Left Atrial Electrokymography in Mitral Insufficiency in Man

A Correlative Study by Angiocardiography and Left Heart Catheterization

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The relationship of the left atrial border movements to underlying pressure and volume changes was investigated in individual human subjects with proved mitral insufficiency. Based on these observations, criteria for the recognition of hemodynamically significant mitral insufficiency have been revised. Special emphasis is placed on a rapid inward movement of the atrial wall during the period of early diastolic emptying. Application of these criteria to a group of patients with surgically proved valvular lesions suggests that they are more reliable than those previously described.

The development of the electrokymograph by Henny and co-workers was followed shortly by its application to the study of left atrial border movements in mitral valve disease. Certain criteria were established on the basis of clinical correlations and theoretical considerations for the recognition of mitral insufficiency. Subsequent study of normal subjects, however, as well as correlations with surgical observations, cast some doubt on the reliability of these criteria. As a result, the electrokymograph has been generally supplanted by other diagnostic methods for the detection of mitral insufficiency.

The complex origin of the records that represent movements of the left atrial border makes their interpretation difficult. Not only may they represent displacement, rotation, and volume change, but, due to the central position of the chamber, they may theoretically be altered by superimposed variations of density of the pulmonary vasculature or aorta, depending upon the projection. No study to date has comprehensively investigated the basic relationship of these border movements to underlying pressure and volume changes in individual human subjects. Frequent reference is made to the studies of Wiggers and Pei on acute, experimental mitral insufficiency in dogs, which correlated left atrial pressure and volume changes. Andersson described similarities between left atrial pressure and electrokymographic curves in 2 patients. Recently these curves have been studied in experimental mitral insufficiency in dogs in our laboratory. The application of electrokymography, angiocardiography, and left heart catheterization to patients undergoing mitral valve surgery now allows a more accurate documentation of these interrelationships in man.

With these considerations in mind, we have undertaken a reappraisal of the electrokymographic criteria for mitral insufficiency by correlating left atrial border movements with atrial volume variations as determined by angiocardiography, and with pressure curves obtained by left atrial puncture. In the interest of completeness, the original electrokymograms in experimental mitral insufficiency have been critically re-evaluated. On the basis of criteria established by these observations, left atrial electrokymograms from a group of 44 patients who ultimately underwent mitral surgery were evaluated for evidence of mitral insufficiency.

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METHODS

Electrokymographic tracings were made with the patient sitting erect, with breathing suspended in midinspiration. Recordings were made in the frontal position over the left atrial appendage and, when possible, over the right border of the left atrium. Right and left anterior oblique and lateral projections were also used to record atrial movements, both directly and from the adjacent barium-filled esophagus. Most records were obtained with a Cambridge* electrokymograph coupled to a Cambridge Simplitrol string galvanometer, with a simultaneous phonocardiogram and carotid sphygmanogram. More recently an Elema† dual phototube electrokymograph system and Mingrafft jet writer have been used with electroangiographic timing. Film and paper speeds of 50 mm. per second were routinely employed.

Angiocardiography was carried out by rapid, manual injection of 50 ml. of 70 per cent sodium acetizolate (Urokon+) in the antecubital vein, with the patient sitting in the posteroanterior, left posterior oblique, or left lateral projection, at a target film distance of 36 inches. Exposures of 1/15 or 1/10 second were obtained at rates of 1.3 or 2 per second, and registered on a simultaneous electroangiogram. The patient was instructed to hold his breath in full inspiration during the anticipated period of left heart opacification. Films were selected where the left atrial border was sharply demarcated in its entirety, and its outline was pencilled to facilitate measurement of the area (fig. 1). As a rule the atrial margins were quite sharp, except during atrial systole, despite the relatively long exposures. The atrial appendage, however, had to be excluded because of indistinct outline, and arbitrary straight lines were drawn across the base of the pulmonary veins. The average of 2 measurements of the area obtained with a polar planimeter (seldom differing as much as 1 cm.2) was plotted against the exposure instant in the cardiac cycle. In this way a curve of the relative cyclic variations of the left atrial area was obtained. In 2 patients curves were obtained in both frontal and lateral projection. Since these had almost identical shapes, it was assumed that a single area curve was representative of variations of relative atrial volume. Corrections for image magnification, necessarily different for each patient, were not made, since our interest lay only in relative variations.

Left atrial pressure records were obtained by transthoracic puncture with a thin-walled 18-gage needle as described by Björk and associates. Pressures were recorded directly from the needle with a Statham pressure transducer (P23G) and a modified Grass† electroencephalographic direct writer.

In evaluating the electrokymographic tracings from candidates for valvulotomy, the criteria developed from the studies mentioned were applied without knowledge of name, clinical findings, or surgical findings. Patients were graded into 2 categories: no insufficiency or insignificant insufficiency, and predominant, clinically significant insufficiency. The latter diagnosis was decided on if typical patterns were clearly identified.

Critique

Most of the factors that are likely to cause electrokymographic records to be unsatisfactory or erroneously interpreted in mitral disease can be recognized. They can be separated into the following categories:

1. Failure to obtain representative tracings due to: inability of the patient to cooperate by sitting immobile and suspending respirations; pleural or pericardial effusions; obscure left atrial borders (usually due to massive cardiac enlargement); rapid or very irregular rhythm; and inaccurate position of the slit.

2. Failure of the electrokymogram to reflect the underlying physiologic changes due to: a large left atrial clot; and giant atrial size or other factors (calcification, fibrosis) resulting in rigidity of the wall.

3. Additional hemodynamic abnormalities that alter the pattern, such as aortic valve disease and congestive failure.

4. Lack of quantitation of the pulse amplitude. Without a method of standardization, considerable distortion can be introduced via indiscriminate manipulation of the amplifier gain. If the amplitude of the deflections could be measured in absolute units, calculation of the slope of the various emptying curves could be expected to improve the reliability of the method. This problem is under consideration.

In spite of these drawbacks, the electrokymogram has certain advantages. It is simple. It can be performed by a single person in 20 to 30 minutes following routine fluoroscopy. It carries no hazard for the patient. It causes no discomfort. With an understanding of the underlying hemodynamics reflected by the electrokymographic pattern, its interpretation may be placed on a more rational and reliable basis than previously. Left atrial (and ventricular) puncture may then be necessary only in very select cases.

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At simple venous angioangiography the circulation of contrast material through the heart is sufficiently prolonged by mitral valve disease so that filming rates of 1 to 2 per second will provide 8 to 10 films showing a well-opacified left atrium. These are generally, although not always, scattered in random fashion throughout the heart cycle. If their position in the cycle is known through a timing device, one can measure diameter, circumference, or area of the left atrium, and gain some idea of the relative cyclic volume variations.

The method has distinct limitations, and even under fortunate circumstances supplies only a minimum of points for plotting a curve; (ideally, 15 to 20 films in 2 planes at right angles in a single cardiac cycle with some mechanical event for timing would be desirable). The method used requires that the heart rate be regular but asynchronous with the filming rate. Respiration must be suspended to prevent motion. In some instances, through an unintentional Valsalva effect, there may be progressive reduction of venous return so that diastolic filling of the atrium is not uniform for each cycle. A number of circumstances may invalidate the method: rapid circulation as in the normal; atrial fibrillation with an irregular ventricular rate (found more often than not in serious mitral disease); synchronous heart and filming rates; uncontrolled respiration; unsuccessful timing; poor angioangiographic technic resulting in indistinct atrial margins. Due to 1 or more of these factors, satisfactory curves could be drawn for only 11 of 45 patients with mitral disease studied. Surgical exploration was performed in 9 of these and disclosed high grade stenosis in 5 and predominant insufficiency in 4.

Observations and Results
Relation of Left Atrial Border Movements to Volume Variations

The left atrial volume variations in mitral valve disease follow simple curves with minima occurring at or slightly after the Q wave and maxima at about the end of the T wave (fig. 2). A more accurate statement cannot be made because of insufficient observations at the critical points, but the basic patterns are consistent. They correlate well with the mechanical events known to occur at these times, and with other angioangiographic observations.

The ascending or filling limb of the curve is steep in both stenosis and insufficiency and would not allow their differentiation based on its form alone, according to our very limited observations (fig. 2). The descending or
emptying limb, however, has distinctive patterns. In mitral insufficiency emptying is rapid and quite complete shortly after its inception. In all but 1 instance the chamber emptied faster than it filled. This emptying pattern is to be expected, for, as will be seen, the pressure gradient is high at this time and there is no mechanical impediment to flow. It is reassuring to find a very similar curve in the pioneering studies on mitral insufficiency by Wiggers and Feil.\textsuperscript{5} Our tracings, however, lack the secondary distention of the atrium late in ventricular diastole, as shown in their curve.

The emptying pattern is quite different in mitral stenosis. Some emptying occurs early in ventricular diastole, but most of it occurs later with atrial systole. The curve has a decided midepistolic convexity or plateau, for the mechanical obstruction to flow interferes with atrial decompression. During early diastole flow probably depends mainly upon maintenance of the pressure gradient by the elasticity of the left atrium and pulmonary veins. A more rapid decrease in volume then occurs with additional compression incident to atrial systole. (Since this work has been completed a similar independent angiocardiogram of emptying in mitral stenosis, with a similar pattern of atrial emptying, has been reported by Beall and associates.\textsuperscript{4})

\textbf{FIG. 2.} Cyclic variations in left atrial area in surgically proved patients with either dominant mitral stenosis or insufficiency. Scale is square centimeters. \textit{Vertical lines}, Q wave; \textit{crossed lines}, end of T wave. Contradicting measurements at the same time are averaged. Slight irregularities on both ascending and descending limbs might be plotted in some curves, but this is doubtfully permissible within the accuracy of the method.

\textbf{FIG. 3.} \textit{Top.} Patient LR. Mitral insufficiency (surgically proved). Correlation of left atrial border movements (electrokymogram) and relative atrial volume (L.A. area). Heart rates, indicated on the left, are not identical. \textit{Bottom.} Patient RP. Mitral insufficiency (surgically proved). Correlation of left atrial border movements (electrokymogram) and relative atrial volume (L.A. area). Heart rates, indicated on the left, are nearly the same. Electrokymograms were recorded from the left atrial appendage (L.A.A.) and left atrium (L.A.).
graphic determination of the relative volume variations of the left atrium in mitral disease has been published by Arvidsson and Odman. More rapid filming simultaneously in 2 planes allowed the preparation of curves quite similar to those described above. The authors note the same features of the atrial emptying patterns and further suggest that the atrial filling curve may be somewhat steeper in mitral insufficiency. The amplitude of the relative volume variations was greater in insufficiency.)

In all 4 cases of mitral insufficiency the electrokymogram invariably showed an inward movement in early ventricular diastole. Its onset, shortly after the second heart sound, followed closely the maximal outward position. Comparison of curves in 2 cases shows great similarity between volume changes and border movements throughout ventricular diastole (fig. 3).

In mitral stenosis movements during ventricular diastole followed the volume curves also (fig. 4). The relatively prolonged inward movement of large amplitude, during atrial systole, as emphasized by Andersson, is quite distinctive.

The movement and volume curves are not always similar throughout ventricular systole, however. The electrokymogram often shows an inflection and sometimes a distinct downward deflection (inward atrial movement) during early ventricular systole in both mitral stenosis and insufficiency. There is no suggestion of comparable change in the volume curves. Yet, as we have said, our data in this period are inadequate. Nevertheless, this is the period for the atrium to fill from the pulmonary veins, so that no decrease in volume can be reasonably expected. This movement, then, is probably a matter of atrial displacement or change in shape, occurring in time with the descent of the atrioventricular ring, and obscuring a coincident increase in volume.

In addition to defining the qualitative resemblance of the atrial border movements to volume changes, angioelectrokymographic also gives a clear indication of their relative magnitude.

Figure 5 is representative of many experiences showing that the bulk of chamber-size variation is not necessarily reflected in surface movement. Wide oscillations of the atrioventricular rings allow reciprocal changes in atrial and ventricular volumes with relatively little surface movement.

Relation of Left Atrial Border Movements to Intracavitary Pressure Changes

A further understanding of the left atrial border movements in mitral valve disease has resulted from comparisons of the electrokymogram with the direct left atrial pressure tracing from the same patient. This has been possible in 11 cases to date. Nine of these were surgically verified, 5 showing predominant stenosis and 4 predominant insufficiency. Two were not operated on because of convincing evidence of predominant insufficiency. The electrokymographic pressure studies were not simultaneous, so that the conclusions that may be drawn from them must be limited. Furthermore, the electrokymographic studies were made with subjects erect with phonocardiographic timing, whereas pressure studies were made with subject prone with electrokardiographic timing. Despite these factors, an obvious qualitative similarity may be recognized in records from the same patient.

The form of the left atrial pressure tracing in experimental mitral insufficiency is well
established\textsuperscript{5, 12} and correlates with recently reported clinical records.\textsuperscript{13, 14} There is some reduction of the normal descent that follows the C wave in early ventricular systole, but the striking feature is the large, late systolic V wave (or so called regurgitant wave). The importance of a steep descent with rapid disappearance of a measurable gradient between left atrium and ventricle in early diastole has been stressed by Owen and Wood.\textsuperscript{15} Our records have shown these characteristic features in all instances of predominant insufficiency. From some cases of mitral stenosis with slight insufficiency we have obtained similar pressure curves, but there was the distinguishing feature of a diastolic gradient across the mitral valve in these patients.

There were similarities between the pressure record and the border movement tracings in all of our cases. With atrial fibrillation this was true throughout the entire cardiac cycle. Where a normal sinus mechanism prevailed, it was true except during atrial systole, when inward movement was accompanied by increased pressure. The form of the electrokymogram in surgically proved cases of insufficiency had the same general outline as the pressure record. Figure 6 shows one example. Figure 7 shows 4 other cases demonstrating the similarity of the pressure-electrokymogram relationship. Thus, it would seem that the left atrial border movements qualitatively reflect variations in pressure except during atrial systole.

\textit{Electrokymographic Records in Experimental Mitral Insufficiency}

The records of experimental studies carried out with Nordenström and co-workers\textsuperscript{7} were reviewed. In 3 dogs with chronic mitral insufficiency and considerable left atrial dilatation border movements were similar. The prominent inward movement noted preoperatively in early ventricular systole was partially or completely effaced. The curve became essentially a single, large wave, rising to a peak in late ventricular systole and falling more rapidly than it rose in early ventricular diastole. Inward movement during atrial systole was reduced in amplitude and, because of tachycardia, merged with the early diastolic descent. In the fourth animal with acue
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mitral regurgitation and with no recognizable left atrial dilatation, the only change was the appearance of a large positive wave in late ventricular systole.

**Correlation between Surgical and Electrokyographic Evidence of Mitral Insufficiency**

On the basis of these observations, certain criteria were developed for the recognition of clinically significant mitral insufficiency by the left atrial electrokymogram (fig. 8). (A) A distinct and prominent outward (upward) movement in early systole synchronous with valve closure, succeeded by, (B) an inward (downward) movement, forming a trough of from 0.08 to 0.16 second duration in mid-systole, (C) a late systolic wave of greater amplitude than the initial peak with a gradual upward slope, (D) rapid collapse of this wave in early diastole, with return to baseline within 0.12 second, (E) complete or almost complete absence of inward (downward) movement due to atrial systole.

Electrokymograms from 44 patients who had surgical or pathologic verification of their lesions were evaluated without knowledge of
name, clinical data, or surgical findings. Wave patterns fulfilling the above criteria were searched for and, if clearly present in one or more projections, were considered indicative of significant mitral insufficiency. Patients were divided into 2 groups of absent or insignificant insufficiency and predominant insufficiency. The principal valvular lesion was correctly predicted in 9 cases of proved mitral insufficiency and in 33 cases of proved stenosis. Two patients with significant insufficiency failed to show a characteristic wave form in the available tracings (fig. 9).

Other observations of help in differentiating the basic valvular lesion can be made in retrospect. 1. With insufficiency of more severe degree deflections A and B (fig. 8) became smaller, while C and D increased in size. 2. With sinus rhythm the atrial systolic descent was broad and deep in severe mitral stenosis. 3. Border movements were of relatively greater amplitude with predominant insufficiency than with predominant stenosis. 4.

Atrial fibrillation tended to accentuate the electrokymographic signs of insufficiency.

**FIG. 8.** Diagrammatic representation of a normal and insufficiency curve, showing features important in recognizing predominant mitral insufficiency by the electrokymogram. The rapid inward movement in early diastole in the lower curve, representing unimpeded atrial emptying, is of great diagnostic importance. Criteria include: An inflection, A, in early systole synchronous with valve closure. A deflection forming a trough, B, of from 0.08 to 0.16 second duration in midsystole. A late systolic wave, C, of greater amplitude than the initial peak, A. Rapid return of this wave to the baseline, D, within 0.12 second. Reduction in the duration and amplitude of the inward movement, E, due to atrial systole.

**FIG. 9.** Representative electrokymograms from 2 cases in which border movements failed to correlate with the surgical findings. A. Predominant mitral insufficiency: Electrokymogram failed to show diagnostic pattern, despite the presence of atrial fibrillation. B. Aortic stenosis and insufficiency: Electrokymogram suggested mitral stenosis (prominent inward movement present with atrial systole). Another patient with this combined lesion showed a similar pattern.

**DISCUSSION**

"Systolic expansion" of the left atrium (apparent enlargement of the atrium during ventricular systole) with mitral regurgitation was first described clinically by Owen and Fenton in 1901 and radiologically by Holzknecht in that same year. Its value as a sign of insufficiency has been repeatedly emphasized (most recently by Brigden and Leatham). Elkin and associates, however, have reported this fluoroscopic finding in both stenosis and insufficiency. We believe that our angiocardiographic and electrokymographic observations make it perfectly clear that to speak of "systolic expansion" of the left atrium with reference to the differentiation of mitral stenosis and insufficiency is meaningless. In either case (figs. 1-5), rapid filling of the atrium occurs during ventricular systole, whether from pulmonary veins alone or from the veins and left ventricle together. The difference lies not here, but in the manner of diastolic emptying, which is early and rapid with insufficiency, and prolonged and slow with stenosis. In our opinion the term "early diastolic collapse" would be more descriptive of the altered left atrial border movements in mitral insufficiency.
Early workers established criteria for normal atrial border movements\(^{20-24}\) and pointed to distortion of this pattern with the development of a "systolic plateau" in mitral regurgitation.\(^{25-28}\) The reliability of this sign was very quickly disputed, however, as a result of reports of plateau curves in normal subjects\(^ {29-31}\) and in cases of pure mitral stenosis.\(^ {30, 32}\) Haring, Liu, and Trace\(^ {33}\) again emphasized a "plateau" contour of both the pressure and border movement records during ventricular systole, designating them "early," "intermediate," or "late," depending on their timing. There is no question that the contour of the left atrial electrokymogram changes during ventricular systole in both experimental and clinical mitral insufficiency. The normal descent during early ventricular ejection (fig. 8) may be distorted or effaced, and there is a definitely prominent upward movement throughout the last half of systole. But these changes are seldom of "plateau" configuration and of themselves are not distinctive. The rapid, early diastolic descent gives the curve its diagnostic contour. This inward movement is identical in time to the early diastolic decrease in left atrial volume, left atrial pressure (measured directly\(^ {12}\) and indirectly,\(^ {15}\)) and esophageal pressure\(^ {34, 35}\) in patients with surgically verified mitral insufficiency. Neither the volume nor the pressure changes in the left atrium are characterized by an abrupt prolonged systolic rise to a plateau. In our opinion, the accumulated evidence indicates that the descriptive term "systolic plateau" has no relation to underlying hemodynamic events and is therefore not a justifiable basis for the electrokymographic diagnosis of mitral insufficiency.

Based on the described observations, our concept of the relation of left atrial border movements to changes in volume and pressure can be stated simply. The movements during ventricular systole are qualitatively similar to pressure changes, while the diastolic movements are qualitatively similar to volume changes. The details in relation to mechanical events are as follows.

The initial outward movement during isometric contraction of the ventricle may be either positional or volumetric, for while the mitral valve is closed and thrust up into the floor of the atrium, the atrial volume has begun to increase by filling from the pulmonary veins. The recession that follows, coincident with rapid ventricular ejection and downward movement of the atrioventricular ring, is purely positional, for there is continued increase in the volume at this time. This recession is reduced or absent in mitral regurgitation. Our studies suggest that this change is most likely due to enlargement of the left atrium and distention of the pulmonary veins (features regularly present in mitral valvular disease) that might be expected to reduce their mobility without reducing the movements of the atrioventricular ring (figs. 1 and 2). In the experimental records a normal systolic recession was demonstrated only in the animal with acute insufficiency and no left atrial enlargement. This hypothesis provides explanation for the similarity of the systolic contour of the electrokymogram in mitral stenosis,\(^ {6}\) where atrial dilatation is likewise present.

The atrial position in late ventricular systole and its movements during rapid ventricular filling and diastasis are qualitatively similar to both volume and pressure changes. This period, when the atrium passively reflects these phenomena, is the most important for the differentiation of mitral insufficiency and stenosis.

Atrial movements during atrial systole are qualitatively similar to changes in volume and are inversely related to pressure. Atrial emptying limited mainly to atrial systole is a feature of mitral stenosis (with normal sinus rhythm) and is not found in pure mitral insufficiency.

This simplified account of these relationships is much the same as that given in more detail by Andersson.\(^ {6}\) It neglects the atrial surface used for recording and other seemingly minor influences, such as change in atrial shape or rotation. We claim no origi-
It must also be clear that the inward movement in early ventricular diastole upon which we place emphasis does not specifically identify mitral insufficiency. It means simply that there is no impediment to left atrial emptying at this time. It occurs normally and it means mitral insufficiency only in established cases of mitral valve disease by excluding, with rare exception, significant mitral stenosis.

SUMMARY

Correlation of the left atrial electrokymogram with volume variations and pressure curves in experimental and clinical mitral insufficiency has resulted in a greater understanding of the basis for the changes observed in the border movements. The form of the electrokymogram in ventricular diastole appears to reflect primarily changes in the volume of this chamber. The pattern during ventricular systole seems to be a combination of slight changes in atrial position or shape superimposed on an expanding atrial volume. Based on these observations, criteria for the recognition of hemodynamically significant mitral insufficiency by the electrokymogram have been revised. Special emphasis is placed on a rapid inward movement of the atrial wall during the period of early diastolic emptying. Application of these criteria to a group of patients with surgically proved valvular lesions suggests that they are more reliable than those heretofore described.

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SUMMARIO IN INTERLINGUA

Le correlazione del electrokymogramma sinistro-atrial con variationes de volume e curvas de pression in insufficientia mitral experimental e clinic ha resultate in un clarification del bases del alterationes observate in
le movimenti marginal. Le forma del electrokymogramma in diastole ventricular parte reflecter primarmente alteraciones in le volume de iste camera. In systole ventricular le conformation electrokymographic parte reflecter un combination de leve alteraciones del position o del forma atrial superimponite a un volume atrial in expansion. Sper le base de iste observationes, le criterios pro le recognition electrokymographic de hemodynamicamente significatieve mitral ha essite reformulate. Attention special ha essite prestate al rapide movimento introrse del pariete atrial durante le periodo del vacuation diastolic initial. Le application de iste criterios a un gruppo de patientes con chirurgicamente provate lesions valvular parte indicar que illos es plus solide que le criterios descritbe in le passato.

REFERENCES


The authors on the basis of 21 cases proved at surgery come to the conclusion that no characteristic roentgenologic picture exists, that the typical small heart was present about half of the time, while the others were moderately or even markedly enlarged. Right ventricular and atrial enlargement occurred in 11 of 18 cases. Pulmonary artery dilatation involving the trunk and hilar branches occurred frequently, as did pulmonary congestion. The superior vena cava was frequently observed to be dilated, often involving also the adjacent azygos vein. Pulsations were regarded as of diminished amplitude in two thirds of the cases. Kymographic tracings indicated an increased period of diastolic filling with a long, flat diastolic plateau, while the amplitude of excursions was significantly decreased in most cases. Four had distinctly normal pulsations, even though subsequent surgery indicated considerable pericardial thickening. The authors suggest that based on the presented evidence that such roentgenologic observations as cardiac enlargement, normal pulsations, and pulmonary arterial widening should not be considered incompatible with the diagnosis of constrictive pericarditis when clinical observations to the contrary are present.

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