Two-dimensional Echocardiographic Assessment of Mitral Stenosis

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SUMMARY A real-time, phased-array, two-dimensional echocardiography system was used to assess mitral valve motion in 30 catheterized patients with pure mitral stenosis. Suitable images for analysis of mitral valve motion were obtained in 25 patients. The valve leaflets were most thickened and immobile at the leaflet tips while maximum mobility was at the leaflet body. Diastolic movement of anterior mitral leaflet toward the septum pulled the posterior mitral leaflet mid-portion inferiorly. Systolic bulging of the mid-portion of the anterior mitral leaflet into the left atrium was seen in 40% (10 of 25). Movement of the anterior mitral leaflet in diastole is primarily due to movement of the whole mitral apparatus in patients with mitral stenosis. The anterior mitral leaflet E to F slopes did not correlate (r = 0.38) with the mitral valve area determined at catheterization. Planimetry of the mitral valve area directly from the videotape images compared favorably to the valve area determined at catheterization (r = 0.95). Thus, mitral valve area determined by this technique is an accurate noninvasive method for assessing the severity of mitral stenosis.

Methods

Patients

Over a nine-month period, 30 patients with pure mitral stenosis or mitral stenosis with insignificant mitral insufficiency underwent both two-dimensional echocardiographic examination and cardiac catheterization within three days of each other. Twenty-five of these patients had adequate two-dimensional echoes for analysis of the mitral leaflets throughout the cardiac cycle. Fifteen of these patients had time-motion echocardiograms.

Echocardiographic Methods

Two-dimensional echoes were obtained using a previously described real-time, phased-array, imaging system. This system uses a hand-held, 24-element, 2.25 MHz transducer array that measures 14 × 24 mm at the site of skin contact and relies upon phased-array principles to electronically steer and focus the sound beam through the structures under investigation. Real-time, cross-sectional images of cardiac structures are presented in circular sector format, 50, 60, or 90 degrees in azimuth. Images are permanently recorded on videotape for later playback and analysis.

Figure 1 schematically shows the planes of view used for examination of the long axis of the mitral valve and left ventricle and the short axis of the left ventricle and mitral valve orifice. These views were obtained using previously described techniques. A diastolic, single-plane photograph and schematic illustration of the long axis of a normal mitral valve are shown in figure 2. A diastolic, single-plane photograph of the short axis of the left ventricle at the level of...
of the tips of the mitral valve leaflets in a normal individual is shown in figure 7A.

It is important to note that the single-frame images of videotape recordings were made by means of a 35 mm photograph of a sector arc in a stop-frame mode. As such, there is a loss of visual integration of motion that normally accompanies real-time playback. Moreover, during stop-frame mode, there is a severe degradation in image quality caused by photographing a single field of a complete videotape frame which consists of two interlaced fields. For example, an individual videotape recording frame represents the scan information collected in only 1/60th of a second. When operating in the 90 degree, 160-line format, therefore, each single-frame video field represents only one-half (80 lines) the information provided in the actual scan or in real-time playback.

The E to F slopes of the anterior mitral leaflet and of the mitral ring movements were determined from the long axis, two-dimensional images according to a method recently described in a preliminary report from this laboratory. In brief, this was done by tracing the positions of the anterior mitral leaflet and posterior aortic root when visualized in long axis, relative to the anterior chest wall, at multiple points in time throughout the cardiac cycle (fig. 3). The anterior mitral leaflet, mitral ring, and aortic root move posterosuperiorly during diastole. Serial measurements from the anterior chest wall to the anterior mitral leaflet and to the mitral ring were made during diastole from the point of initial leaflet opening (E point) to the instant just prior to the beginning of valve closure near the end of diastole which coincides with the F point on time-motion echocardiograms. Thus, when the serial measurements were plotted in time, E to F slopes of the anterior mitral leaflet and mitral ring, similar to those seen by time-motion echocardiography, could be derived from the two-dimensional echocardiographic data.

The mitral valve orifice was examined in the short axis view in diastole. The two-dimensional mitral valve area was determined by planimetering the mitral valve orifice echoes along their internal margins on stop-frame videotape images.

**FIGURE 1.** Schematic diagrams showing the planes of view through the long and short axes of the left ventricle. The view in the left panel normally interpolates the aortic root, left atrium, mitral valve, and left ventricle. The view in the right panel interpolates the short axis of the left ventricle at the level of the tips of the mitral valve leaflets. The asterisk marks the tops of the scan images in subsequent figures.

**FIGURE 2.** Panel A shows a photograph from a stop-action videotape frame through the long axis of a normal left ventricle during diastole. Panel B is the schematic illustration of panel A. AoR = aortic root; IVS = interventricular septum; LVC = left ventricular chamber; LA = left atrium; AML = anterior mitral leaflet; PML = posterior mitral leaflet. Note the wide distance between the AML and PML and that the tip of the AML approximates the IVS.

**FIGURE 3.** Schematic diagram illustrating the diastolic movement of the anterior mitral leaflet and mitral ring. Arrow indicates the posterosuperior direction of movement. Distances that the mitral ring and anterior mitral leaflet moved along the broken lines during diastole were used to derive E to F slopes.
of five successive cardiac cycles. Care was taken to assess the mitral valve area on cross-sections through the tips of the mitral valve leaflets and at the time of maximum diastolic opening according to the method of Henry. The planimetry was performed blind with respect to the mitral valve area determined by cardiac catheterization.

Time-motion echocardiograms were performed according to previously described methods using a commercially available ultrasonoscope equipped with a 2.25 MHz, 7.5 cm focused transducer. Strip-chart recordings were obtained using a Tektronics recorder.

Catheterization Methods

All patients underwent complete left and right heart catheterization using the percutaneous Seldinger technique from the right groin. Simultaneous left atrial and left ventricular catheterization and transeptal left atrial catherization. Cardiac output was determined by the Fick method. Mitral valve orifice area was calculated using the Gorlin formula.

Results

Mitral Leaflet Morphology

Two-dimensional echocardiography showed that the mitral leaflets were thickened in all 25 patients. The degree of thickening observed in the long axis examination was greater at the tips of the leaflets (fig. 4). Nodular appearing leaflet borders around the valve orifice were seen in all patients in both long and short axis views. Commisural fusion was seen in the short axis views (fig. 7). There was no correlation between the degree of thickening and the severity of stenosis measured by the mitral valve area determined at cardiac catheterization.

Mitral Leaflet Movement

The anterior mitral leaflets of the 25 patients were seen to be anchored at the basal attachment to the mitral ring in the normal fashion, and abnormally at the stenotic tips. This resulted in maximum amplitude of motion occurring in the mid-section of the leaflets giving an arched appearance, convex toward the left atrium in systole, and alternately convex toward the left ventricular outflow tract in diastole (fig. 4). In two of the 25 patients, the anterior mitral leaflet was so markedly thickened and rigid that motion of its mid-portion was severely restricted. There was no correlation of the mobility of the mid-portions of the anterior mitral leaflets and the mitral valve areas determined by cardiac catheterization. In 40% (10 of 25), the mid-portion of the anterior mitral leaflet bulged above the level of the mitral ring into the left atrium during ventricular systole (fig. 5).

After the anterior mitral leaflet opened at the beginning of diastole, it remained immobile relative to the mitral ring as the whole mitral apparatus (mitral ring and anterior mitral leaflet) moved posteriorly and cephalad during diastole. The anterior mitral leaflet then shut abruptly at the end of diastole. The time difference between the diastolic and systolic images seen in figure 4 was only 1/60th of a second. Thus, primary anterior mitral leaflet movement was restricted to its opening at the onset of diastole and closure at the end of diastole. The E to F slope of the anterior mitral leaflet closely approximated the E to F slope of the mitral ring (table 1).

As was noted with the anterior leaflet, the primary leaflet motion of the posterior mitral leaflet was also restricted to its opening and its closing. Throughout the remainder of the cardiac cycle, the posterior mitral leaflet moved in unison with the mitral ring. With diastolic opening, the tip of the posterior mitral leaflet was pulled toward the left ventricular outflow tract by the anterior mitral leaflet in all patients (figs. 4 and 6). In 80% (20 of 25), there was systolic convexity of the posterior mitral leaflet mid-portion toward the left atrium which flattened during diastolic opening. The net direction of motion of the posterior mitral leaflet mid-portion during the initial diastolic opening was inferior. This can be seen in figure 4 and is illustrated diagrammatically in figure 6. In one patient, the posterior mitral leaflet was

Figure 4. Sequential diastolic (panel A) and systolic (panel C) frames through the long axis of the mitral valve in patient with mitral stenosis. In panel A note the thickening of the valve leaflets, arching of the mid-portion of the anterior mitral leaflet as the valve apparatus is open in diastole. In panel C note the superior arching of the posterior mitral leaflet as both mitral leaflets coapt in systole.
markedly thickened and rigid and its mid-portion movement was severely restricted. In another four patients, the mid-portion of the posterior mitral leaflet could not be seen clearly throughout the whole cardiac cycle.

Mitral Valve Orifice Area

The E to F slopes of the anterior mitral leaflet and mitral ring did not correlate with the mitral valve orifice area determined by cardiac catheterization ($r = 0.38$ and $r = 0.32$, respectively). However, anterior mitral leaflet E to F slopes ranged from 0 to 35 mm per second which is within the accepted range of E to F slopes in mitral stenosis.

Figure 7 shows the short axis views of the mitral valve orifice in a normal individual and one patient with mild and one patient with severe mitral stenosis. It should be noted that in the normal state, the mitral valve orifice area must be determined at the level of the mitral ring rather than at the tips of the mitral leaflets as in mitral stenosis and, therefore, the mitral valve area was not determined for the normal image seen in figure 7. The mitral valve area calculated by two-dimensional echocardiography was compared to the mitral valve area determined at catheterization (fig. 8). There was linear relationship between the valve areas obtained by the two methods with a correlation coefficient of 0.95 and a linear regression equation of $y = (1.0) x + 0.1$. The mitral valve area from two-dimensional echocardiography and cardiac catheterization ranged from 0.9 to 4.4 cm² (mean 1.8 cm²) and 0.6 to 3.9 cm² (mean 1.7 cm²), respectively. The standard error of two-dimensional echocardiographic estimate was 0.3 cm².

Cardiac Chamber Morphology

The left ventricular contour as seen in the short axis cross-section deviated from the normal round (fig. 9A) configuration in 76% (19 of 25) patients. These changes ranged from mild straightening of the septum (fig. 9C) to severe flattening of the ventricle (fig. 9E). There appeared to be some mild association between the subjective estimate of severity of this change and the degree of elevation of the mean pulmonary arterial pressure. This is illustrated in figure 10. A subjective estimate of the left atrial size was also made. There was no enlargement noted in two patients, mild enlargement in six patients, moderate enlargement in 15 patients, and severe enlargement in two patients.
mitral leaflet spatial motion and morphologic characteristics. This method, however, has not been totally acceptable since dense opacification of contrast material that surrounds the leaflets occasionally obscures visualization of the movement of the entire diseased leaflets. Real-time, two-dimensional echocardiography has a distinct advantage for observing leaflet motion and morphology because it images moving cardiac structures in cross-section.

In this study, the results of two-dimensional echocardiography revealed that the diseased mitral leaflets were thickened, particularly in the distal third, and that the deformity around the stenotic mitral orifice gave rise to a nodular appearance. These observations were in accordance with the gross anatomic description of the appearance of stenotic leaflets published by Roberts and Pomerance.

The hemodynamic abnormality of mitral stenosis results because of fusion of the leaflets at the mitral commissures. Because the leaflets are anchored at the basal attachments to the mitral ring and also at the mitral valve orifice by the commissural fusion, the only parts of the leaflets remaining relatively free to move are the less thickened mid-portions. On two-dimensional echocardiograms, these are seen to arch in a convex fashion toward the left atrium in systole and alternately toward the left ventricle in diastole (figs. 4, 5, 6). On M-mode echocardiograms, the diastolic component may be reflected by the maximum amplitude of anterior mitral leaflet motion occurring in the mid-portion of a sweep from the tips of the mitral leaflets to the mitral ring (fig. 11). In two-dimensional echocardiography, the anterior mitral leaflet mid-portion excursion is much greater than that of the posterior mitral leaflet due to the larger size of the anterior leaflet. In contrast to what is seen in mitral stenosis,
maximum excursion and mobility of normal mitral leaflets occurs at the leaflet tips. In 40% (10 of 25) of the patients, the anterior leaflet bulged above the level of the mitral ring into the left atrium in systole. There was very little, if any, posterior motion of the closed mitral leaflets throughout systole in these patients; therefore, it is unlikely that systolic motion characteristic of mitral prolapse would be easily manifest by time-motion echocardiography. Since the leaflet movement into the left atrium occurs with end-diastolic closure, this may account for the curvilinear appearance of the transition between the diastolic and systolic M-mode echocardiographic mitral valve positions (fig. 12A). However, this motion may occur gradually throughout systole and thus account for the occasional presence of pansystolic hammocking seen on M-mode echocardiograms in patients with mitral stenosis (fig. 12B). More rarely, it may occur in mid to late systole giving rise to a picture more suggestive of late systolic prolapse (fig. 12C and D). All patients evaluated in this series by M-mode echocardiography had one or more of these patterns depending upon the specific portion of the mitral leaflet examined. This simulation of mitral prolapse is probably mechanical in origin secondary to distortion of leaflet closure induced by the effects of mitral stenosis on the valve apparatus.

Diastolic opening of the stenotic anterior mitral leaflet into the left ventricular outflow tract at the beginning of diastole pulls the tip of the posterior mitral leaflet forward and gives rise to the time-motion appearance of paradoxical posterior mitral leaflet motion. Occasionally, it has been reported that the posterior mitral leaflet moves in a normal posterior direction on M-mode recordings in patients with mitral stenosis. This may be explained, in part, by the observation that the mid-portion of the posterior mitral leaflet moves inferiorly at the beginning of diastole. Theoretically, a single time-motion echo beam passing through the mid-portion of the leaflet from a superior direction would result in a transducer perceiving this motion as being away from the transducer, which would be considered its normal posterior motion (fig. 6). This is illustrated in figure 13, where 13A shows the usual paradoxical posterior mitral leaflet motion, and 13B shows normal motion when the transducer is directed from above (same patient). A more common type of normally directed diastolic posterior mitral leaflet motion occurs at the beginning of diastole.

![Figure 9](image_url) **Figure 9.** Panel A shows a short axis systolic frame through the left ventricle at the level of the papillary muscles in a normal individual. Note the round contour of the left ventricle. Panel B is a schematic illustration of panel A. Panel C shows a short axis systolic frame through the left ventricle at the level of the tips of the mitral leaflets in a patient with mitral stenosis and mean pulmonary arterial pressure of 28 mm Hg. Note the truncation of the normal round contour along the interventricular septum, indicated by arrows in the schematic illustration in panel D. Panels E and F show the comparable short axis frame and schematic illustration for a patient with a mean pulmonary arterial pressure of 52 mm Hg. Note the more diffuse and severe degree of left ventricular contour flattening. PM = papillary muscle; MV = closed mitral valve apparatus.

![Figure 10](image_url) **Figure 10.** The loose relationship between the severity of the left ventricular contour distortion (horizontal axis) and the mean pulmonary arterial pressure (vertical axis).
when the valve orifice opens. This is followed by the usual paradoxical motion (fig. 13C).

In a preliminary study of normal mitral leaflet motion from this laboratory, it was noted that there was a wide spectrum of primary leaflet mobility in diastole. This primary leaflet mobility was reflected by the difference between the anterior mitral leaflet E to F slope and the mitral ring E to F slope. For the normals, leaflet slope was $62 \pm 35$ mm/sec (mean $\pm$ SD), and for patients with mitral stenosis in this study it was $7 \pm 7$ mm/sec. Thus, in marked contrast to normals, the results of the present study suggest that there is very little primary leaflet diastolic motion in mitral stenosis after leaflet opening has occurred. E to F slopes of the anterior mitral leaflet and mitral ring were quite similar (within 10 mm/sec) in 72% (18 of 25). In seven patients the slopes of the ring and leaflet differed from 11 to 25 mm/sec. The explanation for the latter finding is not readily apparent since there was no correlation with the severity of stenosis or any other parameter that was measured in these patients. One possible explanation is that the degree of shortening and thickening of the chordae tendineae may have been less severe than in the majority of patients. Unfortunately, this feature is difficult to assess by two-dimensional echocardiography.

The derived E to F slopes of the anterior mitral leaflet and mitral ring were compared poorly with the mitral valve
orifice area measured by cardiac catheterization and $r$ values of 0.38 and 0.32 were obtained. The anterior mitral leaflet slope is apparently not as dependent on the severity of the mitral stenosis as much as on the diastolic movement of the structures to which it is attached. These structures, including the mitral ring, stenotic mitral orifice and chordae tendineae, move posteriorly and superiorly in diastole as a result of left ventricular filling and most likely carry the fully open mitral leaflet in the same direction.

The insensitivity of the time-motion E to F slope has been demonstrated by Cope, and the results of this study are in agreement. However, the E to F slopes of the anterior mitral leaflet derived from the long axis two-dimensional echocardiographic images range from 0 to 35 mm per second which is within the accepted range of E to F slopes in mitral stenosis. Therefore, time-motion echocardiography can be relied upon to indicate the presence but not the severity of mitral stenosis.

It is very difficult to obtain an accurate value for mitral valve area in patients with mitral stenosis. Surgical estimation of valve area is commonly made by inserting a finger into the valve orifice. In an effort to overcome this problem, Henry inserted a specially designed sizer into the valve orifice at surgery. Although seemingly ideal, this method has certain limitations. During such evaluation, there is no circulation and the mitral apparatus is not subject to the normal stress of a hemodynamic load. In addition, a fixed sizer may deform the irregular, slit-like orifice during the measurement. Despite these considerations, there was a very good correlation between the two-dimensional echocardiographic and the surgical measurements.

Cardiac catheterization remains the only generally available method for assessing the severity of mitral stenosis. Other preoperative methods should also be judged by this criterion, particularly since an absolute figure for valve size cannot be obtained. Mitral valve orifice area determined by planimetry of the stop-frame videotape images from the phased-array, two-dimensional echocardiographic system compared favorably to the mitral valve orifice area determined by cardiac catheterization (fig. 8) ($r = 0.95$, see $0.3 \text{ cm}^2$). Therefore, the results of this study support the findings of Henry that real-time, two-dimensional echocardiography is a reliable, noninvasive method for the determination of mitral valve orifice area in patients with mitral stenosis.

It should be noted that there are several limitations to the assessment of mitral stenosis by two-dimensional echocardiography. One of the most important is that 17% of the original 30 patients assessed had inadequate two-dimensional images for evaluation due to poor sound transmission qualities induced by abnormal chest wall configuration, patient age, the presence of interposed lung, or some other, as yet undescribed reasons.

In addition, one must have a firm appreciation of potential errors that may result due to the use of ultrasonic techniques for cardiac imaging. The quality of mitral valve orifice images is dependent upon 1) the inherent resolution properties of the imaging system, and 2) the gain control setting which varies for each individual patient. For example, a 1 mm error in resolution will result in approximately 10% error in the estimation of the area of an ellipse $3 \text{ cm}^2$ in area. For an area of $0.5 \text{ cm}^2$, a 1 mm error in the linear dimension will produce a 20% error in the area estimation. In mitral stenosis, rather bright echoes are reflected from a thickened and often calcified mitral valve. As a result, when assessing mitral stenosis, the gain setting should be adjusted lower than what would be used to observe other cardiac structures. It should also be noted that loss of echo targets when the interrogating pulse is parallel to a structure (drop out) is most commonly seen in the commissural areas when the stenotic orifice is viewed in short axis. Careful attention to echo technique is, therefore, most important.

Seventy-six percent (19 of 25) of the patients in this study
showed abnormal geometrical configurations of the left ventricular cavity when viewed in short axis (fig. 9). These changes ranged in appearance from the normally circular configuration to straightening of the ventricular septum or severe flattening of the ventricle in the anteroposterior dimension. The severity of these changes showed a loose association with the degree of elevation of the pulmonary arterial pressure. The clinical importance and the reasons for these changes are uncertain at the present time. It may be that progressive elevations in pulmonary arterial pressure that result in enlargement of the right ventricle, in turn, may alter the normal convexity of the interventricular septum and distort the appearance of the left ventricle.

In summary, it appears that two-dimensional echocardiography is a useful method for the evaluation of mitral valve orifice size in patients with mitral stenosis. Furthermore, two-dimensional echocardiographic assessment of mitral leaflet spatial motion explains many of the M-mode findings commonly observed in these patients. In the future, these baseline two-dimensional echocardiographic observations concerning stenotic mitral leaflet motion and morphology may provide a method for answering other important clinical questions such as determining the suitability for mitral valvulotomy.

References

Premature Pulmonary Valve Opening

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SUMMARY Premature opening of the pulmonary valve (opening independent of atrial or ventricular systole) was originally described in a case of sinus of Valsalva rupture into the right atrium. Since that time we have observed five additional cases in which the pulmonary valve opened prematurely. Entities encountered included: 1) constrictive pericarditis; 2) Loeffler's endocarditis; 3) Ebstein's anomaly with tricuspid regurgitation; 4) tricuspid regurgitation following tricuspid valvuloectomy; and 5) pulmonary regurgitation accompanied by atrial septal defect. In the first two cases, premature pulmonary valve opening is felt to be due to restriction of diastolic filling of the right ventricle with subsequent early diastolic rise in pressure equaling or exceeding pulmonary artery diastolic pressure. In the latter three cases, the increased volume of blood entering the right ventricle again appeared to result in a rapid rise in initial right ventricular diastolic pressure and to produce premature opening of the pulmonary valve. Premature pulmonary valve opening, therefore, does not appear specific for any particular clinical entity but reflects the relative pressures in the right ventricle and pulmonary artery during diastole.

A NUMBER OF RECENT REPORTS have demonstrated the clinical usefulness of recording the echocardiographic pattern of pulmonary valve motion. Characteristic echocardiographic patterns have been described in patients with pulmonary valvular stenosis, pulmonary infundibular stenosis, pulmonary regurgitation, Uhl's anomaly, and pulmonary hypertension. We have previously reported a case of sinus of Valsalva aneurysm rupture into the right atrium in which one of the echocardiographic manifesta-

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