THE DYNAMICS OF FLOW ACROSS THE NATURAL MITRAL VALVE

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Abstract: The natural mitral valve has been studied in vivo in its normal and pathologic states. Phasic pressures, flows, and cusp motion have been studied simultaneously and synchronously in large mongrel dogs. A physical model has been developed which describes the dynamics of the cardiohemic system in terms of non-linear resistance, compliance, and inertance. Not only can the data be analyzed in these terms, but pressure-flow curves simulating the in vivo results can be produced by an electrical analog.

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INTRODUCTION

Physiologists and clinicians alike have long been interested in the dynamics of flow across the mitral valve, the driving pressure between these two chambers of the heart, and the movements of the valve cusps. Such knowledge is essential for a comprehensive understanding of the events of the cardiac cycle, the origin and timing of heart sounds, and the hemodynamics of valvular disease. Those of us concerned with the design and testing of prosthetic heart valves are interested also in understanding the primary standard; that is, the normal mitral valve.

Investigations of mitral valve function have traditionally relied on models or on isolated-heart studies of cusp motion (1, 2)[1]. More recently, the valve has been studied <u>in situ</u>: cinefluorgraphically, by clipping markers on the cusps (3); cineendoscopically, by perfusing with a clear fluid (4, 5); and ultrasonically, by echosounding the moving cusps (6). The technology required for accurate measurement of instantaneous intracardiac pressure has been available for several years. Only recently, however, has it become possible to record phasic flow across the intact valve. A major contribution toward our understanding of valvular physiology was made by Nolan et al (7) in 1969 when they published the first records of phasic flow across the intact mitral valve[2]. These remarkable results were soon corroborated by others including ourselves (8, 9, 10). Nolan et al. (7) were primarily interested in the role of atrial

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[1] Numbers in parentheses refer to similarly numbered references in bibliography at end of paper.

[2] In 1965 in a discussion of a paper, Davilo showed some slides which were not published, but which from the comments, clearly indicated he had measured phasic mitral flor. (Journal of Thoracic and Cardiovascular Surgery, vol. 50, no. 6, 1965, page 821).

contraction and while they recognized the inertial character of the flow they did not develop an analytical approach to all the physical processes involved in valvular mechanics. In 1971 we presented for the first time, a preliminary report of studies in which we simultaneously recorded instantaneous pressure, flow, and cusp position for the canine mitral valve. With this report we present a unified description of mitral valve dynamics incorporating the concepts of inertance, dissipation, and compliance. This approach has also been supported by an electric analog simulation (11).

METHODS

Large mongrel dogs were anesthetized, thoracotomized, and placed on total heart bypass. As shown in Fig. 1, a toroidal electromagnetic flow probe (Carolina Medical Electronics) was sutured to the mitral valve in the supra-annular position and the wires brought out through the appendage. Catheters were placed in the ventricular apex and the left atrium, and pressures were measured with Statham P23H matched differential strain gages. An aortic flow probe was placed around the root of the aorta and aortic flow continuously monitored (for clarity and simplicity, these flow traces have been omitted from the illustrations). The calculation of stroke volume from the aortic flow was useful in the determination of mitral flow zero and filling volume. Minute amounts of barium were injected into selected spots on the valve cusps, ring, and papillary muscles. Cinefluorograms of valve motion were taken at 60 frames per second simultaneously and synchronously with the oscillographic records of instantaneous mitral flow, pressure difference, and the EKG (Electronics for Medicine DR8 Recorder). Incompetence was created in some of the animals by cutting one or two chordae; and in some studies the valve cusps were sutured together to create a stenosis. Total heart block was created in selected animals by crushing the AV node; heart rate was then varied by right ventricular pacing. Very slow but transient rate could be achieved by vagal stimulation.

With one exception, all of the data were recorded in the anesthetized, open-chest preparation. In one dog the chest was closed, he was allowed to recover, and was able to come off the respirator. Data were recorded eighteen hours after surgery and the animal succumbed shortly thereafter.

RESULTS

Figs. 2 - 6 are representative oscillographic records of the data. In Figs. 2 - 5 vertical lines have been drawn at the start and cessation of flow (diastolic filling period). In these cases it is evident that the onset of rapid forward flow (from the atrium to the ventricle) coincided with the reversal of the pressure difference between the two chambers of the heart (left atrial pressure exceeding left ventricular pressure). The records also show with great clarity that the blood continues flowing into the ventricle for several milliseconds after the pressure gradient has reversed, that is, well into the phase of isovolumetric contraction. That this is not an artifact is substantiated by the simultaneous plot of cusp position taken from the cines and synchronized with the pressure-flow records (Figs. 3 and 4). Finally, it can be seen (most clearly in Fig. 2) that the pressure difference reaches its maximum before the flow, and becomes zero after the flow has reached its maximum. These results suggest that the flow field possesses the properties of both resistance and inertia.

The flow traces of Figs. 2 - 4 also indicate that there is nearly always a phase of very slow forward flow which occurs before the pressure difference reverses. In Figs. 2 and 3, this is preceded by a phase of what appears to be sharp, transient, and oscillatory backflow. The cines, however, show the cusps to be closed. These observations suggest that the closed valve possesses the properties of both compliance and resistance.

Several other observations are in order. The normal mitral valve (Fig. 3) opens rapidly and immediately and rapidly starts moving toward closure. At fast rates or short diastolic filling periods (Fig. 3, first two beats) the cusps continue toward closure at a slower rate. With long filling periods (Fig. 3, third beat) the cusps may oscillate, open rapidly with atrial contraction, and then again move toward closure. The stenotic valve, on the other hand, will demonstrate different properties (Fig. 4). In this case, the nature of the stenosis and the state of cardiac function was such that flow increased slowly and the cusps were slow in opening and reaching their maximum orifice.

The rupturing of a primary chordae (Fig. 5) produced a small but significant degree of regurgitation (approximately 25% of the filling volume). The phase relations between pressure and flow remain unchanged, but the small prediastolic forward flow no longer exists. The nature of the gradient is such that it goes rapidly to zero and stays there, while the flow continues forward at a decreasing rate. Gross incompetence is illustrated in Fig. 6. Forward flow no longer starts in phase with the gradient,but follows it. The timing and the shape of these curves (especially the forward flow curve during the phase of zero gradient) once again suggest the inertial and resistive character of the flow.

DISCUSSION

In 1960 (in abstract form) and in 1962 (in complete report) Spencer and Greiss (12, 13) reported that the pressure-flow relations at the aortic valve were inertial in character. While they did not specifically use the term "compliance", they recognized its existence by referring to the "cocking" of the valve and to the release of tension stored in the "cocked" valve leaflets. This major advance in the understanding of hemodynamics has yet to find its way into most textbooks of physiology. The ventricular pressure/is still shown to exceed the aortic pressure during the entire period of ejection. It is not surprising, then, to discover that nearly all descriptions of ventricular filling assume that the flow, gradient, and cusp position are all in phase with each other. A major advance was made by Nolan et al (7) when they showed that ventricular filling also was inertial and that the mitral valve was compliant. Based on the results of this study, and our knowledge of pulsatile flow across an orifice reported previously (14), we are including resistance in our synthesis of the cardiohemic system.

If the flow were purely inertial, and the valve competent, the pressure gradient and flow would start at the same time, since the flow is the integral of the gradient and the competent valve prevents backflow. The pressure gradient would peak first and the flow would reach its maximum when the gradient went to zero. The flow would then either decelerate under the influence of an adverse gradient, or remain at its maximum velocity if the gradient remained zero (see, for example the late gradients of Figs. 5 and 6). An incompetent valve would permit backflow and therefore the pressure difference would lead the flow at all times.

A purely resistive flow, that is one with dissipation only, would always be in phase with the pressure gradient. Since the fluid is incompressible, during the time the valve is open there can be no compliance in the system. Our data clearly demonstrate that the flow field has both resistive and inertial properties. Valve closure exhibits the properties of a damped oscillation due to the viscoelastic properties of the valve and its attachments to the ventricular muscle tissue. What appears to be backflow at valve closure is in reality the ballooning of the closed valve into the atrium. This should not rule out the possibility that in some circumstances a portion of this negative flow may be regurgitation (15). This stored energy is then given up when the ventricle starts relaxing and the pressure falls, thereby allowing the valve to move away from the atrium. The damped oscillation of the flow curve during the period of valve closure may be explained by the viscoelastic nature of the system. Quite possibly, the first one or two large amplitude oscillations at closure give rise to the first heart sound.

The effects of moderate and gross incompetence are shown in Figs. 5 and 6. In the former case the compliance is overshadowed by the backflow, but pressure gradient and flow cross zero together. In the latter case the gross incompetence not only dominates the effect of any compliance, but also the timing of the events; there is so much inertia in the backflow that it must be decelerated before flow can reverse, and the gradient leads the flow at all times. Of particular interest in Figs. 5 and 6 are the flow records at the time of prolonged zero gradient during late diastole. At moderate or high flow rates energy is lost through dissipation of eddies and therefore is a function of the velocity squared. When the gradient goes to and stays at zero, the velocity will rapidly decrease. At low flow rates energy is lost through viscous dissipation and is directly proportional to flow. During the later phase of diastole with the gradient still at zero, the flow decreases at a decreasing rate and eventually reverses under the action of an adverse gradient.

There are two possible sources of error in our data: physiological and electromechanical. How valid is data from an open-chest, anesthetized preparation? In our one attempt at a chronic experiment the results from the closed-chest, unanesthetized animal were qualitatively the same as the other experiments. Furthermore, Folts et al. (10) have reported pressure-flow records from chronic animals which corroborate our results. What about mechanical transmission delays and electronic phase shifts in the oscillographic signal? We have simultaneously recorded pressures from the Statham, fluid-filled-catheter-system, and a Konigsberg, catheter tip solid state transducer. They are identical.

The flow signal has been checked by varying the time constant on the meter and running at the lowest time constant which shows no further change in signal. That this is indeed accurate has been verified by the cines which are not subject to electronic phase shifts and which show the same diastolic filling period as the flow trace in addition to the same opening and closing times. Finally, our observations of cusp motion agree with those of other investigators using different techniques (2- 6); and our pressure-flow records agree with those of the three other groups reporting on mitral flow (7, 8, 10). We are, therefore, confident that our data are valid.

ANALOG SIMULATION

We have developed an electrical analog (Fig. 7) which simulates the observed phenomena (11). The square law resistor gives a loss which is proportional to the square of the flow and is always in the direction of the flow. This is analogous to eddy dissipation. A path for backflow is provided with a resistor and inductor separate from, and in addition to, the ones in the forward flow path. An incompetent valve will exhibit the properties of an orifice in the backflow path and a nozzle in the forward path. A more complete description and results of the analog simulation are presented elsewhere (11). Some representative records are presented and described in Figs. 8 and 9.

ACTIVE ELEMENTS IN MITRAL VALVE MECHANICS

Thus far we have discussed only the passive properties of inertia, resistance, and compliance, and treated them as lumped parameters. The power of this approach is evident from its ability to elucidate the data and model valvular mechanics. There are, however, active elements involved in the valve-fluid system, and they should be discussed for their possible major or second order effects.

Mechanical Factors: The papillary muscles will contract early in systole and may be responsible for the overshoot in the flow trace following the initially sharp downward deflection (most evident in Figs. 2 and 3). Nolan et al. (7) put forth this interpretation. We do not dispute this, but we feel that this overshoot is part of the damped oscillation in the viscoelastic system and could exist even without a papillary muscle contraction. Both mechanisms may, of course, exist simultaneously. We intend to study this by paralyzing or destroying the contractile mechanism in the papillary muscle and observing the result. Furthermore, since the ventricle is constantly changing its shape, the papillary muscle may transmit this motion to the valve cusps. The timing of this phenomenon would place it during the late systolic phase when the "cocked" valve is releasing fluid toward the ventricle and the two mechanisms would produce similar results, that is, a slow phase of forward flow before the gradient reverses. Contraction of the atrioventricular ring (16) and the septal valve cusp (17) have recently been reported and would influence the flow in an as yet unknown manner.

Flow Factors: It is unlikely that in the short time available for flow, a significant boundary layer will develop on the valve cusps. It is quite probable, however, that separation occurs at the valve margins where the jet of blood enters the ventricle in which there is fluid stasis. Bellhouse and Talbot (18) have reported on this phenomenon in the aortic position, but no data is as yet available on the mitral position. The fact that the ventricle is at all times larger than the mitral orifice can only lead to the formation of vortices and eddy currents behind the cusps. The many physiologists who feel that these vortices help close the mitral valve are relying on valid, albeit heuristical, physical insight (See, for example, Rushmer (19)). The observation that aortic regurgitation into the ventricle may lead to incompetent mitral closure (15) strongly supports the vortex hypothesis.

Another fluid dynamic mechanism which influences valve closure was proposed in 1912, and beautifully demonstrated, by Henderson and Johnson (1). They felt that an atrial contraction sent a sudden spurt of blood across the valve, which, when it passed into the ventricle, left a low pressure region behind. The cusps thus started toward closure even before ventricular contraction generated an adverse pressure difference. Clearly, there is merit in both of these theories of valve closure and they are not, as some of their partisans are wont to have us believe, mutually exclusive.

Finally, we must mention the proposal by Reid (20) which treats the ventricle as a diffuser. The fact that the ventricle does expand as it fills, and the fact that the pressure drop across the normal mitral valve is very small, lends support to this thesis. By acting as an active diffuser, the ventricle will recover pressure from the kinetic energy of the jet. One further variable which we are planning on investigating is the role of pulmonary venous inflow into the atrium during the time the mitral valve is open.

SUMMARY

By simultaneously measuring cusp position, and pressure and flow at the mitral valve, we have demonstrated that it possesses the properties of a system with inertia, dissipation, and compliance. The timing of the events of the cardiac cycle has thus been clarified and should lead to a more accurate interpretation of physiological and clinical observations.

We are also currently applying the physical insight described herein, in an investigation of prosthetic mitral valves.

Addendum: The technique we have used to measure mitral flow is totally unacceptable for clinical research. But qualitatively similar and clinically useful results of flow across the tricuspid valve has been obtained during human catheterization by Kalmanson et al. (21) using a Doppler ultrasonic flow probe mounted on a catheter.

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CAPTIONS FOR FIGURES

Fig. 1. The left side of the heart in cross section showing the instrumentation. LVP = left ventricular pressure catheter, LAP = left atrial pressure catheter; AOF = aortic flow probe; MF = mitral flow probe. Omitted for clarity is the cloth sewing ring which anchors the flow probe to the mitral annulus.

Fig. 2. Typical results of pressure and flow at the natural mitral valve. The vertical time lines enclose the period during which flow is occurring across the open valve. In this case forward flow has continued 40 msec beyond the time of pressure reversal. ΔP is the electronic difference between the atrial and ventricular pressures recorded at greater sensitivity. For clarity, the difference trace is not shown when the ventricular pressure exceeds atrial.

Fig. 3. Typical results of pressure, flow, and mitral cusp motion. The markers on the cusps were about five mm from the margins and when the valve closed the distance between the markers was not zero. The ballooning of the valve into the atrium during ventricular contraction, and the unloading of this stored fluid, can be seen in the traces of cusp position and flow.

Fig. 4. The mitral cusps were sutured together to give an annulus ofabout 15 mm, hence the increased gradient. The slow rate of rise of flow is due to the increased impedance to flow and the depressed state of the myocardium in this animal.

Fig. 5. This valve was rendered moderately incompetent by cutting a chordae which allowed the cusp to partially invert into the ventricle under the action of a high pressure. The sudden increase in ventricular pressure at mid-diastole is probably due to backflow from the aorta which may have been "kinked". As a result, a very interesting period of zero pressure difference allowed the flow to be decelerated via dissipative forces rather than by an adverse gradient. This is discussed further in the text.

Fig. 6 The same valve as in Fig. 5 rendered grossly incompetent. The dynamics are discussed in the text.

Fig. 7 The electric analog circuit which simulates the inertance, resistance and capacitance of the mitral valve. The two paths in parallel with the diode (valve) represent the viscoelastic properties of the closed valve and the possibility of backflow. The superscript (2) indicates a square law resistor defined in (b) and explained in the text. Q = flow.

Fig. 8 Oscilloscope traces from an analog computer which solves the equations applicable to the circuit of Fig. 7. These are competent valves, analogous to Fig. 2, and demonstrates the phase relations and viscoelastic properties as discussed in the text. From (a) to (b) the damping has been reduced, while from (b) to (c) the compliance has been increased (note the decrease in the natural frequency of vibration).

Fig. 9 Inertia and dissipation in the backflow path. From (a) to (b) the degree of incompetence is increased by decreasing both the resistance and inductance in the backflow path.

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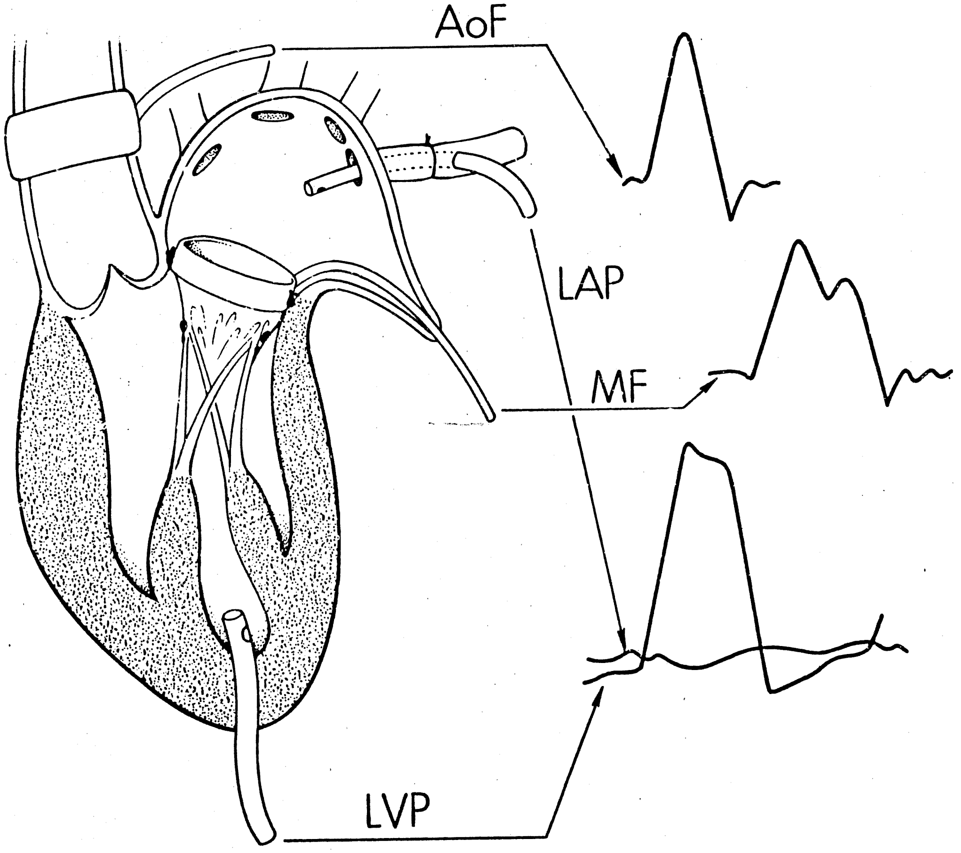
AoF
LAP
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LVP

Fig. 1

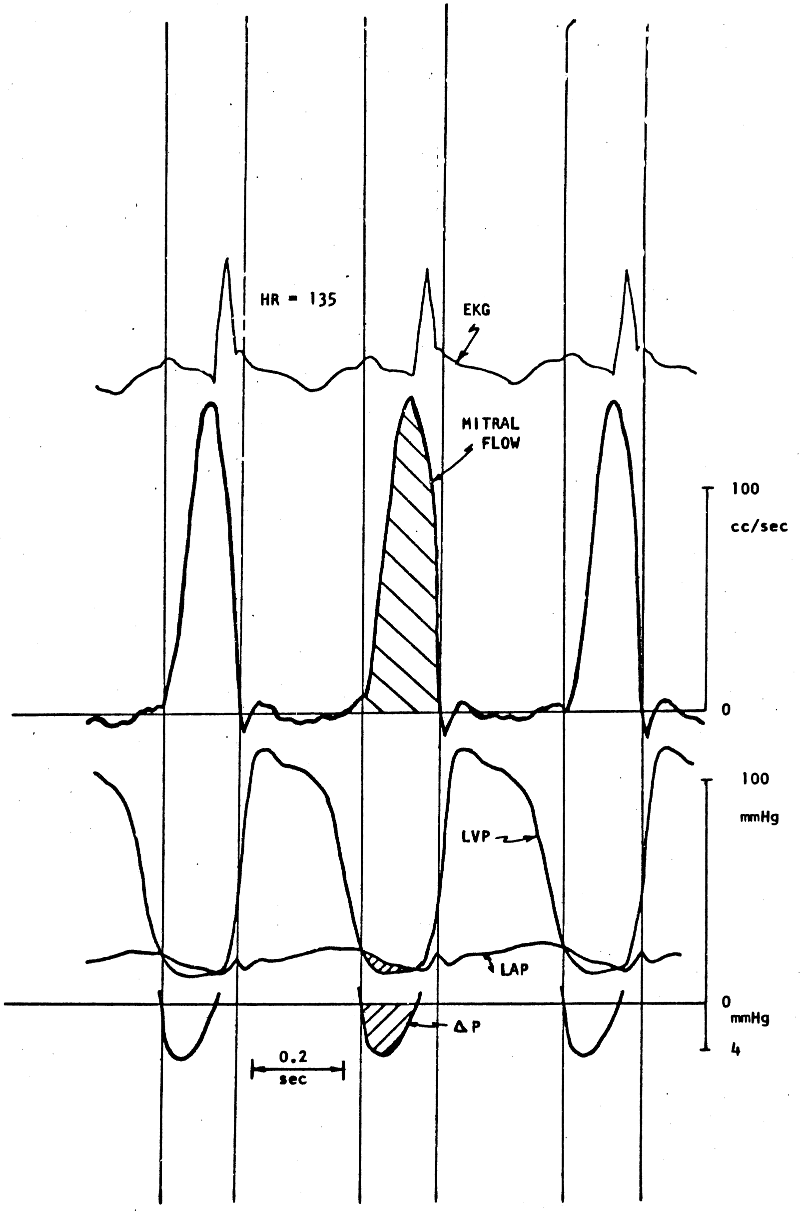
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Fig 2

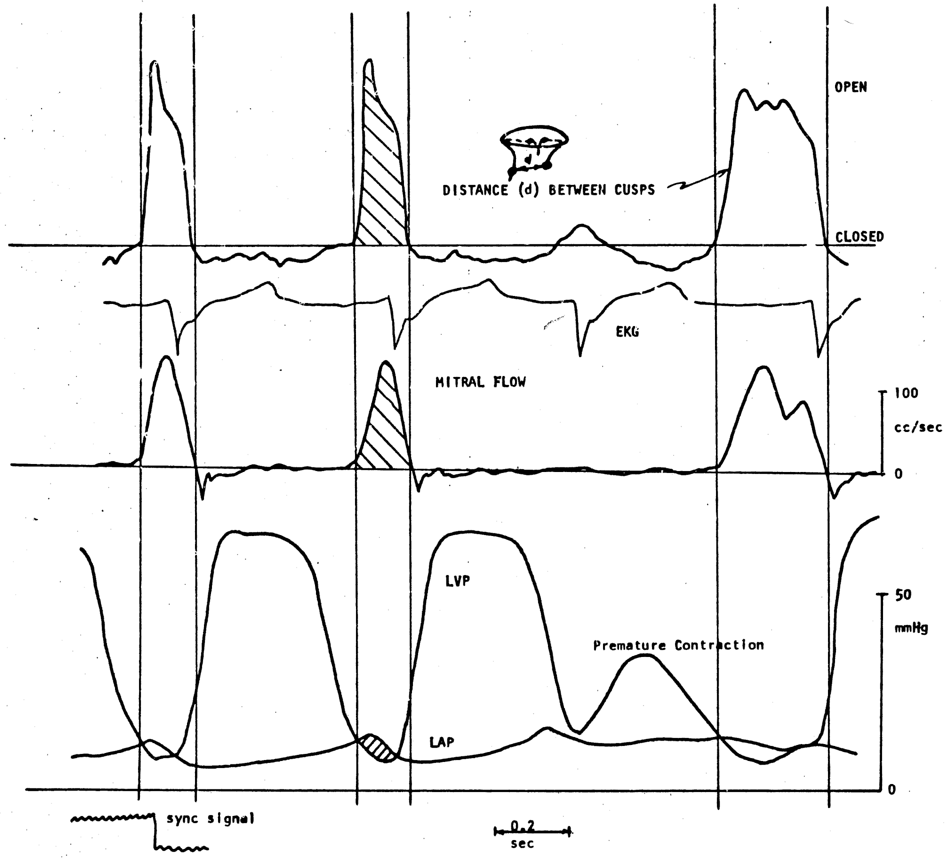
OPEN
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Fig. 3

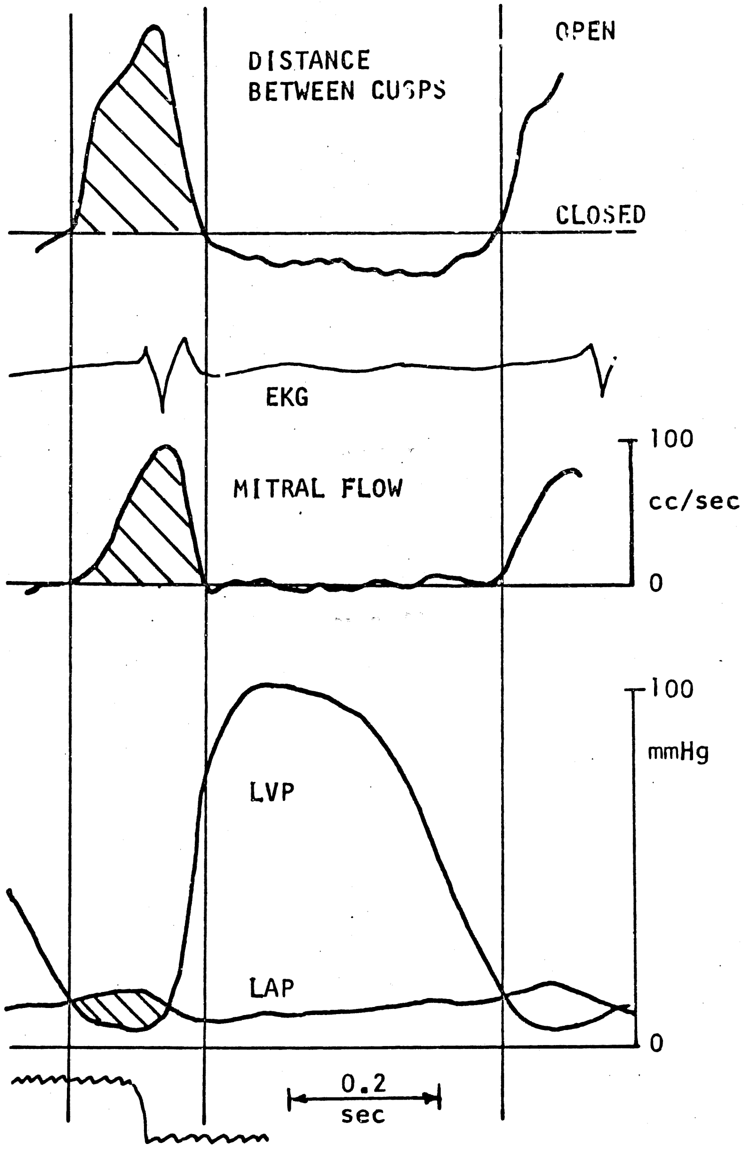
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Fig 4

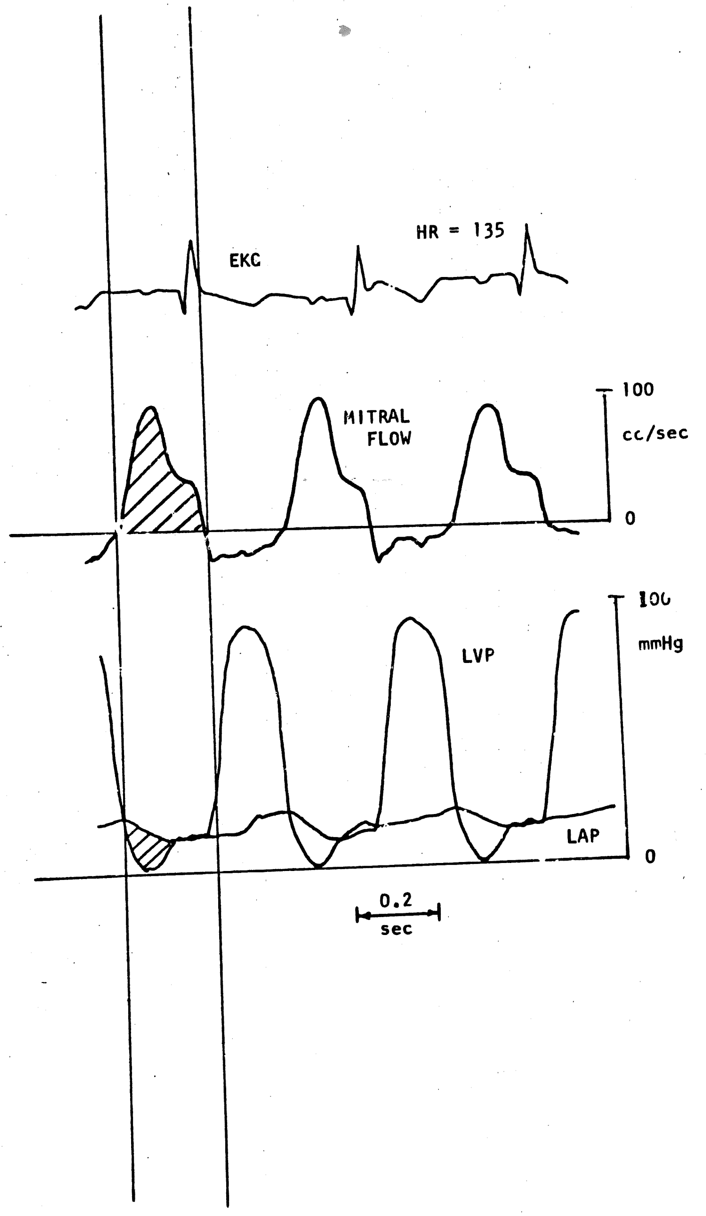
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Fig. 5

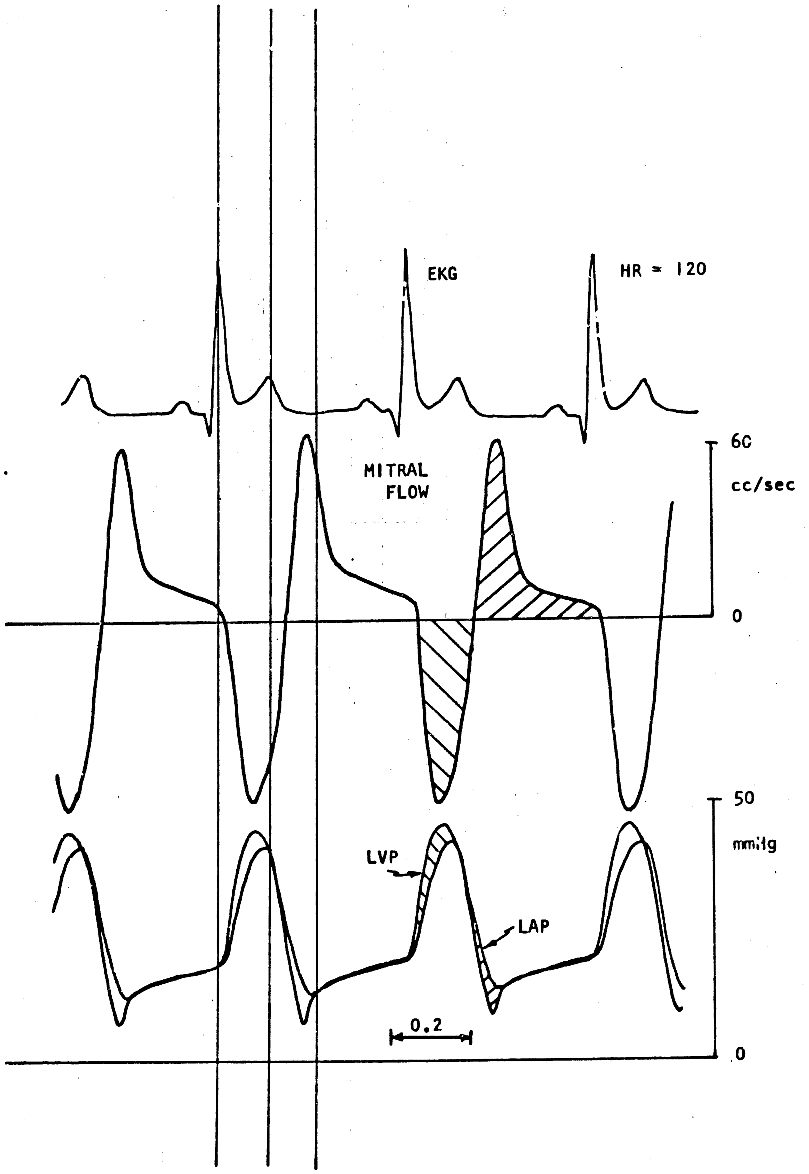
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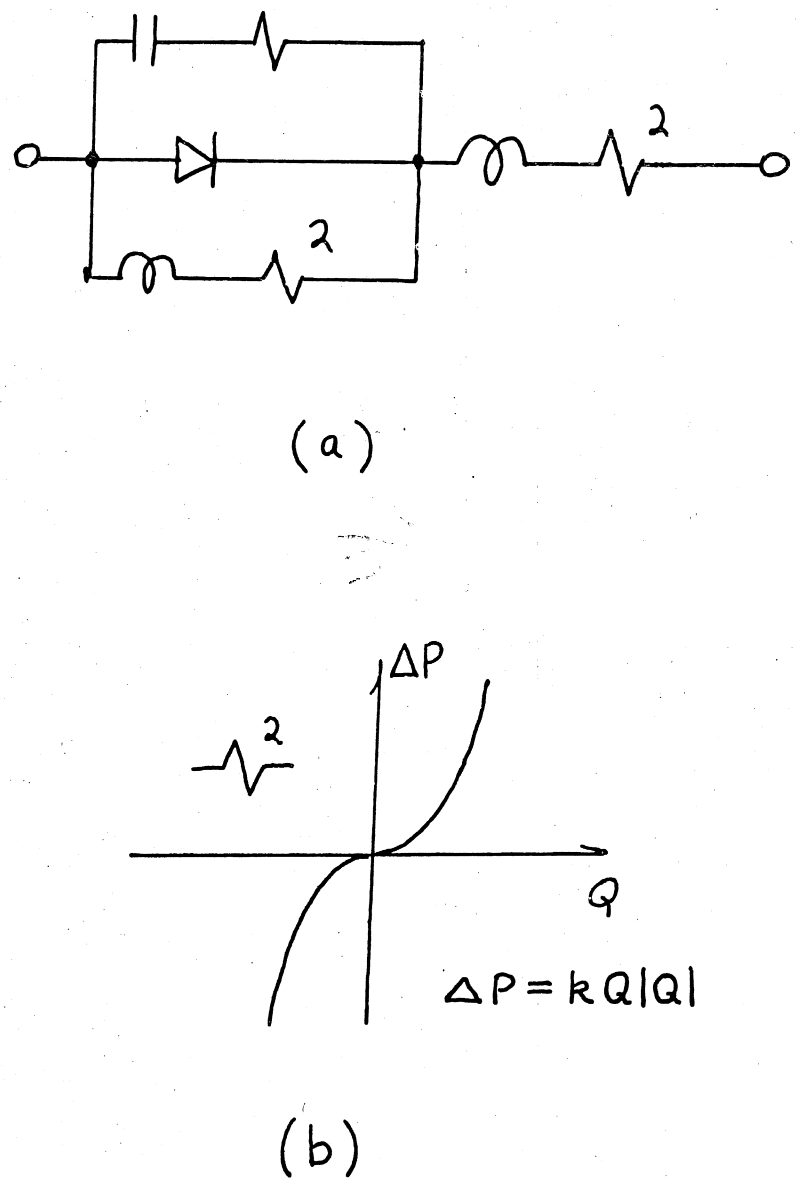
Fig. 6



(a)

(b)

Fig. 7

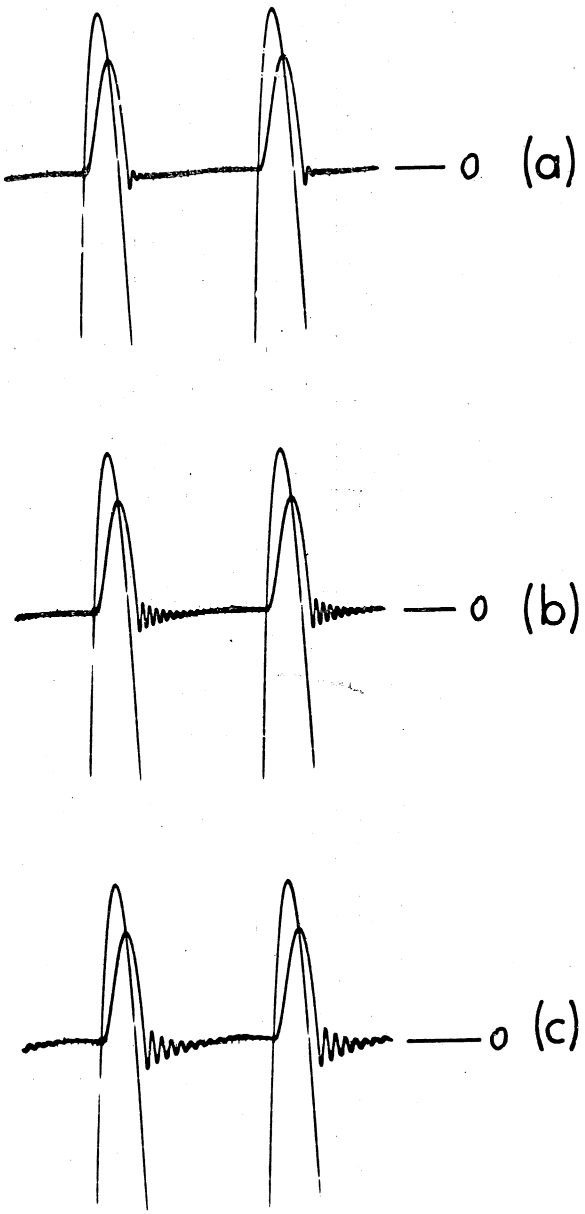


Fig. 8

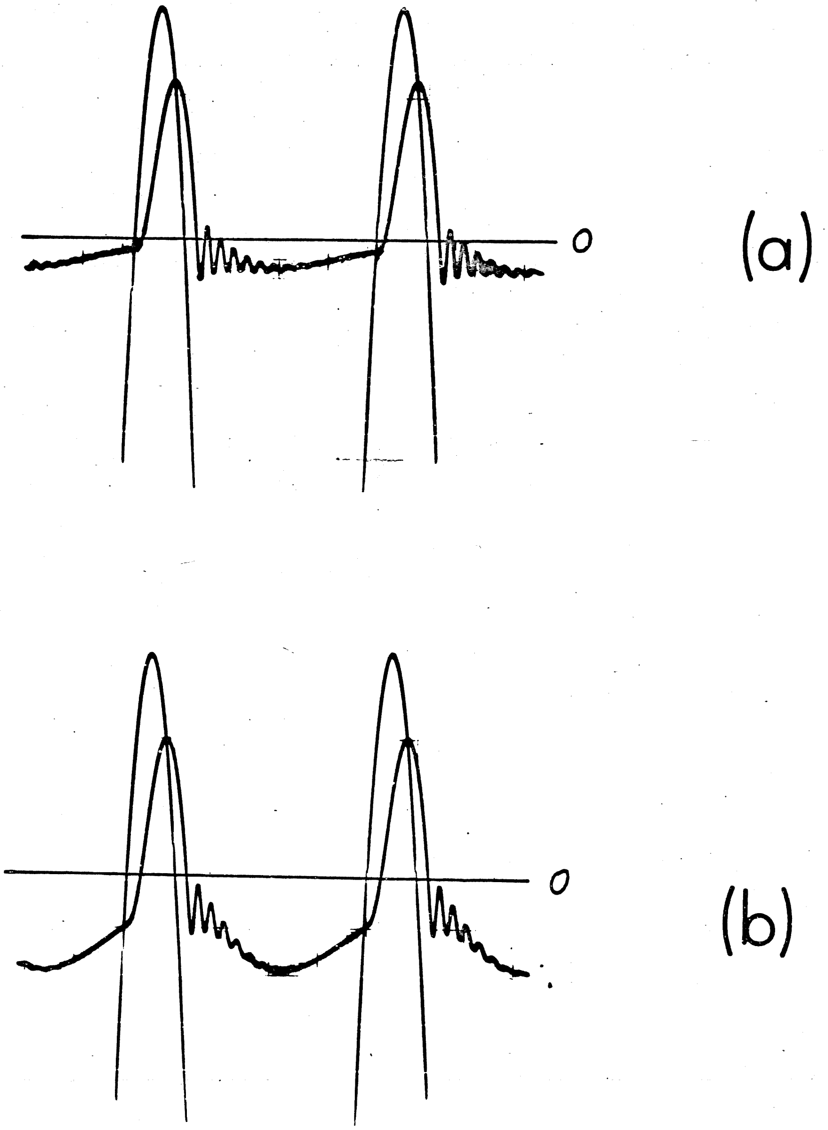


Fig. 9