Movements of the Mitral Valve

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Cinefluorographic analysis of mitral valve motion in intact dogs provided evidence that the motility of the valve cusps is restrained by tension exerted through the chordae tendineae throughout the cardiac cycle, except for the rapid filling phase. At the onset of ventricular systole, early contraction of the papillary muscles may play an important role in approximating the mitral valve cusps. During ventricular ejection, the mitral cusps and valve ring move toward the apex of the heart. During diastole, separation of the valve cusps is remarkably slight. The valves were observed to fling wide during rapid ventricular filling when the heart was much smaller than normal, immediately after surgery.

The current concepts of mitral valve function were derived primarily from anatomical analysis, supplemented by a few direct observations made on isolated hearts. For example, Haycraft1 presented evidence that papillary muscles generally shorten simultaneously with contraction of the ventricular walls. Henderson and Johnson2 described two mechanisms for valve closure based on studies of model valves and of isolated bovine mitral valves. Dean3 recorded movements of mitral valve cusps in isolated, perfused, feline hearts. Movements of the heart valves have also been directly observed and photographed in perfused hearts.4,5 Thus, valve function has been directly studied only in functionally isolated hearts except for occasional roentgenographic observations on calcified valves in humans.6

Overshadowing the few direct observations on heart valves is a voluminous literature on valve function in which heart sounds are related to mechanical and electrical events in the heart. Clearly, heart sounds are questionable criteria for valve action, particularly if the fundamental observations on isolated hearts are not entirely applicable to intact animals and man. The size of the heart and of the individual ventricular chambers has been shown to diminish markedly in thoracotomized dogs.7 Since the atrioventricular valves and chordae tendineae are fibrous structures, they probably do not participate in this “shrinkage” of the heart. Thus, there may be much more slack and mobility of the atrioventricular valves in isolated than in normal hearts. With the advent of plastic operations on diseased valves, specific information concerning their normal function has become increasingly important. For these reasons, movements of the individual mitral valve cusps have been studied in intact, unanesthetized dogs by cinefluorographic techniques.

METHODS

Motion pictures of fluoroscopic images (cinefluorography) provide a technique for studying the movement of any internal organ or structure which can be rendered radiopaque. The apparatus used for cinefluorographic recording in this laboratory has been previously described.8 Opacification of the mitral valves was first attempted by the injection of Lipiodal into the mitral valve ring at several sites. In some animals the Lipiodal was distributed widely throughout the mitral cusps, occasionally penetrating almost to the peripheral edge. However, this technique was abandoned for three reasons: (1) the valves were not well outlined because the Lipiodal was not uniformly dispersed, producing poorly circumscribed, diffuse opacities, (2) the valve cusps could not be consistently opacified by this technique, and (3) the most successful injections produced abnormal valves with large, bulbous excrescences, which appeared to be reactions to the presence of a foreign substance.

Delicate silver chains were surgically installed within the heart chambers in nine dogs. In these animals, they were fastened at one end to the atrial wall just above the atrioventricular valve ring, the other end swinging free within cardiac cavities. However, the currents of blood usually failed to carry the chains through the mitral orifice into the left ventricle, and their free ends remained within the atrial...
Fig. 1. A Doubled silver chain mounted with both ends fastened to the left atrial wall just above the mitral valve ring. Center of chain fastened only at the edge of the anterolateral mitral valve cusp (see also fig. 2A). B Instrument for insertion through the left atrial appendage into the left ventricular cavity. As it was withdrawn back through the mitral valve, the open clip near its tip caught the valve edge or chordae tendineae, and was crimped into place by pressing the plunger. C Single silver clip fastened at or near the edge of a mitral cusp in six animals. D Multiple clips fastened to valves or their adnexa in six animals.
cavity. It was therefore considered necessary to anchor the chains at both ends, leaving the central portion free to move in response to displacement of the valve cusps. In three animals, chains (3 to 4 cm. long) were sutured at one end to the atrial wall, passed through the mitral orifice and the other end fastened to the ventricular wall by elastic threads. Some of these chains became adherent to the valve cusps or to the chordae tendineae. One such chain passed through the edge of the anterolateral cusp during insertion.

Since it was apparent that movements of the valve cusps would be more reliably indicated by chains fastened at or near the edge of the valve, additional efforts were made in this direction. In one animal, a chain was anchored at both ends to the atrial wall just above the valve ring with its center fastened to the edge of the anteromedial mitral cusp (fig. 1A). In another dog, a chain passed through the ventricular wall to the edge of the posterolateral cusp and back through the ventricular wall (fig. 2B). Cinefluorographic films were obtained immediately after operation and at varying intervals until the animals were sacrificed (16, 3, 29, 85, 50, 13, 30, 87 days after operation, respectively). Although some of these preparations provided interesting information (fig. 2A, B), the chains frequently became stiffened by accumulated fibrin (fig. 1A) and could have interfered with normal valve action.

After several trials, an instrument was developed (fig. 1B) which would consistently fasten small silver clips to the edges of the mitral valve or to the chordae tendineae near their attachment to the valve cusps (fig. 1C, D). The end of the instrument holding the clip was passed through the atrial appendage and through the mitral orifice. As the instrument was gently withdrawn back through the mitral valve, a valve edge or chorda tendinea was caught in the open clip. Advancing the plunger crimped the clip in place. Rotation of the external barrel released the clip from the instrument. Single clips were applied to the valve cusps of six animals, and multiple clips (2 to 5) were applied in six more.

Cinefluorographic recordings, displaying the moving chains and clips, were obtained on 35 mm. film exposed at 30 frames/sec. These films were studied during repeated projection at normal and slow projection speeds and supplemented by tracings of the cardiac silhouette and metal markers from successive frames by means of a 35 mm. enlarger. When one tracing was superimposed on another, displacement of the various points of interest were observed. However, precise registration of the tracings was extremely difficult because all portions of the cardiac silhouette move somewhat during each cardiac cycle. For this reason, the initial interpretation of the tracings led to the erroneous conclusion that the valve edges moved toward the atrium during systole (see fig. 8B, chapter 13) which was contrary to the movements observed during projection. The analysis was repeated using a special 10 mm. projector developed by Weinberg, Watson and Ramsey* for flickerless projection of films at rates as slow as 6 frames/sec. Tracings obtained during single frame projection with this equipment provided accurate registration of successive frames (see fig. 2).

The temporal relations of the valve motion to ventricular systole and diastole were determined in three ways: (1) by observation of the borders of the cardiac silhouette, (2) by cinefluorographic angiocardiography (fig. 2A) and (3) by simultaneous recordings of heart sounds in some instances (fig. 2B). A 3 inch cathode ray oscilloscope was mounted next to the fluorescent screen so that the image of its face appeared in the corner of each frame on the cinefluorographic films. Heart sounds displayed on the cathode ray tube appeared on the appropriate frame in the film (fig. 2B). The identity of the two heart sounds could be easily established by observing the movements of the cardiac borders.

The movements of the clips as recorded cinefluorographically were much more re-

* This projector was obtained through the courtesy of Dr. Robert Bruce, Department of Medicine, University of Washington, Seattle, Wash.
restricted than anticipated. Since movements of the opaque markers in a direction perpendicular to fluoroscopic screen would not be detected on routine cinefluorograms, stereoscopic cinefluorographic equipment was developed specifically to study the movements of the valve markers in three dimensions.11

Results

The results of the study can be much more effectively visualized after having observed the films during projection. For this reason, some of the data was originally reported in the form of a motion picture.12 Even superficial examination of images during projection at normal speeds indicates that the mitral valve cusps generally display limited lateral motion during the cardiac cycle. Stereoscopic cinefluorography confirmed the restricted motion of the metal markers. Indeed, the metal markers fastened at the valve edges moved predominately along the longitudinal axis of the left ventricular chamber.

In motion pictures of isolated hearts,4 the valves appear to be flung wide open in early diastole, snap closed at the onset of systole and bulge toward the atrial cavity during ventricular ejection. Such wide and rapid lateral excursions of the valve edges were apparent on certain cinefluorographic films exposed immediately after operation, when the cardiac silhouette was much smaller than it had been on preoperative control films. This flapping type of valve motion may result from increased slack in the valves and chordae tendineae associated with the "shrinkage" of the ventricular myocardium which accompanies thoracotomy.7 In dogs which had fully recovered from surgery, the valves appeared to be held down within the ventricular cavity throughout both systole and diastole, apparently by tension exerted through the chordae tendineae. At no time during ventricular systole did the edges of the valve cusps move toward the atrium.

The results of the study are summarized by tracings, selected from those used for single frame analysis of the cinefluorographic films. The movements of a chain attached to atrial wall and to the edge of the anterolateral cusp of the mitral valve (fig. 1A) are illustrated in figure 2A. This particular sequence was obtained during cinefluorographic angiocardiography when the right atrium and ventricle were rendered opaque by contrast media. The atrial attachment of the chain at no. 1 moved downward during atrial systole without a change in the position of the valve edge at no. 2. During the next 1/30th sec. the chain straightened as the edge of the valve cusps was drawn toward the apex at no. 3. On the next frame, the chain had moved toward the septum as the valves opened during early diastolic filling (E.D.). The changes in the configuration of the right atrium and ventricle are illustrated by interrupted lines in the upper portion of the cardiac silhouette.

Movements of a chain, which passed through the ventricular wall, pierced the edge of the posterolateral leaf of the mitral valve, and extended on through the ventricular wall, are illustrated in figure 2A. The solid line indicates the position of the chain at the moment the first heart sound appeared on the cathode ray oscilloscope (C.R.O.), and the interrupted line indicates the chain's position at the second heart sound. Apparently, the basilar portion of the left ventricle and the edge of the valve cusps moved together toward the apex of the heart during ventricular systole. The posterolateral cusp was very short in this particular animal, and moved very little in relation to the atrioventricular ring.

Displacement of single and multiple clips on the anterolateral (aortic) cusp is illustrated in figure 2C. Note that in both instances, the edges of the valve moved toward the apex of the heart, while the mitral valve ring also descended. Thus, the mitral valve cusps were drawn down into the left ventricular cavity against the high pressure which develops during ventricular systole. During diastole, they first moved laterally and then rapidly reascended toward the atrium as the mitral valve ring moved in the same direction. Movement of clips applied to the posterolateral cusp of the mitral valve was consistently more restricted than that of the longer anterolateral (aortic) cusp.

Discussion

Current concepts of mitral valve function are based predominately on the direct recordings obtained by Dean3 from isolated, perfused, cat hearts. The atrioventricular ring was sutured.
to a fixed metal ring, and a human hair transmitted movements of the anterolateral cusp to a lever. Ventricular contraction was recorded by a thread between a recording tambour and the apex of the heart. In these experiments, closure of the valves was indicated by a movement toward the left atrium but this does not mean that the valves move toward the atria under normal conditions. In the intact animal, the apex of the heart remains relatively fixed in position, and the mitral valve ring and valve edges move toward the apex during systole.

The movement of the mitral valve toward the apex during ventricular systole is particularly interesting in view of recent observations indicating that the left ventricle assumes a more spherical configuration at the onset of systole. Continuous recordings of various left ventricular dimensions have demonstrated that the initial systolic elevation of ventricular pressure is accompanied by a pronounced lateral bulging of the walls. Since both sets of valves are closed when the intraventricular pressure rises, lateral expansion of the chamber must represent a change in the shape of the ventricular cavity without a change in its volume. Thus, during the initial phase of ventricular systole, the cylindrical left ventricular chamber tends to become more spherical because its length is actively reduced and its transverse diameter and circumference are passively expanded.

Reduction in left ventricular length implies that the closed mitral valve moves toward the apex, presumably by contraction of the trabeculae carnae and papillary muscles. The ejection phase of ventricular systole begins with a reduction in the transverse diameter and circumference, presumably due to contraction by the powerful cuff of deep muscle layers encircling the chamber. Thus, the sequence of contraction follows the sequence of excitation, papillary muscles and trabeculae carnae contracting first.

Considering their anatomical relationships, the papillary muscles should play an important role in mitral valve function. Chordae tendineae, originating from a papillary muscle, insert on both cusps of the mitral valve. Tension exerted by the papillary muscles on the chordae tendineae should draw the valve cusps toward a position of partial closure. Movements of the mitral valve cusps appear to be restricted during both systole and diastole, suggesting that the chordae tendineae and valve leaflets are normally under tension throughout the cardiac cycle.

These data suggest the following sequence of valve action. At the end of diastole, the ventricles are distended with blood, and the ventricular walls and papillary muscles are under elastic tension. Atrial systole adds an additional increment of blood which further distends the ventricular chambers, increasing the distance between the mitral valve ring and the root of the papillary muscles. This tends to increase the tension exerted through the chordae tendineae, drawing the valve cusps toward apposition. Incomplete or transient valve closure may occur immediately after atrial contraction due to a combination of factors, including: traction on chordae tendineae by ventricular distension, eddy currents impinging on the under surface of the valves or the interruption of the flow of blood from atria to ventricles as proposed by Henderson and Johnson. The valves may spread apart again unless ventricular contraction begins promptly after atrial systole. The mitral orifice is closed and tightly sealed only after ventricular pressure rises abruptly with the onset of ventricular contraction. Ventricular systole apparently begins with contraction of the papillary muscles and the trabeculae carnae. As the mitral cusps and mitral ring are pulled toward the apex, interventricular pressure rises, the valve orifice is sealed, the lateral walls are distended, and the chamber becomes sphericalized. Ejection of blood begins when the deeper myocardial layers begin to shorten, reducing the circumference and transverse diameter of the chamber. The longitudinal axis may continue to shorten during the ejection phase. As soon as left ventricular pressure drops below left atrial pressure, the valve edges separate and blood flows rapidly into the ventricular chamber. The valves do not normally gape wide, even during rapid filling. Apparently, a relatively narrow aperture between the valve cusps accommodates the rapid flow of blood from atrium to ventricle. As the ventricle fills, the ventricular walls become distended and the papillary muscles are also stretched. The papillary muscles...
may exert an elastic tension on the valve cusps even during diastole. Thus, the movements of the valve cusps are probably restrained by tension exerted through the chordae tendineae during the entire cardiac cycle except the phase of rapid ventricular filling. The early contraction of papillary muscles may play a decisive role in mitral valve closure. Such a mechanism appears essential to explain the restricted mobility of the valve cusps observed in this study. The clinical significance of this valvular mechanism in the production of murmurs during abnormal ventricular distention has been considered elsewhere.9

SUMMARY AND CONCLUSIONS

Radiopaque markers were applied to the mitral valve cusps, and their motion was recorded on cinefluorographic films.

Movements of the valve cusps were apparently restrained by tension exerted through the chordae tendineae during both systole and diastole. Such traction seems to hold the valve cusps in a position of partial apposition during diastole, and to draw the valves toward the apex during ventricular systole. Thus, early contraction of the papillary muscles may be essential for efficient mitral valve closure.

Rapid wide excursions of the valves were noted in certain animals when the cardiac silhouette was greatly reduced in size immediately after the operation. Unusually great slack in the valves and chordae tendineae apparently permitted the valves to fly open widely in response to the rapid blood flow in early diastole. This situation may obtain in isolated and exposed hearts, but does not appear to be characteristic of the intact normal animal.

SUMMARY IN INTERLINGUA

Marcas radio-opac esseva applicate al cuspides del valvula mitral, e lor motion esseva registrate super pelliculas cinefluorographic.

Le movimentos del cuspides valvular esseva apparentemente restringite per un tension exercite via le chordas tendinose durante systole e diastole. Il pare que iste tension mantene le cuspides in un postura de apposition partial durante le diastole e trahe le valvula verso le apice durante le systole ventricular. Assi le prompte contraction del musculos papillari es possibilemente essential pro le efficace clausura del valvula mitral.

Rapide excursiones distante del valvulas esseva notate in certe animales quando le silhouette del corde esseva grandemente reducec immediatemente post le operation. Un inusualmente grande relaxation del valvulas e chordas tendinose pareva permette al valvulas aperir se grande- e rapidemente in responsa al rapide fluxo de sanguine durante le initio del diastole. Iste situation pare esser characteristic de isolate e exponite cordes, sed illo non es apparentemente un phenomono normal in animales intacte.

REFERENCES

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Circ Res. 1956;4:337-342
doi: 10.1161/01.RES.4.3.337

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

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