The Left Atrial Pressure Pulses in Experimental Mitral Valve Lesions

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Comparative studies of left atrial electrokymograms, left atrial pressure tracings, and pulmonary wedge pressure tracings were made in dogs with experimental mitral insufficiency or stenosis. Typical patterns were found in pure insufficiency or stenosis. A remarkable coincidence was found between pressure tracings and electrokymograms of the left atrium.

Interest in the pressure changes of the left atrium caused by mitral valve lesions was reawakened by:

1. The need for accurate diagnosis of the hemodynamic disturbance in view of a possible surgical correction.
2. The possibility of recording in man the pressure pulse of the left atrium through direct puncture of this chamber.
3. The ease with which left atrial electrokymograms are recorded in man, and the need to correlate them with pressure tracings.

While the study of left atrial pressure patterns required in the past opening of the chest, these can now be studied by means of left heart catheterization, thus permitting long range experiments.

For these reasons, a new experimental study of the results of mitral stenosis and insufficiency was considered as having some interest.

The most accurate study of the cardiac dynamics in experimental mitral insufficiency was published in 1921 by Wiggers and Feil. It was recognized that most of the regurgitation occurred "during the phase of systolic ejection and during an interval extending approximately 0.08 to 0.09 sec. into diastole," e.g. after the opening of the mitral valve. In the published tracings, the rise of atrial pressure during systole was rather gradual and the pattern was explained by a rise of intraventricular pressure which was more gradual than in normal animals.

Experimental mitral stenosis was repeatedly induced in dogs. In recent studies, no pressure tracings were published even though the pressure readings were sometimes investigated.

Method

The electrocardiogram, phonocardiogram, and electrokymogram of the left atrium were recorded in 32 dogs prior to the establishment of a valvular defect, with the animal under anesthesia. In 6 right and left heart catheterization was also done; tracings of pressure were recorded, and the pressure pulses analyzed.

The electrocardiogram was recorded by means of a Sanborn apparatus through subcutaneous needles at the root of the limbs. Standard and A-V leads were recorded.

The phonocardiogram was recorded by means of a Sanborn Twin-beam. The microphone with an open chest piece was placed, first at the apex, then at the base, at the left of the sternum, and "stethoscopic" tracings were recorded.

The electrokymogram was recorded by means of a Sanborn electrokymograph. The procedure used is that previously described for man, the only modification being that the animals were placed in the lateral positions. Two right and two left lateral border tracings were recorded, while a phonocardiogram was also recorded for timing the waves.

The pressure pulses were recorded by means of electromanometers and the Sanborn Twin-beam. The technic was recently described elsewhere, and consisted mainly in high magnification of the pulses, high speed of the film, and simultaneous phonocardiograms for timing.

The above tracings were again recorded 3 days, 7 days, and 14 days after surgery. In 2 animals, further tracings were recorded 21 days after the intervention.
**Surgical Procedures.** Mongrel dogs were anesthetized with pentobarbital. Intermittent positive pressure respiration was obtained by means of a device which used the compressed air system of the operating room and was connected to the lungs by means of a large intratracheal tube.

Mitral insufficiency was created by a blind intracardiac technic. In three dogs, damage to the valve was done by means of a sharp, right-angled hook, passed under the septal leaflet of the mitral valve and pulled until the leaflet was torn. In two dogs, instead of a hook, a bone Kerrison laminectomy punch was used to bite out segments of the mitral valve.

For the production of mitral stenosis, four different methods were tried:

1. In 1 dog, the mitral leaflets were sutured with a strip of nylon by a closed technic. This proved unsatisfactory.
2. In 1 dog, a vertical baffle of Ivalon sponge was placed through the left heart and anchored at the left atrial appendage and at the apex of the left ventricle. This method caused some regurgitation and was abandoned.
3. In 1 dog, instead of the sponge, a 26 Fr. Polyvinyl catheter was used. However, it also caused regurgitation.
4. The atrioventricular orifice was narrowed by a purse string passed around the fibrous ring, so that it was reduced to about \( \frac{1}{2} \) of its previous diameter. Postmortem revealed that the narrowing occurred slightly proximal to the fibrous ring.

Postmortem examination was made in all animals. Out of 32 animals, 8 survived for more than 24 hours. The conclusions of the study proved that 4 had a pure mitral insufficiency, 1 had a pure mitral stenosis, and 1 had both insufficiency and stenosis. The other 2 animals gave contradictory results, so that no conclusion was drawn from their study.

**RESULTS**

**Normal Animals**

The electrocardiogram and phonocardiogram of the normal dog are too well known to deserve a description. Examples of the latter are given in the various tracings.

The electrokymogram of the left atrium was found similar to that of man and consisted of two negative waves, one in presystole (inward motion caused by atrial contraction) and one in systole (inward motion caused by ventricular contraction and pull on the atrial floor). A positive wave during ventricular systole was found in only 4 of 128 tracings, and was probably due to faulty technic causing recording of an arterial pulse. Examples of normal tracings are given in figures 1 and 5. In none of the tracings was a squarish, positive wave recorded during systole.

The pressure pulses were similar to those recorded in humans. No positive wave existed in the patterns of either the left atrium or the pulmonary wedge tracing during ventricular systole.

**Pure mitral insufficiency**

Pure mitral insufficiency resulted in Dogs no. 3, 5, 17 and 22.

**Electrocardiogram.** A definite rotation of the
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FIG. 2. Dog no. 3. A. Left atrial pressure tracing (systolic plateau, high diastolic pressure). B. Left ventricular pressure tracing showing coincidence of the peak with that of the left atrium.

electric axis toward the left was noted in 2 animals while the tracing was unchanged in 1 and unreliable in 1.

Phonocardiogram. A systolic murmur appeared in all animals (figs. 1, 3, 5, 7 and 9). A diastolic murmur also appeared in two (nos. 3 and 22) and possibly in another (no. 17) (fig. 1). The low diastolic pressures of the left atrium and the low pulmonary wedge pressures excluded the occurrence of mitral stenosis. Therefore, the diastolic murmur was considered as due to "relative" mitral stenosis.

Pressures and pulses. The left atrial pressures rose remarkably during ventricular systole as a result of the incompetence, while the pressures were normal during ventricular diastole. The obtained values (ventricular syst./diast.) were 30/8, 14/2, 17/5 and 22/0 mm. Hg. The pulmonary wedge tracings revealed important pulsations in 2 animals, with values of 17/5 and 22/5.

In all cases the pattern of the left atrial pulse presented a plateau-like rise during and slightly after the end of ventricular systole (figs. 1, 4, 5, 7). This plateau was an intermediate type of plateau* in Dog no. 3, and in the first tracing of no. 22. It was an early plateau in Dog no. 5 and in the second tracing (a week later) of no. 22. The unusual shape of the systolic plateau in no. 3 was related to a similar left ventricular pattern caused by left ventricular strain (fig. 2) while, in no. 22 (fig. 7), a different explanation will be given later. The end of the plateau took place from 0.04 to 0.06 sec. after the second sound.

The pulmonary artery wedge tracing revealed a pattern similar to that of the left atrium in nos. 3, 17 (fig. 6), and 22 (this type of tracing was not recorded in the other animals). The time relationship between PA wedge wave and LA wave was as follows: there was about 0.05 sec. delay in the rise; on the other hand, there was nearly no delay in the onset of the fall. The explanation of this fact is

* The definitions "early," "late," and "intermediate," as applied to a systolic plateau, were suggested by us in previous studies dealing with left atrial electrokymograms. They were based on the time interval between rise of the plateau and first sound and, respectively, drop of the plateau and second sound. Here, the same definition is applied to pressure pulses of the left atrium.
similar to that given in the normal pattern: marked delay of the A wave which moves from LA toward the lungs; slight delay of V which represents the forward motion of a column of blood from the lungs towards LA.

Electrokymogram. The border tracing of the left atrium presented a remarkable transformation following the surgical intervention. The tracings of all animals revealed the existence of a plateau during ventricular systole. This was an early plateau in nos. 3, 5 and 22 (figs. 1, 3, and 7); there was a late plateau at first, an early plateau later in no. 17 (fig. 5). It is important to note that, in every case, this tracing was remarkably similar to the pressure tracing of the left atrium. In one instance (fig. 7A), simultaneous electrokymograms and pressure tracings were recorded. The slight difference between the two tracings will be discussed later.

Pure mitral stenosis

Electrocardiogram. Dog no. 20 presented a slight rotation of the electric axis toward the right following the intervention.

Phonocardiogram. Both a systolic and a diastolic murmur were recorded in Dog no. 20. The pressure tracing revealed only a minimal regurgitation, and the systolic murmur was explained as being due to moderate, relative insufficiency.

Pressures and pulses. There was a moderate increase in the mean pressures of the left atrium and of the pulmonary wedge tracing. The tracing of the left atrium revealed only a decrease of the systolic collapse followed by a tall V wave both after 1 and 2 weeks (fig. 8).
**Electrokymogram.** This tracing resembled the pressure tracing of the left atrium and failed to reveal any plateau (fig. 8).

**Mitral insufficiency plus stenosis**

In one of the animals (Dog no. 9), the intervention led to establishment of both insufficiency and stenosis.

The electrocardiogram showed no rotation of the electric axis, and the phonocardiogram, a systolic and a diastolic murmur (fig. 9). The left atrial pressure was 24/16 indicating both insufficiency and stenosis, while there was a plateau pattern of an intermediate type. The electrokymogram of the LA had a plateau pattern varying from early to late in different projections (fig. 9B).

**DISCUSSION**

The first electrokymograms of the left atrium in mitral valve patients were described by Luisada and Fleischner¹⁰ in 1948. The most commonly observed pattern was that of a "positive plateau" during ventricular systole. This positive plateau, which replaced the gentle negative wave of normal tracings, was explained as due to transmission of intraventricular pressure to the atrium due to valvular insufficiency causing expansion of the atrial wall in the same phase. Whenever a similar pattern was recorded in a patient with clinically "pure" mitral stenosis, it was interpreted as due to concomitant, unrecognized insufficiency.

The frequency of this pattern in mitral patients was confirmed by several authors. On the other hand, some objections were raised to this interpretation of the pattern, mostly because, in some of the cases, the cardiac surgeon did not feel with his finger a regurgitant jet.

Subsequent to this, an effort was made to better differentiate the pattern of pure insufficiency from that of insufficiency and stenosis. Studies of the authors¹⁶ led to description of two somewhat different patterns, the "early plateau," typical of free regurgitation, and the "late plateau," typical of regurgitation through a narrowed valve.

Pressure tracings of the left atrium have been recorded in mitral patients, either through direct registration at the surgical table, or through puncture of the left atrium from the back or the left bronchus. In many of the cases, a plateau-like pattern during ventricular systole was recorded. However, the interpretation of this pattern was sometimes made under the influence of the surgeon and with complete acceptance of their diagnosis. Moreover, poor technique was responsible for the controversial results of some authors.*

No experimental study has tried to compare and correlate electrokymograms and pressure tracings of the left atrium in mitral valve le-

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*Most of the tracings are recorded with inadequate film speed or poor accuracy of the manometers. All of them use the electrocardiogram as a timer. This tracing is completely inadequate and should be replaced by a phonocardiogram.
sions. Our data indicate that, in 4 animals with pure mitral insufficiency, an early plateau was present in both types of tracings; in 1 animal with pure mitral stenosis, no plateau was present in either; and in 1 animal with both insufficiency and stenosis, a late plateau was present in both types of tracings. An interesting observation was prompted by the study of Dogs nos. 3 and 22. In Dog 3, the pressure tracing of the left atrium had a conical appearance with a late peak (fig. 1B and 1C). This is due to a late peak in the ventricular pressure tracing (left ventricular strain?). It is, therefore, remarkable that the electrokymogram had an intermediate type, e.g., revealed an early dilatation of the atrial wall.

In Dog no. 22, the first observations were made 1 week after creation of a mitral insufficiency. The pressure tracing shows a systolic plateau with a slowly rising ascending branch while the electrokymogram shows a tall, systolic plateau (fig. 7A). One week later, the pressure tracing shows an early systolic plateau (fig. 7B). This was explained as follows: at first, there was moderate distention of the atrium and the elastic left atrial wall absorbed part of the kinetic energy of the regurgitant jet; an early-systolic distention of the atrial wall took place (electrokymogram) while the pressure rose more slowly. Later on, there was greater tension of the atrial wall, possibly because the left ventricle was more powerful. As a result, the pressure rose more steeply in the left atrium.

While extremely severe mitral insufficiency always had a square, systolic plateau (fig. 7B), in more moderate degrees of defect, the normal systolic drop of pressure was still visible, but was displaced upwards by the systolic plateau (fig. 5D), a square wave with a concave top. In severe insufficiency, a plateau-like pattern during ventricular systole was also revealed by the pulmonary artery wedge tracing (fig. 6); the beginning of this plateau wave was typically delayed over that of the left atrium, indicating that it was transmitted through the capillary-venous system of the lungs. On the contrary, the end of the plateau was nearly simultaneous with the end of the left atrial plateau. The causes for this slight discrepancy are similar to those which bring about a delay in the transmission of the A wave, but not of the V wave, in the normal tracing.11

**Summary**

A comparative study of the left atrial electrokymogram, left atrial pressure tracing, and pulmonary wedge pressure tracing was made in 32 dogs with experimental mitral lesions. Electrocardiograms, phonocardiograms, and autopsy observations were also made. Exact determination of mechanical events, supplied by the relationship of the waves with the heart sounds, was found extremely useful.

Out of 32 operated animals, 8 survived for 2 weeks or more and were repeatedly studied. As the tracings were considered of difficult interpretation in 2, the final conclusions were drawn from 6 animals, 4 of which had a pure mitral insufficiency, 1 had a pure mitral stenosis, and 1 had both.

It was confirmed that, while mitral stenosis, alone or with insufficiency, raises the left atrial
mean pressure and the pulmonary artery wedge pressure, pure mitral insufficiency does so to a much lesser extent.

It was determined that pure mitral stenosis, while raising the left atrial pressure during ventricular diastole, leaves the left atrial pattern relatively unchanged. Taller A and V waves and a steeper rise during the second part of the systolic collapse were the only modifications.

Pure mitral insufficiency was revealed by the substitution of a squarish plateau for the systolic collapse of the left atrial pattern. In general, the rise of the plateau was rapid (early plateau). A more gradual rise occurred in 2 animals and was explained as due to incomplete compensation by the left ventricle in the early stages following surgery. The pulmonary wedge pattern was found similar to the left atrial pattern in two animals with severe insufficiency; however, the rise of the plateau was delayed in the former tracing.

In mitral insufficiency and stenosis, the same abnormal patterns were found, with the exception that the rise and fall of the plateau wave were gradual (late plateau) and that the diastolic pressure was higher than in normal animals.

The electrokymograms of the left atrium were similar to the pressure pulses of this chamber. They revealed a plateau-like wave instead of the normal collapse during ventricular systole whenever there was regurgitation. If no mitral stenosis was associated, the plateau was of an “early” type. If there also was stenosis, the plateau was of a “late” type. Pure mitral stenosis had no plateau. In one instance, the pressure tracing rose more slowly than the electrokymogram tracing. This fact, due to elastic distention of the atrial wall, may be duplicated in clinical cases.

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Summario in Interlingua

Esseva executate, in 32 canes con lesiones experimental del valvula mitral, studios comparative del electrokymogramma sinistroatrial, del registration de pression sinistroatrial, e del registration del pression pulmonar a impaction. Esseva etiam executate electrocardiogrammas, phonocardiogrammas, e observationes autopsic. Le determination precise del evenimentos mechanic, fornite per le relation del undas al sonos cardiac, se provava extremely utile.

Ex un serie de 32 animali operate, S superviveva durante duo septimanias o plus e poteva esser studiate repetitamente. In duo casos le interpretation del registrationes esseva considerate como difficile. Per consequente le conclusiones final esseva basate super le studio del remanente sex casos. Quatro de illos presentava pur insufficientia mitral, un caso esseva stenosis mitral, e un caso esseva un combination de insufficientia e stenosis mitral.

Esseva confirmate le facto que stenosis mitral, sin o con insufficientia, augmenta le median pression sinistro-atrial e le pression a impaction in le arteria pulmonar, durante que insufficientia mitral pur produce le mesme effectos a grados muito minus extense.

Esseva constatate que pur stenosis mitral augmenta le pression sinistro-atrial durante le diastole ventricular sed alteremente lassa le configuration sinistro-atrial relativamente inalterate. Plus alte undas A e V e un plus acute ascendita durante le secunde parte del collapse systolic esseva le sol modificationes.

Pur insufficientia mitral esseva revelate per le substitution de un plateau quadratoide pro le collapse systolic in le configuration sinistro-atrial. In general, le ascendita del plateau esseva rapide. Un plus lente ascendita esseva notate in duo animali e esseva explicate como effecto del incomplete compensation per le ventriculo sinistro durante le prime studios post le operation. Le configuration pulmonar a impaction se monstrava simile al configuration sinistro-atrial in duo animali con sever grados de insufficientia, sed in le prime de iste registrationes le ascendita del plateau esseva retardate.

Le mesme anormalitates esseva trovate in le registrationes de insufficientia combine con stenosis mitral, con le exception que le ascendita e le descendita del unda del plateau esseva.
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gradual e que le pression diastolic eseva plus alte que in animales normal.

Le electokymogrammas del atrio sinistre eseva simile al registration del pulsos de pression sinistro-atrial. Illos revelava un unda plateau-oide in loco del collapse normal durante le systole ventricular quandocunque il habeva regurgititation. In casos de insufficentia sin stenosis mitral, le plateau eseva del typo “ precoce.” In le caso in que stenosis eseva combine con insufficentia, le plateau eseva del type “ retardate.” Pur stenosis mitral habeva nulle plateau. In un caso le registration del pression ascenda plus lentemente que le curva del electocardioogramma. Isto eseva le effecto de un distension elastic del pariete atrial e pote occurrer etiam in casos clinic.

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