A Study of Mitral Valve Action Recorded by Reflected Ultrasound and Its Application in the Diagnosis of Mitral Stenosis

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SUMMARY

The movements of two ultrasound echo signals, believed to arise from the anterior mitral leaflet and from the mitral ring, were studied in 30 normal subjects and in 100 heart-catheterization patients. Fifty patients had proven mitral stenosis. The echo from the anterior mitral leaflet is shown to have a complex pattern of movement. This pattern is analyzed into the opening and closing movements of the leaflet, and the underlying movement transmitted from the mitral ring. In the normal condition, the characteristic feature of leaflet motion is a sharp closing movement that follows the initial opening in diastole. This sharp closing movement is not seen in the presence of mitral stenosis. It is believed that the demonstration of a sustained wide-open position of the leaflet in diastole has the same diagnostic significance as the finding of a persistent positive-pressure gradient across the valve. The value of this method in diagnosing the severity of the stenosis is discussed.

Additional Indexing Words:
Anterior mitral leaflet  Echography  Mitral pressure gradient  Mitral ring

It is widely accepted that the method of reflected ultrasound can be used to record the movement of the anterior leaflet of the mitral valve in the intact subject. Edler and his group1-2 were the first to recognize an "echo" signal from the anterior leaflet and to describe its pattern of movement. They found this pattern to be fairly constant, except when mitral stenosis was present, in which case the pattern showed a characteristic change. The practical value of this method in the diagnosis of mitral stenosis has been exten-

sively confirmed in Europe,2-5 and more recently in this country.6,7

In a previous publication,8 another echo signal was described, which apparently was reflected from a neighboring segment of the ventricular wall. The movement of this structure, believed to be the mitral ring, was described in detail in the normal subject. It was then suggested that the anterior mitral leaflet echo pattern consisted of both leaflet and ring movements.

This study includes the two echo signals and attempts to analyze the anterior mitral leaflet echo pattern into its "leaflet" and "ring" components. The independent movement of the leaflet is described, both in the normal condition and in the presence of mitral stenosis. An effort is made to explain the mechanism of the change seen in cases of stenosis, by combining the ultrasound study with a study of the pressure gradient across the mitral valve.
Methods

Subjects and Procedures

This paper is based on the ultrasound cardiograms of 30 normal young adults and of 100 patients admitted for heart catheterization. Significant mitral stenosis was present in 50 patients.

The diagnostic methods of ultrasoundcardiography have been described in previous publications. The commercially available apparatus used in this study produces brief pulses of ultrasound energy with a wave frequency of 2.25 megacycles per second. A barium titanate crystal in a %-inch transducer emits 200 or 1,000 pulses each second, and receives the echoes in the intervals between pulses. The various echo signals appear on an oscilloscopic screen, either as spikes (“A form”), or as bright spots (“B form”). Signal motion can be recorded photographically in the B form (fig. 1). In this study, the ultrasound examination was performed in the recumbent position. The mitral valve echo (MVE) was obtained from the third or fourth left intercostal space 1 or 2 inches from the midsternal line with the transducer directed mainly posteriorly. The signal of the MVE was encountered at a depth of about 6 to 8 cm² and was easily identified by its fast anterior movement (“anterior kick”) in early diastole. The other echo, which will be referred to as the mitral ring echo (MRE), was also obtainable from the same area with the ultrasound beam directed about 10 to 15° medially. It was preferred, however, to record the MRE routinely from the region of the heart apex, with the ultrasound beam directed toward the heart base—that is, medially and superriorly as well as posteriorly. In all instances, the MRE was identified as the strong “intracardiac” signal located 1 or 2 cm posterior to the MVE. The movement of the desired signal was then recorded on a multiple-channel oscillograph, simultaneously with other parameters, such as the electrocardiogram (ECG) and the phonocardiogram (PCG). The movement of the signal was magnified twice; the PCG was filtered between 120 and 500 cycles per second, and a paper speed of 100 mm per second was preferably used. As a rule, during the recording of signal motion the subject was asked to hold the breath in the phase in which the best tracing was obtained.

Simultaneous left atrial (LA) and left ventricular (LV) pressures, when performed, were obtained by standard transseptal and retrograde left heart catheterization. The pressures were measured with Statham strain gauges (P 23 Db), which were mounted at midthoracic level and calibrated for comparable sensitivity. To ascertain the identical responses of the transducers, the catheters were switched during the recording of pressures.

In the appropriate case, the presence or absence of mitral valve disease was further confirmed by selective cineangiocardiology.

Method of Separating the Two Components of the MVE Pattern

To understand the method used in this study for separating the components of the anterior mitral leaflet echo pattern, it will be helpful to consider first a recording of the movement of a prosthetic valve. The movement of a mitral Starr-Edwards valve can be readily traced on x-ray cine film as well as recorded by ultrasound, and the results by the two methods are closely similar. Figure 1 shows the movements of both

Figure 1

The patterns of movement of a Starr-Edwards valve cage and ball recorded simultaneously by reflected ultrasound (photographic method), together with an electrocardiogram. The valve ball undergoes the same movement as the cage in addition to its own opening (upward) and closing (downward) movements. Note the identical movement of cage and ball during systolic ejection. In this as in all other illustrations, an upward movement of the ultrasound tracing represents a displacement of the source of the echo toward the transducer and the chest wall. The dots in this illustration mark ½ second horizontally and 1 cm vertically.

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the cage and the ball recorded simultaneously by the method of reflected ultrasound. The valve cage derives its movement from the mitral ring to which it is sutured, and is displaced toward the cardiac apex in systole, and away from the apex in diastole. The amplitude of this movement recorded in figure 1 is about 1 cm. The recorded pattern of ball movement may be divided into two components: the first component is due to the excision of the cage, and explains the identical movement during the greater part of systole. During this period of systolic ejection, the ball maintains a position of closure at the base of the cage, and the whole valve moves in one piece. The second component of the ball pattern consists of the opening and closing movements of the ball itself. Early in diastole, the ball moves into an open position at the apex of the cage (upward movement in the tracing). Later on, it moves back within its cage and settles once more into a closed position in the early part of the following systole. The separation of the “cage” and “ball” components of the ball pattern is made easy in this illustration by the simultaneous recording of cage movement.

In the case of the natural valve, the mitral ring and the anterior mitral leaflet are oriented in different planes and move in different directions; it is rarely possible to record their echoes simultaneously with the same transducer. Figure 2, from a normal subject, shows the superimposed patterns of movement of the two structures: the mitral ring (MRE) and the anterior leaflet (MVE), from two cardiac cycles of identical length. There is obvious similarity between this pair of patterns from the natural valve and the pair from the prosthetic valve shown in the previous illustration. Unlike cage and ball, however, the MRE and MVE show different amplitudes of movement during systolic ejection. As explained before, the movement during this period is due to the displacement of the ring, and the leaflet passively follows in a position of complete closure. The difference in the recorded amplitudes may be explained by the different methods of recording. The MRE is recorded from the region of the cardiac apex with the ultrasound beam directed toward the heart base—that is, parallel to the movement of the ring. This method is believed to record the full excursion of the ring, which amounts to $1.6 \pm 0.4$ cm in the normal subject. The MVE, on the other hand, is recorded from the anterior chest wall in an anteroposterior direction, parallel to leaflet motion. In the MVE, therefore, ring motion is recorded at an angle and must have an apparently smaller amplitude.

The pattern of movement transmitted from the ring is obvious in the MVE during the period of systolic ejection, but is otherwise masked by the opening and closing movements of the leaflet. On the basis of the previous argument, the ring component of the MVE may be extrapolated beyond systolic ejection in the following manner: the MRE is separately recorded on the same subject. The total amplitude of movement during systolic ejection is measured in the two tracings, vertically between the most posterior point in early systole and, for convenience, the beginning of the second heart sound (see vertical lines with arrowheads in figure 2). The

**Figure 2**

The normal pattern of movement of the anterior mitral leaflet echo (MVE) recorded on a multiple-channel oscillograph simultaneously with the electrocardiogram (ECG) and the phonocardiogram (PCG). These tracings are superimposed on the pattern of the mitral ring echo (MRE) from another cardiac cycle of identical length. The leaflet undergoes the same movement as the ring in addition to its opening and closing movements. Because of the different methods of recording, however, the movement during systolic ejection is different in the MVE from that of the MRE (compare vertical lines with arrowheads). The plain letters on the MVE follow Edler’s designations, and the letters in parentheses on the MRE follow Wiggers’ designations for the various phases of the cardiac cycle. The cm scales refer to movement of the reflecting structures.

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MRE is reduced according to the ratio between the two amplitudes, and is then superimposed onto the MVE as in figure 3. In this way, the "projected" MRE constitutes the ring component of the MVE and serves as a base line for its leaflet component.

Results

The normal patterns of movements of the two echo signals that concern this study are shown superimposed in figure 2. The pattern of the mitral ring echo (MRE) is comparable to experimental recordings of ventricular dimensions, such as ventricular volume curves.11 The pattern of the echo from the anterior mitral leaflet (MVE) may be visualized as MRE that is reduced in amplitude, and on top of which two peaks are added in diastole. These two peaks represent the opening and closing movements of the leaflet. Before proceeding to describe leaflet motion, however, the base-line pattern of the MRE will be briefly outlined.

Movement of the Mitral Ring in the Normal Subject

An upward movement of the MRE (fig. 2) represents a displacement of the mitral ring toward the apex of the heart. The letters between parentheses follow Wiggers' designations for the various phases of the cardiac cycle.11 At the beginning of systole, the normal pattern of the MRE shows a small movement toward the apex to point B, which usually coincides with the beginning of the main vibrations of the first heart sound. The direction of movement is then briefly reversed to C. The main movement of the MRE toward the apex, C-F, takes place during the period of systolic ejection. The next point, G, is taken at the beginning of the second heart sound, and there is usually a further small movement toward the apex between G and H. The main movement during diastole is directed away from the apex and consists of two stages: the first stage starts from point H, 0.06 ± 0.02 second after the beginning of the second sound, and takes place during the period of rapid filling, H-I. After an interval of diastasis, I-J, the second stage takes place during atrial filling, J-K.

Movement of the Anterior Mitral Leaflet in the Normal Condition

An upward movement of the MVE, in all illustrations, represents an anterior displacement of the leaflet. It should also be mentioned that the anterior leaflet opens anteriorly in the direction of the ventricle, and closes posteriorly in the direction of the atrium.2, 12 The independent movement of the leaflet becomes more obvious when the ring component is isolated in the manner described under "Methods." In figure 3, a separately recorded MRE has been reduced and superimposed on the MVE, so that it overlaps the MVE during systolic ejection, and is then extrapolated as the dotted line. This "projected" MRE constitutes the ring component and is used as a base line for the leaflet component. Where the MVE and the projected MRE overlap, the leaflet is in a fully closed

Figure 3

*The MVE, ECG, and PCG from another normal subject. The MVE is divided into its "leaflet" and "ring" components. The ring component is served by a reduced "projection" from an MRE (see text), which overlaps the MVE during systolic ejection and is extrapolated as the dotted line. The MVE and the projected MRE overlap when the leaflet is closed and separate when it is open; the degree of opening is judged by the vertical distance that separates the two lines. The rate of "diastolic descent" (tangent of angle alpha) is about 190 mm per second in this case.*
position. A relative anterior (superior) position of the MVE indicates an open position of the leaflet, the degree of opening being proportional to the vertical distance separating the two tracings.

During systolic ejection, the MVE and the projected MRE completely overlap as a rule; the leaflet remains in a fully closed position during this period. With the onset of diastole, the leaflet starts to alter its position in relation to the ring. There is at first a slow anterior movement, perhaps bowing in the direction of the ventricle, to point D. Then the leaflet is thrown fully open to peak E. Meanwhile, the ring commences to recede from the apex at the beginning of the rapid opening movement, D-E. Once fully open, the leaflet tends to remain in this position during the period of rapid filling (H-I on the ring component); the vertical distance between the MVE and its ring component remains practically the same between E and F₀. But since the ring is receding during this period, the MVE shows a posterior movement between the two points. Toward the end of rapid filling, the leaflet undergoes a fast closing movement, F₀-F. If the length of diastole permits, the leaflet tends to reopen slowly and partially, only to drift again toward closure and possibly to settle in mid-position. When the atrium contracts, the leaflet is once more thrown to a wide-open position at peak A. This peak occupies a posterior position relative to peak E, owing to the change in the position of the ring. At the commencement of the “atrial” opening movement, the ring starts to recede for the second time. A tendency toward closure is seen immediately after peak A. Slow at first, the rate of closure is accelerated toward the end of atrial filling. In the average case, closure is completed by ventricular systole, which starts about the peak of the R wave of the ECG. The portion of the posterior movement between B and C is attributed to closure by ventricular systole. In the normal pattern, point B may be taken to coincide with the peak of the R wave.

In figure 4, also from a normal subject, a simultaneous recording of the apexcardiogram aids in correlating the MVE pattern with hemodynamic events in the left side of

\[ \text{Figure 4} \]

The MVE from a third normal subject recorded simultaneously with the ECG, PCG, and the apexcardiogram (ACG). The known timing of the conventional points on the ACG may be used in correlating the MVE pattern with the various phases of the cardiac cycle. Note that the third heart sound (S₃) clearly precedes the closing movement in diastole, F₀-F.

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the heart. This illustration further shows that the third heart sound is unrelated to leaflet closure in diastole, $F_o-F$.

In agreement with previous authors, the “normal” pattern of the MVE, with minor modifications, was also seen in cases of heart disease in the absence of significant mitral stenosis.

**Movement of the Anterior Mitral Leaflet in Mitral Stenosis**

Figure 5 shows a representative MVE from a case of moderate mitral stenosis. Instead of the normally sharp receding movement during early ventricular filling (H-I, figs. 2 to 4), the ring component here shows a more gradual and more protracted movement. The second stage during atrial filling, J-K, is relatively increased. The most striking and characteristic change, however, is seen in the leaflet component, which is well represented in this tracing. (Although the edges of the cusps are usually fused and thickened in mitral stenosis, the “bellies” of the cusps retain considerable mobility, unless the whole structure becomes rigid through fibrosis or calcification.18, 19) After attaining a fully open position at peak E, the leaflet tends to remain in this position for the rest of diastole. The closing movement $F_o-F$ is absent, and peak A is inconspicuous. Valve closure takes place from a wide-open position under the influence of ventricular contraction. The posterior movement of the MVE during diastole, in this case, is almost entirely transmitted from the ring, and reproduces almost exactly the “projected” ring motion. It may also be noted that the opening movement, D-E, is relatively early, that the ring does not start to recede until this movement is completed, and that the closing movement, B-C, is relatively late. The opening snap (O.S.) begins shortly before peak E, at a point where the opening movement usually slows down toward its end. Figure 5B, from the same patient, shows a persistent positive pressure gradient in diastole.

In cases of mild stenosis, where a positive-pressure gradient tends to disappear in later diastole, the MVE shows a gradual closing movement from peak E (fig. 6), but the sharp closing movement $F_o-F$ is again conspicuous by its absence.

**Figure 5**

A case of moderate mitral stenosis: A, the MVE, ECG, and PCG; B, simultaneous left atrial (LA) and left ventricular (LV) pressures and ECG. A shows that the leaflet maintains a fully open position in diastole after peak E. The posterior movement in diastole is almost totally transmitted from the ring, and takes place at the rate of 15 mm per second. B shows a persistent positive-pressure gradient in diastole.

**Figure 6**

A case of mild mitral stenosis and insufficiency (post-commissurotomy). A, the MVE, ECG, and PCG; B, simultaneous left atrial and left ventricular pressures and ECG. A shows a partial and gradual closing of the leaflet after peak E. B shows an early diastolic positive-pressure gradient which gradually disappears. The rate of diastolic descent in this case is 30 mm per second.
A case of predominant aortic insufficiency: the MVE is recorded simultaneously with left atrial and left ventricular pressures and the ECG; A, at rest; B, after amyl nitrite inhalation. The MVE shows a normal pattern at rest. Note the temporary reverse pressure gradient coinciding with the closing movement in diastole, $F_1-F$. After amyl nitrite inhalation, a positive-pressure gradient dominates diastole, and the pattern of the MVE changes accordingly. It should be pointed out that the heart rate is faster in B.

Discussion

The anterior mitral leaflet is generally accepted, at present, as the origin of the echo under consideration (MVE). The pattern of the MVE, however, cannot be explained on the basis of leaflet motion alone. The sustained and often marked anterior movement in systole between C and D can hardly be due to an opening movement of the leaflet. It is of interest in this regard that the MVE was once thought to arise from the "anterior wall of the left atrium."\textsuperscript{1} 3-5 The pattern of movement recorded in the MVE can be satisfactorily explained only as a combination of the movements of the two structures: the anterior mitral leaflet and the mitral ring. This conclusion is unavoidable, since the method of reflected ultrasound records the movement of a structure in relation to the transducer and the chest wall. An ultrasound recording of leaflet motion, therefore, must at the same time record the considerable movement of the ring to which the leaflet is attached. A similar concept has been used in the evaluation of ultrasound recordings from the prosthetic valve ball.\textsuperscript{10} Recordings of leaflet motion are more complicated, however, mainly because of the different directions in which leaflet and ring movements take place.\textsuperscript{21a} The method used in this study for the demonstration of the two components of the MVE starts from the period of systolic

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A case of predominant aortic insufficiency: the MVE is recorded simultaneously with left atrial and left ventricular pressures and the ECG; A, at rest; B, after amyl nitrite inhalation. The MVE shows a normal pattern at rest. Note the temporary reverse pressure gradient coinciding with the closing movement in diastole, $F_1-F$. After amyl nitrite inhalation, a positive-pressure gradient dominates diastole, and the pattern of the MVE changes accordingly. It should be pointed out that the heart rate is faster in B.
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ejection. This is a period during which a high intraventricular pressure is maintained with relatively little change, and the relation between the ring and the completely closed leaflet can be expected to remain virtually constant. The anterior movement of the MVE during this period is taken as a pure representation of its ring component. The use of the pattern of the other echo signal (MRE) as the basic pattern of ring motion is justified for reasons detailed in the previous study.\(^8\) This echo is reflected from a structure that is functionally a part of the ventricular wall, that lies in close proximity to the leaflet, and that moves parallel to the long axis of the ventricle.*

**The Normal Pattern of the MVE**

The characteristic feature of the normal pattern of the MVE is the closing movement, \(F_c\)-\(F\), which follows the initial opening in diastole. Such a closing movement was suggested in the classical experiments of Henderson and Johnson,\(^{22}\) and of Dean.\(^{23}\) It was postulated as the cause of the third heart sound,\(^{24, 25}\) but it seems that the sound precedes the closing movement\(^{26}\) and occurs while the valve is still wide open\(^{27}\) (fig. 4). Valve closure in diastole was concluded by Rytand\(^{27}\) from a study of the varying amplitude of the first heart sound in patients with atrial fibrillation. Warren and associates\(^{25}\) demonstrated a temporary reverse pressure gradient about the expected time of this closing movement in laboratory animals. A similar reverse gradient was reported by other workers.\(^{26, 28}\) The observation in figure 7A, of a reverse gradient coinciding with the closing movement, \(F_c\)-\(F\), seems, therefore, of special interest. Valve closure initiated at this stage and completed by ventricular systole can be well co-ordinated. This may explain the nonleaking valve closure demonstrated in some instances of ventricular premature beats and atrial fibrillation.\(^{29, 30}\) Normally, valve closure is also initiated after atrial contraction.\(^{13, 22, 23, 28, 31, 32}\)

**The MVE in Mitral Stenosis**

The presence of mitral valve stenosis modifies both leaflet and ring movements in the following manner:

1. The leaflet component shows the more dramatic change. In this study, the closing movement, \(F_c\)-\(F\), was never seen in the presence of mitral stenosis of any significance. When a positive pressure gradient persists to the end of diastole, the valve stays in a wide-open position until it is closed by ventricular systole. A similar pattern of leaflet motion has been described in a cineradiographic study by tracing the movement of calcium deposit on the anterior mitral cusp.\(^{21c}\) The mechanism of closure mentioned above is probably a major cause for the accentuation of the first heart sound in mitral stenosis.\(^{19, 33}\) 2. With increasing rigidity of the valve leaflets, the leaflet component gradually loses in amplitude and, consequently, the total amplitude of the MVE becomes smaller.\(^{24, 35}\) When the leaflets are completely rigid, a moving echo can still be obtained,\(^{26}\) but the MVE in such a case is virtually an MRE. 3. The ring component shows a slower and more protracted receding movement in diastole, probably due to a slower rate of ventricular filling. This change in the pattern of ring motion is not diagnostic of mitral stenosis, and was seen in cases of advanced heart disease due to other causes.

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Use of the MVE in Diagnosis of Mitral Stenosis

According to the method suggested by Edler and modified by Effert, the change in the pattern of the MVE in relation to mitral stenosis is expressed quantitatively by measuring the speed of the posterior movement that follows peak E in diastole. The rate of this "diastolic descent" is measured as the tangent of angle alpha, which this segment of the MVE makes with the horizontal (figs. 3, 5, and 6). In the absence of mitral stenosis, the rate of the diastolic descent averages 125 mm per second, and varies from 85 to 200 mm per second. In mitral stenosis, the rate undergoes a marked reduction to less than 40 mm per second. This finding has been confirmed in all subsequent studies. A comparison of the previous illustrations, however, makes it clear that these measurements apply to different components of motion. In the normal pattern (fig. 3), the rate of the closing movement of the leaflet, \( F_c-F \), is being measured. In the full-blown stenotic pattern (fig. 5), it is mainly a measurement of the rate of the receding movement that belongs to the ring component. The marked reduction in the rate of the diastolic descent in cases of mitral stenosis is mainly an expression of the absence of the closing movement, \( F_c-F \). In order that this method may be valid, therefore, two criteria must be satisfied: the MVE must have a leaflet component of adequate amplitude, as evidenced by a sizable opening movement, D-E, and a diastolic interval of adequate length must follow peak E, and precede peak A, or the following ventricular systole in cases of atrial fibrillation. During this interval, it must be clear whether the leaflet closes or remains open. In the presence of tachycardia, interpretation may be difficult or impossible. With these two qualifications, it is believed that the demonstration of a sustained wide-open position of the leaflet in diastole has the same diagnostic significance as the finding of a persistent positive-pressure gradient across the valve. Both parameters may be reliably used in the diagnosis of mitral stenosis, although they cannot be regarded as pathognomonic of this condition. Both are seen, for example, in cases of atrial myxoma.

The change in the pattern of mitral valve action may indicate the presence and the duration of a significant positive-pressure gradient in diastole, but it does not indicate its size. The diagnosis of the severity of the stenosis thus presents a different problem. Most studies have shown that the rate of the posterior movement that follows peak E (rate of "diastolic descent") tends to decrease with increasing severity of the stenosis. In the milder forms of stenosis (fig. 6), this tendency is largely explained by the gradual disappearance of leaflet closure as the gradient extends further in diastole. In the severer forms (fig. 5), the gradient extends to the end of diastole, and the leaflet remains wide open throughout, irrespective of the size of this gradient. The tendency for a progressively slower diastolic descent continues for a different reason: the descent in such cases is a function of the receding movement of the ring, which ultimately depends on the rate of ventricular filling. It may be stated, therefore, that the rate of diastolic descent in cases of mitral stenosis is a function of the duration of the positive gradient and the rate of filling of the left ventricle. The correlation between the rate of descent and the severity of valvular stenosis does not seem to be very close, however, especially in the more advanced

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**Figure 8**

A case of moderate mitral stenosis: two recordings of the MVE from two different points on the chest wall, to show the effect of variation in the site of recording on the components of the MVE and on the diastolic descent. A shows a diastolic descent of 9 mm per second as compared with 15 mm per second in B. The diastolic descent in this case is mostly transmitted from the ring. The ring component is better represented in B, whereas the reverse is true for the leaflet component.
cases. Variation in the site of recording on the chest wall is particularly liable to cause inaccuracy, since it may influence the representation of the two components of the MVE. This point is illustrated in figure 8, where two recordings of the MVE, with two different rates of diastolic descent, were obtained on the same patient. Beyond the point where the diastolic descent becomes virtually a function of the ring component (figs. 5 and 8), it would be more accurate to compare the rate of this movement in recordings of the mitral ring echo (MRE) from a standardized position, preferably the region of the cardiac apex. It should be mentioned, however, that the excursion of the ring depends on the size of the heart as well as on the stroke volume. In a quantitative comparison of ultrasound tracings, therefore, several factors should be taken into consideration, such as variation in the cardiac output (out of proportion to the degree of stenosis), the heart rate, and the presence or absence of other cardiac lesions.

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References

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