The Echocardiographic Determination of Mitral Valve Opening and Closure
Correlation with Hemodynamic Studies in Man

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SUMMARY
The ability of the echocardiogram to define mitral valve opening and closure was assessed by simultaneously recording the echocardiogram of the anterior leaflet (ECHO) with intracardiac pressures, aortic second sound, and ECG on 58 occasions in 14 patients undergoing cardiac catheterization. Hemodynamic opening and closure were defined by intersection of the pulmonary wedge and left ventricular pressures and the onset of left ventricular systole. The onset of the most rapid anterior motion (D') in early diastole and termination of the last rapid posterior movement in end diastole (C0) were used as echocardiographic markers of mitral valve opening and closure. Intervals measured included: the isovolumic relaxation period (IRP) from A2 to either hemodynamic (IRPH) or echocardiographic (IRPE) opening; the Q to closure interval (QCI) from the Q wave to either hemodynamic (QCIH) or echocardiographic (QCI) closure; and diastolic filling period (DFP), either hemodynamic (DFPH) or echocardiographic (DFPE). The following significant (P < .01) regression equations resulted: IRP = (97) IRPH + 30 (SEM ± 8 msec) r = .89; QCI = (68) QCIH + 37 (SEM ± 7 msec) r = .71; DFP = (98) DFPH + 10 (SEM ± 18 msec) r = .98. Thus hemodynamic markers of opening and closure systematically precede echocardiographic markers of opening (D') and closure (C0) and the diastolic filling periods are equal within 10 msec. It is concluded that the echocardiogram of the anterior leaflet is a reliable indicator of hemodynamic markers of opening and closure of the mitral valve in man and is useful in the noninvasive determination of certain systolic and diastolic time intervals.

Additional Indexing Words
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THE ECHOCARDIOGRAM of the mitral valve anterior leaflet (ECHO) is generally easy to recognize and obtain.1 Availability of strip chart recorders has permitted its simultaneous recording with other physiologic parameters, facilitating the use of the ECHO to time intracardiac events. There is disagreement in the literature regarding the precise echocardiographic definition of mitral valve opening and closure.2-9 However, recent work in the canine demonstrates that certain echocardiographic markers of mitral valve opening and closure correlate well with hemodynamic indicators of valve opening and closure.10 It is the purpose of this study to compare in man certain echocardiographic markers related to the opening and closing movements of the mitral valve to hemodynamically defined markers and to establish a role for the echocardiogram in the determination of certain systolic and diastolic time intervals.

Materials and Methods
Echocardiographic studies were performed in fourteen patients undergoing right and left heart catheterization with coronary angiography and left ventriculography for evaluation of chest pain. An SK1 20A echograph, equipped with a 2.25 MHz, 0.5 inch diameter, 10 cm focused transducer having a pulse repetition of a 1000/sec was employed. In ten of the studies, signals from the mitral valve were obtained from a time analog gate preamplifier. In the final four studies the entire echocardiogram was recorded with an Electronics for Medicine DR8 recorder. Simultaneous recording of the gated analog signal and the full strip chart display of the echocardiogram revealed no significant electronic delay in the analog signal. The ultrasound transducer was oriented to obtain maximal excursion of the anterior leaflet of the mitral valve usually just superomedial to the region where both leaflets were imaged. The phonocardiogram was obtained with a Leatham microphone positioned parasternally usually in the second left interspace to maximize the intensity of the second heart sound. The signal was filtered in the
medium high frequency range (100-500 cycles/sec), and the first transient of the second sound was used to identify aortic closure. Patients with paradoxical splitting of the second sound were excluded.

Hemodynamic measurements were made with similar length and diameter fluid-filled catheters connected to Statham P23Db transducers. Prior to pressure determinations, catheters and transducers were carefully flushed to insure absence of visible gas bubbles. In ten cases, the pulmonary capillary wedge pressure was obtained with a 7 Fr Courmand end hole catheter and in four cases with a 7 Fr Swan-Ganz catheter. The temporal delay for the left ventricular catheter system was determined by studying its fluid dynamic characteristics in comparison to the output of an SF-1 catheter tip manometer signal in a canine preparation. A delay of 8 ± 2 msec was found in the fluid filled system. The regression equations are corrected for this delay.

Though the pulmonary capillary wedge pressure tracing may have a variable delay in relation to the left atrial pressure wave form, the absolute pressure of the "V" wave will closely approximate the left atrial "V" wave. Therefore extrapolation of the "V" wave back to the left ventricular pressure generates the moment of left ventricular pressure "V" wave crossover independent of delays in the pulmonary capillary wedge pressure tracing. Furthermore, the rapid rate of left ventricular relaxation at the time of "V" wave pressure (range 1250-3000 mm Hg/sec) causes very small timing errors in response to small differences in the "V" wave pressure (3-8 msec/mm Hg). The electrocardiogram, phonocardiogram, left ventricular and pulmonary capillary wedge pressures, and the echocardiogram were recorded simultaneously on an Electronics for Medicine DR8 recorded at a chart speed of 200 mm/sec.

Echocardiographic and hemodynamic markers of mitral valve opening and closure were defined as follows (fig. 1). The point of onset of the most rapid anterior motion in early diastole (D') was selected as the ECHO marker of opening, and the termination of the last rapid posterior motion in end diastole (C1) was selected as the ECHO marker of closure. The hemodynamic marker of opening was the intersection of the V wave peak of the pulmonary capillary wedge tracing extrapolated back to left ventricular pressure curve. The hemodynamic marker of closure was taken as the point of onset of left ventricular systole. The end diastolic pressure crossover was not selected as the marker for mitral closure, since equilibration of left ventricular and pulmonary capillary wedge pressure frequently subjected this determination to large temporal error.

Time intervals related to mitral valve opening and closure were examined and compared. These included the isovolumic relaxation period (IRP), from A2 to either hemodynamic intersection (IRP1) or echocardiographic D' point (IRP2); the Q-closure interval (QCI1), from the first transient of the QRS to either onset of LV systole (QCI1) or the echocardiographic C1 point (QCI2); and the diastolic filling period (DFP), from either hemodynamic (DFP1) or echocardiographic (DFP2) opening to closing events. The arithmetic mean for each interval was obtained from two to five consecutive cardiac cycles. Of the fourteen patients in this study, eleven had significant coronary artery disease and three were normal. None had significant valvular heart disease. Hemodynamic alterations were induced with radiopaque contrast medium, angiotensin infusion, or atrial pacing to obtain a broad range of values for each of the time in-

Figure 1
Representative recording of simultaneous electrocardiogram (ECG), phonocardiogram (Phono), echocardiogram of the anterior leaflet of the mitral valve (ALMV) with left ventricular (LV) and pulmonary capillary wedge (PCW) pressures. The isovolumic relaxation period (IRP) was measured from the aortic second sound (A2) to either the intersection of the extrapolated "V" wave with the left ventricular pressure (IRP1), or to the onset of most rapid anterior motion in early diastole, D' (IRP2). The Q-closure interval (QCI) was measured from the onset of the Q wave to either the onset of LV systole (QCI1) or to the termination of the last rapid posterior motion in end diastole, C1 (QCI2).

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tervals. Five additional normal patients were studied in the noninvasive laboratory to assess the effects of the respiratory cycle and of transducer position upon the observed echocardiographic intervals. These studies were recorded on an IREX Continutrace Recorder.

Results

The isovolumic relaxation period, the Q to closure interval, and the diastolic filling period measured hemodynamically correlated significantly \((P \leq .01)\) with echocardiographically measured intervals over a wide range. Hemodynamically and echocardiographically determined IRP were related by:

\[
IRP_H = (.97) IRP_E + 30 \text{ (SEM \pm 8 msec)}; \\
\text{ } r = .89 \text{ (fig. 2a)}. 
\]

Echocardiographic \(D'\) followed hemodynamic crossover by 27 to 30 msec over the observed range of isovolumic relaxation periods. Hemodynamically and echocardiographically determined Q-closure intervals were related by:

\[
QCI_E = (.68) QCI_H + 37 \text{ (SEM \pm 7 msec)}; \\
\text{ } r = .71 \text{ (fig. 2b)}. 
\]

Echocardiographic \(C_0\) followed the onset of LV systole by 18 to 37 msec over the observed range of Q-closure intervals. Hemodynamic and echocardiographic diastolic filling periods were related by:

\[
DFP_E = (.98) DFP_H + 10 \text{ (SEM \pm 18 msec)}; \\
\text{ } r = .98 \text{ (fig. 2c)}. 
\]

There was a slight but insignificant increase in the echocardiographically determined isovolumic relaxation period \(IRP_E\) to 4 msec during inspiration, while respiration did not alter the length of the echocardiographic Q-closure interval \(QCI_E\) among the five control subjects. Movement of the transducer to an incorrect position altered the echocardiographic IRP to a greater extent because the point of onset of rapid anterior motion occurred earlier when the amplitude

Figure 2

The above computer plots compare hemodynamic and echocardiographic intervals. The plots represent raw data. a) Isovolumic relaxation period (IRP HEMO vs IRP ECHO); b) Q-closure interval (QCI HEMO vs QCI ECHO); c) Diastolic filling period (DFP HEMO vs DFP ECHO).

Figure 3

Simultaneous recording of the electrocardiogram, phonocardiogram and anterior leaflet echo with respiration to indicate two different transducer positions. a) Maximized anterior leaflet amplitude \(IRP_E = 75 \text{ msec}, QCI_E = 60 \text{ msec}\). b) Superomedially directed transducer near mitral valve ring \(IRP_E = 60 \text{ msec}, QCI_E = 63 \text{ msec}\).
of the mitral valve echocardiogram decreased. Thus, in two of the five control patients the echocardiographically determined IRP erroneously appeared shortened by as much as 20 msec \((P \leq .05)\) when the transducer was directed toward the mitral valve ring (fig. 3). In addition, the point of onset of rapid anterior motion became increasingly difficult to define as the anterior leaflet echocardiogram amplitude diminished. In addition, there was insignificant apparent increase in the echocardiographically determined Q to closure interval as the transducer was oriented toward the valve ring. In one patient the difference was significant \((P \leq .05)\) as the interval was lengthened by 8 msec. In view of the small but occasionally significant movement in the onset of rapid anterior motion and the termination of last rapid posterior motion, all correlative data were obtained with the transducer in a position which maximized the amplitude of the mitral valve echocardiogram.

Discussion

Recent interest in the clinical value of noninvasively determined time intervals within the cardiac cycle\(^{13-15}\) has led to a re-examination of currently available techniques which indicate mitral valve opening and closure. The silence of mitral valve opening excludes the use of the phonocardiogram to indicate this event, and the relationship between the first heart sound and mitral valve closure is not clear.\(^{16}\) The "O" point of the apexcardiogram has been the most widely used marker of mitral valve opening\(^{17-19}\) but recent work demonstrates a substantial and variable delay between the "O" point and the opening snap of mitral stenosis\(^{20, 21}\) and a closer relation of the "O" point to the nadir of the left ventricular pressure than to pressure crossover.\(^{22}\) Furthermore, the need for meticulous attention to technique,\(^{23}\) substantial artifact,\(^{24}\) and the significant proportion of individuals who lack a suitable apex pulse\(^{25}\) have hampered the usefulness of this technique. Furthermore, there is no clear marker of mitral valve closure on the apexcardiogram.

The ultrasonic Doppler technique has been used to identify rapid motion association with mitral valve opening and closure.\(^{26}\) However, instrumentation for this technique is not widely available, and it has not been extensively applied.

Though the morphology of the echocardiogram of the anterior leaflet of the mitral valve has been described for over a decade, there have been few studies relating precise details of that echocardiogram to specific events of the cardiac cycle. In the present study in man and in another study in canines,\(^{10}\) echocardiographic markers of mitral valve opening and closure were demonstrated to be significantly related to hemodynamic markers of these events.

Since Edler's original description of the echocardiogram of the anterior leaflet of the mitral valve\(^{2}\) there has been no general agreement as to what constitutes the best echocardiographic reference point for identification of mitral valve opening. The original description of the "opening wave" of the ECHO encompasses the period from a point D to the maximum anterior excursion E in early diastole (fig. 4a). Early control data in man were reported where the mean interval from aortic closure \((A_2)\) to D was 25 msec (range 10-50 msec).\(^{26}\) This would suggest that point D precedes the left atrial-left ventricular pressure crossing, since the normal isovolumic relaxation period has

**Figure 4**
Simultaneous recording of electrocardiogram, phonocardiogram and mitral valve echocardiogram. a) The maximized anterior leaflet with onset of rapid anterior motion at D. b) Slightly more inferiorly placed transducer includes the posterior leaflet. Note that separation of leaflets occurs at point D within 40 msec of the aortic second sound \((A_2).\) "D" occurs 85 msec after \(A_2.\)
been measured to be 82 msec (range 55-100) hemodynamically in man.27

Others have suggested that the early diastolic separation of the anterior and posterior leaflets identifies the opening point.1 However, figure 4b illustrates that separation of the mitral leaflets occurs within 40 msec of A2 and may represent bowing of both leaflets in opposite directions during early isovolumic diastole. Thus, echocardiographic separation is apparent substantially before actual separation of the free edges which occurs about the time of hemodynamic crossover.10 Kingsley et al.8 suggest that opening occurs just after the beginning of the anterior upstroke of the ECHO in early diastole, while Zaky et al.4 describe early anterior bowing just prior to the valve opening.

In the present study, the onset of the most rapid anterior motion in early diastole D' (figs. 1, 3, 4) was used as the marker of mitral opening and the termination of the isovolumic relaxation period. The use of D' as a marker was suggested by cineroentgenographic observations of mitral valve motion, where the separation of free edge clips occurred just before the onset of rapid anterior motion of the anterior leaflet following anterior bowing in early diastole.10 In addition, D' is easily defined. Since both hemodynamic and echocardiographically determined intervals use the same marker (A2) to define aortic closure, the relationship between echocardiographically and hemodynamically defined opening can be evaluated from the regression line relating IRP E and IRPH. The significant correlation of echocardiographic D' with the hemodynamic marker of mitral valve opening (r = .89, P ≤ .01, fig. 2a) confirms the usefulness of the echocardiogram of the mitral valve anterior leaflet as a marker of mitral valve opening. These results are similar to recent canine studies in this laboratory which demonstrated a significant correlation between rapid anterior motion D' and the hemodynamic marker of opening of the mitral valve.10 An interval of 30 msec occurred between D' and the hemodynamic marker of the mitral valve opening, and a similar interval was observed in the canine studies.

It has been suggested that mitral valve closure occurs at the most posterior point on the anterior leaflet echocardiogram, designated as point C (fig. 4a).2,4,6 However, the possibility of closure just prior to point C has been discussed and supported by Effert7 who found that the C point consistently followed the mitral component of the first heart sound. Others have proposed that mitral valve closure occurs at the point of coaptation of the anterior and posterior leaflets on the echocardiogram and have also labeled this point C.8,9 One recent study4 demonstrates that closure so defined preceded the mitral component of the first heart sound by 20 msec.

In the present study, the termination of the last rapid posterior motion in end diastole (C0) was selected to indicate closure for several reasons. The traditional C point defined by the most posterior movement is occasionally difficult to define. In addition, since the C point most often coincided with or followed the mitral component of the first heart sound,2,7 which has been shown to lag hemodynamic crossover by 25 to 30 msec,16 the point of most posterior motion must be a late manifestation of mitral valve closure. Finally, coaptation of the anterior and posterior leaflets is a less desirable marker since a discrete point of coaptation may be difficult to define in the majority of patients.

The significant correlation of the echocardiographic point C0 with the hemodynamic marker of mitral valve closure (r = .71, P ≤ .01, fig. 2b) confirms the usefulness of the echocardiogram of the mitral valve anterior leaflet as a marker of mitral valve closure. The higher correlation found in the canine study (r = .96)16 likely resulted from a more easily defined point of onset of left ventricular systole. An interval of 18 to 37 msec occurred between C0 and the hemodynamic marker of mitral valve closure. A similar interval was observed in the canine studies. A delay of approximately 20 msec has been demonstrated in the canine preparation between an echocardiographic trace of the mitral valve anterior leaflet and clips on its free edge.10 Thus one might speculate that the echocardiographic markers D' and C0, when corrected for such delays, may approximate the hemodynamic markers of opening and closure.

The small but significant shift in the onset of rapid anterior motion and the termination of the last rapid posterior motion as the transducer position is altered indicates a need for a standardized position (maximized leaflet excursion) when comparing intervals longitudinally in a single patient or among different patients. Though the normal respiratory cycle has little influence upon the echocardiographic markers of opening and closure, it would seem prudent to observe sequential intervals over an entire respiratory cycle to obtain a mean value.

In conclusion, a noninvasive technique for the determination of hemodynamic markers of mitral valve opening and closure in man has been described. This technique employs the increasingly available echocardiograph and the technical ease of obtaining an adequate echocardiogram of the mitral valve anterior leaflet. Simultaneous recordings of the electrocardiogram, phonocardiogram, and the carotid pulse tracing with the mitral valve anterior leaflet echocardiogram may be used to determine systolic and diastolic time intervals and to study the
relationship of cardiac events to mitral valve opening and closure.

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