THE MITRAL VALVE

A Pluridisciplinary Approach

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18 Flow Studies of Experimental Mitral Stenosis and Regurgitation*

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INTRODUCTION

Our understanding of the hemodynamics of valvular pathologies has been hampered by an inability to measure phasic transmitral flow directly. With the development of this technique, new possibilities for the growth of our physiological understanding have opened up.

In this presentation we follow the same general approach as in our previous discussion of the normal mitral valve. Our goal is to elucidate dynamic relations by providing a simple but useful mathematical formulation with which to analyze and quantify mitral stenosis, and by providing a conceptual approach to regurgitant dynamics.

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METHODS

Mitral Stenosis

Placement of the transducers is as described previously in Chapter 16, except that prior to the insertion of the flow probe, the commissural margins of the mitral cusps were sutured together to create a fixed, pliable, and competent mitral stenosis. The diameter of the stenotic orifice was measured at surgery and again at autopsy. The accuracy of the LA-LV pressure difference was checked at intervals during the experiment by matching the catheter-tip records with records from the same chambers using Statham gages. When possible, a complementary method was used: Vagal stimulation or cardiac arrest brought both pressures to a common value.

Mitral Regurgitation

Graded degrees of reversible acute mitral regurgitation were created either by inserting a plastic basket catheter into the mitral orifice, or by applying tension to a length of string which restricted the motion of the posterior cusp.

The determination of zero flow may be difficult since the heart,

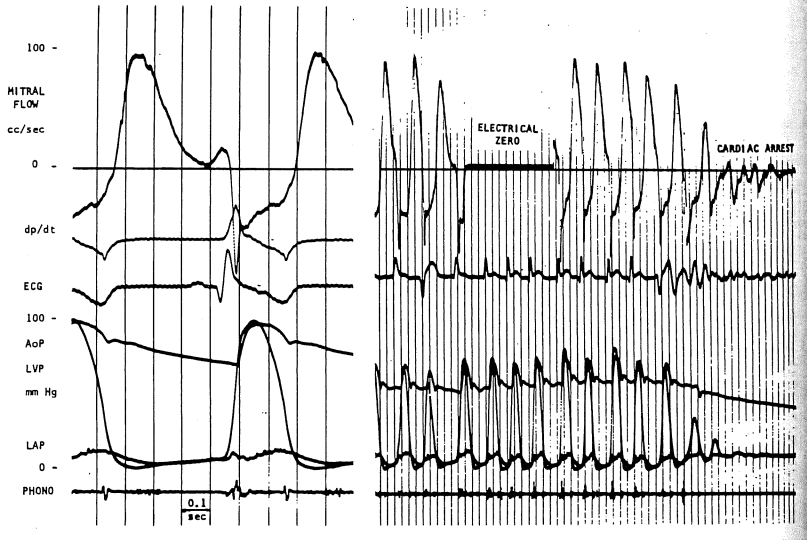

Figure 1. The determination of zero flow during mitral regurgitation. Left panel: exponential decay of flow toward zero during diastasis. Right panel: zero flow at cardiac arrest.

unlike an artery, cannot be occluded to give "mechanical" zero. With a competent mitral valve, the flow baseline can be determined with reasonable accuracy during systole when mitral flow is indeed zero. If there is regurgitation, however, one can slow the heart or create transient periods of prolonged diastasis and observe the exponential decay of the flow toward zero (Fig. 1, left panel); or a true baseline can be obtained by arresting the heart (Fig. 1, right panel).

THEORY

Mitral Stenosis

Because the high velocity jet issuing from the mitral orifice is pulsatile and is dissipated in the left ventricle via turbulent mechanisms, the equation of motion consists of an accelerative term and a term proportional to the square of the flow. Figure 2 presents this formulation and schematically depicts the anatomy of mitral stenosis. The mean of this equation when taken between the two points of zero flow eliminates the accelerative component and leaves the pressure-flow relation as shown in Figure 2. The rationale for this approach can be found in Yellin and Peskin,[1] where we prove that

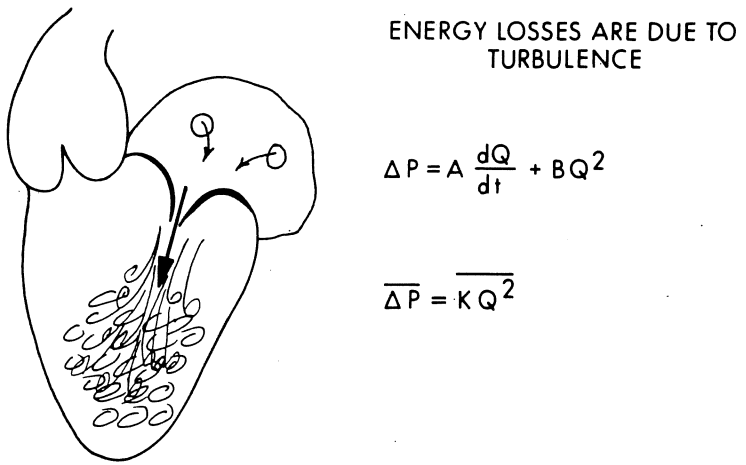

Figure 2. Schematic of the anatomy of mitral stenosis and the equation (upper right) which describes the pressure-flow relation in this geometry. The time averaged equation is in the lower right.

except for some insignificant theoretical errors, it is the equivalent of the Gorlin equation:[2]

$$A_o = \overline{Q}/(0.7 \times 44.5 \sqrt{\Delta p}).$$

Mitral Regurgitation

We have not been successful in deriving a quantitative treatment of the regurgitant path, probably because the orifice changes its size too much during systole. We will, however, analyze mitral regurgitation in a *qualitative* manner, employing the principles developed for the normal and stenotic valves.

RESULTS

Mitral Stenosis

Figure 3 is an oscillographic record from a dog whose stenotic mitral orifice measured 0.8 cm^2. In contrast to the normal valve, the flow tends to remain constant throughout diastole, so that only at onset and at cessation of flow will any significant force be required to accelerate and decelerate the blood. As a consequence, resistance dominates the pressure-flow relations across the stenotic valve, and flow at any time other than onset and cessation is determined primarily by the pressure gradient at that time. Thus, peak flow occurs early in diastole, regardless of the rate of ventricular relaxation. Augmentation of flow by an atrial contraction is small, approximately 5% (shaded area, Fig. 3, beat 2). Were the diastolic period to be shortened by a premature contraction occurring just prior to what would have been the atrial contraction, then flow would be decreased by approximately 30% (Fig. 3, beat 3). Diastolic periods were chosen for analysis from stable beats at various heart rates, from premature contractions, and from post-extrasystolic periods. Using the Gorlin approach,[2] the calculated orifice area was remarkably close (Avg. 5%) to the measured area.

Mitral Regurgitation

Figure 4 is an oscillographic record which has been chosen because it dramatically illustrates the salient features of regurgitant dynamics under conditions of moderate incompetence. The results are presented in the lower portion of Figure 4 as the change in ratio of

regurgitant to stroke volume (RV/SV). (Note that in this paper, stroke volume refers only to the forward volume flow.) In Panels A and B, beats numbered 1 are the last of a series of controls; beats numbered 2 are ventricular premature contractions (VPC); and beats numbered 3 are post-extrasystolic contractions (PESC). In Panel A, the VPC fails to open the aortic valve; it is followed by a prolonged diastolic period; there is a decreased aortic end diastolic pressure leading to an early opening of the valve; and the PESC is potentiated, leading to an increase in LVP, stroke volume, and dp/dt. In Panel B, the VPC occurs later so that the aortic valve opens, but stroke volume and dp/dt are reduced. The PESC (beat No. 3) is only slightly potentiated and the aortic end diastolic pressure only slightly reduced.

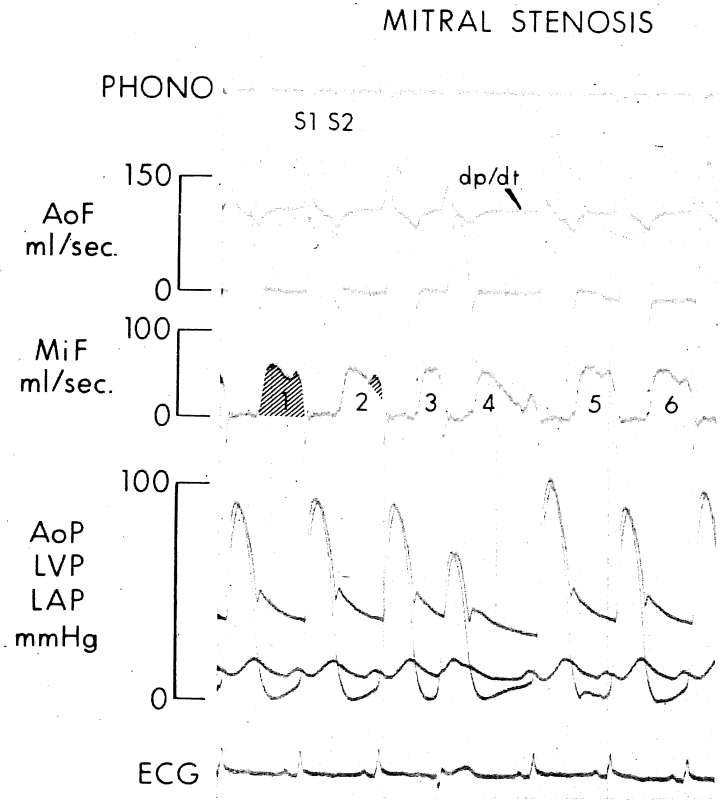

Figure 3. An oscillographic record from a dog with mitral stenosis created by suturing the commissural margins together during cardiopulmonary bypass. Phono = Intracardiac Phonocardiogram; AoF = Aortic Flow; MiF = Mitral Flow; AoP, LVP, LAP = Aortic, Left Ventricular, and Left Atrial Pressures; ECG = Electrocardiogram; dp/dt = Derivative of LVP. Time lines at one/sec.

Under these conditions, in both panels of Figure 4 the absolute value of the regurgitant volume and the RV/SV ratio both increase during the VPC. In Panel B, the regurgitation during the PESC remains the same as normal, but since there is a small potentiated increase in stroke volume, there is an insignificant decrease in the relative regurgitation.

DISCUSSION

Mitral Stenosis

The dynamic pressure-flow relations in mitral stenosis are characterized by the equation of motion in Figure 2. Most important, the time-averaged equation, which is closely equivalent to the Gorlin equation, has been shown to be applicable to mitral stenosis under conditions of induced arrhythmias and heart rate changes, i.e., under

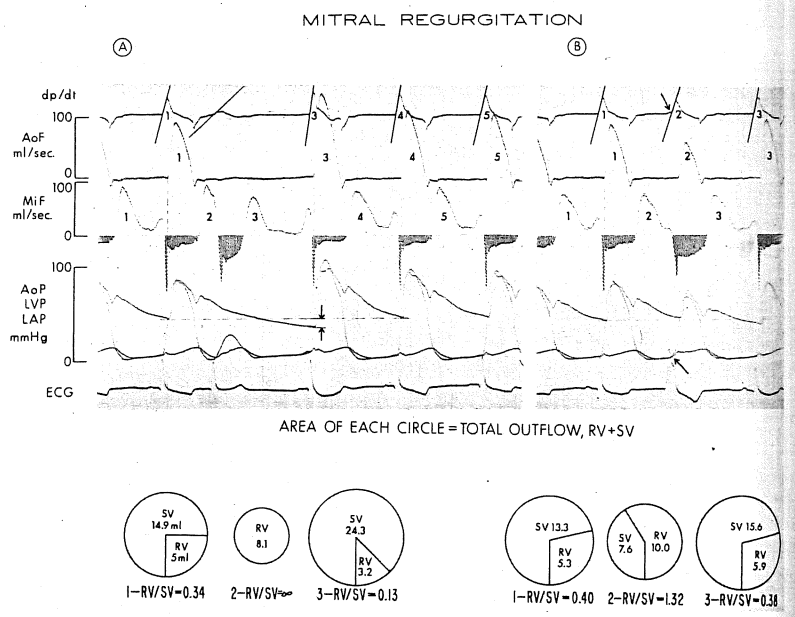

Figure 4. An oscillographic record from a dog with mitral regurgitation (shaded). In the upper trace the slope of dp/dt is emphasized with the solid line. Vertical broken lines indicate the amount of regurgitation occurring between mitral valve closure and aortic valve opening. Note that most of it is due to a closing volume artifact. Horizontal broken lines emphasize aortic end diastolic pressure differences. In Panel B, the arrows point to a period of slow ventricular contraction, resulting in a large regurgitant volume. The lower part of the figure illustrates the changes in the ratio of regurgitant to stroke volume. Time lines at one/sec.

various flow conditions. A reasonably good approximation to the orifice area can be calculated, and it is clear that the average pressure difference required to fill the ventricle is proportional to the square of the flow. Our work, therefore, supports the clinical application of the Gorlin equation as an adequate first approximation to the orifice area.

Mitral Regurgitation

The incompetent mitral valve presents an interesting study in dynamics because during ventricular contraction two paths are available for flow. Each path has its own impedance and each is under the action of a different driving force. Our data, of which Figure 4 is representative, are consistent with the work of others (Wiggers and Feil,[3] Rodbard and Williams,[4] Braunwald et al.,[5] Ross et al.[6]), but the following interpretation is not always in agreement with theirs. While these results are not comprehensive (not all conditions of acute and chronic regurgitation have been studied) and should be considered speculative, they present for the first time an experimental model which is truly in vivo and preserves the system characteristics completely. There are no analogs, external shunts, or internal paths that change the intrinsic properties of the system.

The conclusions presented below are based on the analysis of records with the heart in normal sinus rhythm; with peripheral resistance modified by vasoactive drugs; and with ventricular function modified by inotropic agents and volume loading. Particularly interesting is the analysis of extrasystolic and post-extrasystolic beats (Fig. 4).

Following ventricular contraction and reversal of the A-V gradient, mitral inflow is decelerated, and in normal sinus rhythm the mitral valve closes approximately 10 msec before the aortic valve opens. During this short time, flow is accelerated along the regurgitant path. When the aortic valve opens, there is an additional path for flow. The distribution of the filling volume along these two paths then becomes a function of the relative driving forces and impedances.

The two impedances are apparently highly dependent on frequency, so that flow can cross the aortic valve and enter the systemic circulation more readily than it can cross the incompetent mitral valve. Thus, the aortic end diastolic pressure influences the flow distribution in two ways: via the time to valve opening, and via the compliance characteristics of the aortic "windkessel." The value of the former is clear: forward flow will begin sooner. Regarding the latter, at low pressures the aortic compliance increases and hence the impedance decreases. More important, however, the initial rate of

rise of left ventricular pressure (that is, its contractility and synchrony of contraction), will determine the distribution of flow between the forward and regurgitant paths, because the impedance of the compliance path decreases with increasing frequency.

The regurgitant orifice, on the other hand, in addition to resistive properties, also has inertial characteristics which lead to an increase in impedance with increasing frequency. Because inertance is dominant at acceleration, the regurgitant path during isovolumic contraction has its largest impedance. Hence regurgitation is less than expected at that time (note the vertical broken lines in Fig. 4).

The data and analysis suggest that in mitral regurgitation the regurgitant fraction can be decreased and the forward fraction increased by the use of peripheral vasodilators in conjunction with positive inotropic agents and anti-arrhythmic therapy. This conclusion is based on hemodynamic considerations; its clinical applicability is, of course, subject to other medical considerations.

INTRA-AORTIC BALLOON PUMPING FOR MITRAL REGURGITATION

The results presented above and the favorable clinical experience of Gold et al.,[7] have led us to undertake a study of the dynamics

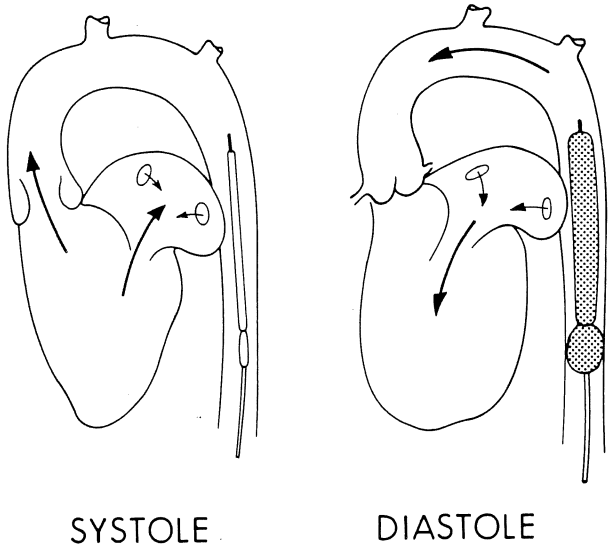

Figure 5. Schematic of the deflation and inflation of an intra-aortic balloon during systole and diastole.

of IABP in dogs with mitral incompetence. Our rationale was that this procedure would serve a two-fold purpose. 1) During systole, deflation of the balloon (Fig. 5) would lower aortic pressure, thereby increasing its compliance and lowering the impedance to outflow; a well-timed deflation would also decrease the time to aortic valve opening. The decreased afterload might also result in a reduced LVP

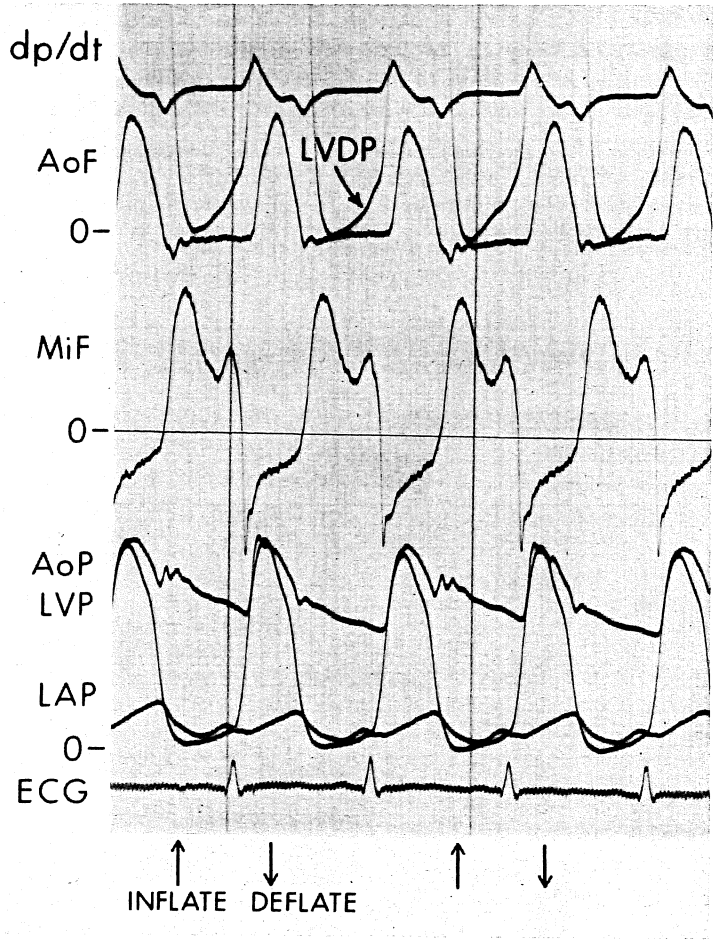

Figure 6. Oscillographic record of the hemodynamic data during 1:2 IABP in a dog with mitral regurgitation. Note that diastolic pressure augmentation during inflation is quite small, but the increase in negative aortic flow indicates an increase in coronary perfusion. There is an 11% increase in stroke volume during balloon deflation. Time lines at one/sec.

and thus a reduced driving pressure for regurgitation. Balloon deflation should, therefore, decrease RV/SV ratio. 2) During diastole, inflation of the balloon (Fig. 5) would increase the aortic diastolic pressure and augment coronary flow. Myocardial performance should improve, LVdp/dt should increase, and by the reasoning discussed previously, systemic flow would also increase.

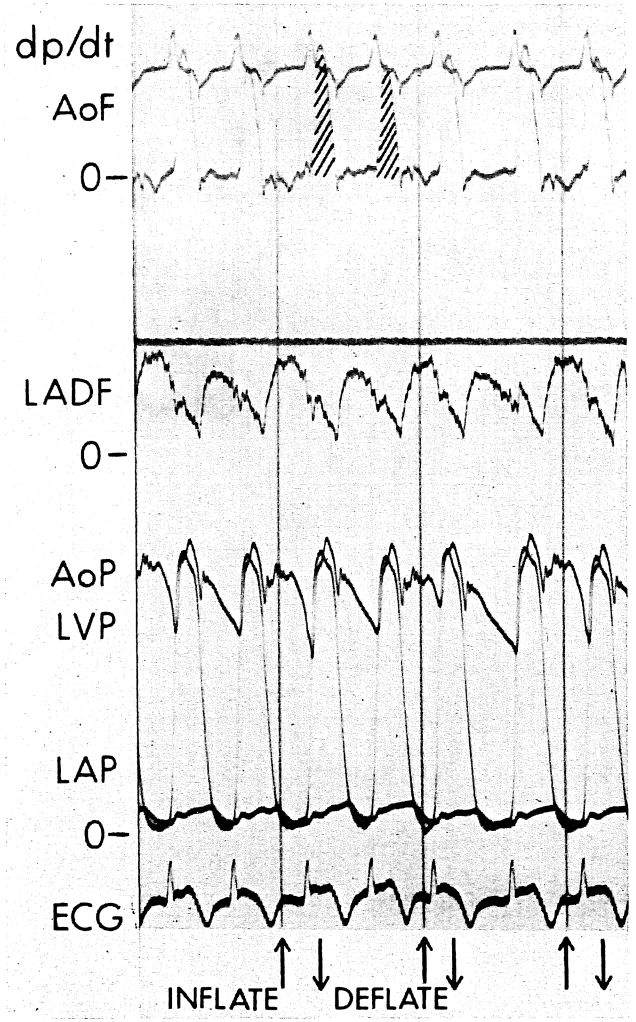

Figure 7. As in Figure 6, but the mitral flow is replaced by the Left Anterior Descending Coronary Artery flow (LADF). Pumping in the 1:2 mode illustrates the clear augmentation of coronary flow and improvement of stroke volume (shaded areas). Time lines at one/sec.

Some preliminary results are shown in Figures 6 and 7. In order to elucidate the dynamics of IABP on a beat-to-beat basis, the pump was operated in the 1:2 mode, so that the transient dynamic effects were observed before they became masked by reflex control mechanisms. In Figure 6, balloon deflation increased stroke-volume by 11%; regurgitant volume did not change, so that the RV/SV ratio decreased by 10%. This increase in stroke volume with IABP is normal, but unless there is a decrease in LVP, the regurgitant volume does not change. The effects of IABP on coronary flow are shown in Figure 7. The augmentation of coronary flow is clearly seen during balloon inflation and the increase in stroke volume is evident during deflation.

These data substantiate the physical analysis of the dynamics during mitral regurgitation, and they therefore indicate the desirability of further investigation. It must be pointed out, however, that these studies in dynamics are by no means definitive, because in both acute and chronic mitral regurgitation other physiological factors must be taken into consideration.

CONCLUSION

The methodology presented here is admittedly highly invasive and traumatic. Nevertheless it has enabled us to elucidate atrioventricular dynamics in a way not possible by less invasive means. We are now able to interpret the results of cardiac catheterization and noninvasive clinical methods more meaningfully.

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19 Flow Dynamics in Mitral Regurgitation

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Clinically, the hemodynamic assessment of mitral regurgitation has been limited by the lack of a method for the measurement of instantaneous blood flow across the mitral valve. Our studies have been carried out in the experimental laboratory and have been limited to two areas: 1) the measurement of flow dynamics in acute mitral regurgitation, and 2) the study of diastolic mitral regurgitation occurring with aortic valvular regurgitation.

Calves were prepared with electromagnetic flow transducers in a manner similar to that used in studies of the normal mitral valve. Instantaneous ventricular volume was determined by integrating the differential flow—the mitral flow minus the aortic flow—and extrapolating this measurement to absolute volume by gauging the left ventricular compliance at the end of the experiment. Acute mitral regurgitation was produced by the serial division of chordae tendineae in order to produce approximately 40% mitral regurgitation. Aortic regurgitation was produced by rupture of a single aortic cusp.

Figure 1 is a recording from a calf with approximately 40% mitral regurgitation. The simultaneous aortic flow and the left ventricular