposed to normalized ratios (z values/mean z values), the normalized average curve was multiplied by the grand mean of annular height z for the 20 patients.

Analysis of variance revealed a highly significant effect of rotational angle on annular height, with p < .0001; the individual peaks and troughs differed at p < .01, with correction for multiple comparisons. The average configuration curve could be fitted to a bimodal function of cos 2θ, with an r value of .96, as shown by the solid curve in figure 8, bottom.

Observer variability. The overall interobserver variabilities for the r and D values were 0.1 cm for each measurement (1% and 4% of the respective mean values). The variability strictly due to observer, eliminating observer-patient and observer-cycle interactions, was less than 1% of the mean for r and 1% of the mean for D. It should be noted that the resulting variability in the calculated z values is approximately the same as that for the r values: changes in D contribute an order of magnitude less than those in r, as can be determined by differentiating the equation for z.

The overall intraobserver variabilities were 0.1 cm for each measurement; when the variability due to interactions between observer, patient, and cycle was excluded, the variabilities strictly due to observer were less than 1% of the mean for each measurement.
SADDLE SURFACE
LONG-AXIS VIEW

Figure 6. Discrepancy in leaflet-annular relationships in echocardiographic views of a saddle-shaped model structure. Arrangement and abbreviations are as in figure 5.

Discussion

Mitral valve prolapse, initially believed to be an uncommon finding,19, 20 has evolved into a pervasive clinical problem.6, 7, 21 The physician is frequently faced with diagnosing disease in individuals who are apparently in good health6, 7, 21-28, who may have no auscultatory findings, or only evanescent ones6, 7, 22, 24, 26-28; and who, on the basis of what is often an isolated finding, are ascribed an uncertain prognosis that includes endocarditis and stroke as well as sudden death.19, 20, 29-32

At the root of the clinical perplexity lie some basic problems of definition.33 Mitral valve prolapse is a displacement of the mitral leaflets from their usual or normal position or relationship to surrounding structures,1 generally taken to be the mitral anulus. Therefore, two prerequisites must be satisfied for its proper diagnosis: (1) a technique must be available that can display this fundamental anatomic relationship between leaflets and anulus, and (2) the range of normal leaflet position must be established.

Regarding the first prerequisite, two-dimensional echocardiography has provided, for the first time, a noninvasive technique capable of simultaneously visualizing the mitral leaflets and anulus in a given plane and determining their interrelationships.2, 3 Regarding the second prerequisite, however, the range of normal has not been defined by this technique; instead, it has been assumed that the mitral leaflets normally lie on the ventricular side of the anulus, and that any displacement to the atrial side of the annular plane is abnormal.3, 4 A further assumption has been that prolapse can be diagnosed with equal validity in all tomographic views of the mitral leaflets and anulus.4, 5; im-
The current study. The purpose of this study was to explore the implications of the observed discrepancy of leaflet-annular relationships as they relate to the assumption of mitral annular planarity. The model
studies demonstrate that the appearance of prolapse can occur without actual leaflet displacement above the most superior points of the mitral annulus, and can be a consequence of annular shape as opposed to any localized leaflet distortion or abnormality. In particular, a saddle-shaped annular configuration can reproduce the clinically observed discrepancy between leaflet-annular relationships in roughly orthogonal views. The leaflets will appear to lie below the high points of the annulus in a view that passes through those points, and above the low points of the annulus in an orthogonal view. If the high points are located anteriorly and posteriorly, then the leaflets will appear to lie below the annulus in the long-axis view of the left ventricle, and above it in the apical four-chamber view.

The postulate of a nonplanar annulus is supported by our observations in patients, in whom such a configuration was demonstrated consistently, with the high points of the annulus (those farthest from the apex) located anteriorly and posteriorly. It is also supported by two studies in which radiopaque markers were implanted along the mitral annulus in dogs and the alignment of the markers was examined in lateral views. It should be noted that the data presented in
this study pertain to end-systole only. The presence of an anterior high point at this point in the cardiac cycle is reasonable, since the anterior mitral leaflet extends superiorly in the region of the fibrous trigone and the aortic root to which it is attached moves anteriorly in systole. The systolic configuration of the anulus must ultimately be determined by the architecture of the cardiac muscle bundles and their contraction pattern.

It must be emphasized, however, that mitral annular shape is not the sole determinant of the leaflet-annular relationship. Other factors include leaflet shape, size, and chordal support as well as the physiologic state and volume of the left ventricle. Clearly, for example, there are patients with thick, redundant mitral leaflets that billow deeply into the left atrium who are subject to progressive and at times severe mitral regurgitation. The implications of this study relate not to such individuals but to those with normal leaflet thickness and lesser degrees of apparent leaflet displacement above the anulus in one view only. Also, although it is conceivable that the mitral anulus is truly planar and that focal leaflet distortion above that plane occurs selectively in a portion of the valve intersected by the four-chamber view only, there are no pathologic or angiographic data to support the contention that selective, localized distortion occurs so frequently in the general population as to explain the observed high prevalence of superior systolic displacement in echocardiographic views. In a study of excised human hearts, for example, Becker and DeWit showed that despite the frequent presence of gaps in the chordal network supporting the mitral leaflets, localized leaflet distortion when the leaflets are exposed to systolic pressure is uncommon. While the angiographic-pathologic correlations of Ranganathan et al. and the autopsy-pathology series of Davies et al. show predominant distortion of the posterior leaflet and the posteromedial scallop, those studies by their very nature apply specifically to small, selected groups of individuals with moderate to severe changes. The results of such studies in patients coming to angiography, surgery, or autopsy cannot be extrapolated to the general population in which echocardiographic findings attributed to prolapse, particularly of the anterior mitral leaflet, have been described with high frequency, often in the absence of other evident abnormality.

If, as discussed above, the current two-dimensional echocardiographic criteria for mitral valve prolapse raise questions of sensitivity and specificity, one might reasonably ask whether other techniques could be used to greater advantage. Two-dimensional echocardiography, however, remains an ideal technique for displaying leaflet-annular relationships and ultimately defining a state of abnormality or prolapse, once appropriate criteria are established. In particular, it provides improved spatial appreciation of the structures and relationships in question compared with M mode echocardiography, which displays mitral valve motion along the direction of a single beam oriented with respect to the chest wall. Angiography, on the other hand, in addition to its susceptibility to problems of interobserver variability, is ultimately limited in applicability to selected groups of patients, and cannot be used to define normality of leaflet position in the general population.

Limitations. The significance of this study is that it provides an explanation, other than that of localized leaflet distortion, for the frequent observation of superior systolic leaflet displacement in the four-chamber view in apparently healthy individuals. The purpose of the studies in vivo was only and specifically to demonstrate that the proposed nonplanar annular configuration actually occurs in patients, not to establish the range of normal leaflet-annular relationships. The consistent findings of annular nonplanarity in all 20 subjects selected only for the absence of other primary cardiac pathology and for image quality and availability demonstrate the occurrence of such a configuration in human beings. To establish the normal range of leaflet-annular relationships and annular configuration, however, a prospective study of a large, representative population will be required to determine whether specific patterns of leaflet closure and size are associated with a state of illness or an adverse prognosis. Nevertheless, until such data are available, it would seem judicious to rely on the parasternal long-axis view for the diagnosis of prolapse, since that at least would decrease the frequency with which prolapse, an abnormality, is diagnosed in a population preselected to be normal.

To summarize, the relationship of the mitral leaflets to the surrounding anulus is essential to any definition of mitral valve prolapse. Therefore, if the mitral anulus is not planar, no single two-dimensional view can fully portray the leaflet-annular relationship. The implications of annular nonplanarity apply not only to echocardiography, but to any planar or tomographic imaging technique. We can conclude from the analysis presented that a nonplanar annular configuration can produce the appearance of mitral valve prolapse on the two-dimensional echocardiogram without actual leaflet displacement above the most superior points of the three-dimensional anulus. The human mitral anulus
had such a nonplanar shape in the patients we examined. This shape is particularly important because it can explain the clinically observed discrepancy between leaflet-annular relationships in roughly orthogonal views. These results, therefore, challenge the assumption of a planar mitral annulus and the diagnosis of prolapse in many otherwise normal individuals based on that assumption.

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Appendix

Since $z_1$ in figure 4 is the projection of raylength $r_1$ onto the axis $AX$, and since $r_1$ makes an angle $\alpha_1$ with the axis, 

$$z_1 = r_1 \cos \alpha_1$$

The quantities $r_1$, $r_2$, and $D$ can be directly measured as the distances between two points on the echocardiographic image; $\cos \alpha_1$ can then be obtained from these measured quantities by applying the trigonometric formula relating the sides of a triangle to the cosine of an included angle. Let $M$ be the midpoint of segment $BC$, so that the axis bisects $BC$ at point $M$. Let $c$ = the length of segment $AM$; $\beta = \angle ADB$; $d = D/2$. We then obtain three equations that can be solved for $\cos \alpha_1$ in terms of $r_1$, $r_2$, and $D$:

$$d^2 = r_1^2 + c^2 - 2rc \cos \alpha_1$$

(from triangle $ABM$)

and

$$c^2 = r_2^2 + d^2 - 2rd \cos \beta$$

(from triangle $ABM$)

and

$$r_2^2 = r_1^2 + D^2 - 2rD \cos \beta$$

(from triangle $ABC$)

Solving for $\cos \alpha_1$ allows us to express $z_2$ as a function of the measured quantities $r_1$, $r_2$, and $D$.

An analogous procedure gives a similar expression for $z_2$ in which the roles of $r_1$ and $r_2$ are reversed.

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