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LEFT VENTRICULAR INFLOW PATTERNS AND MITRAL VALVE MOTION: ANIMAL STUDIES AND COMPUTER ANALYSIS

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The dynamics of flow across the mitral valve and the motion of the cusps have been investigated and analyzed by us both in vivo (1,2) and ex vivo (3) utilizing lumped parameter and distributed parameter approaches. This paper unites these studies and demonstrates that the results complement each other and are mathematically and physiologically consistent.

In vivo: In the open-chest anesthetized dog, phasic transmitral flow and the mitral valve echogram were recorded simultaneously with left ventricular and atrial pressures, aortic flow and electrocardiogram. In some experiments, cinefluorograms of opacified cusp motion were recorded along with the hemodynamic parameters. The pressure-flow relations across the normal mitral valve (Fig.1) follow a lumped parameter model:

$$\Delta p = A\ dQ/dt + B\ Q \qquad (1)$$

where Δp is the pressure difference across the mitral valve (LAP-LVP), Q is the volume flow, and A and B are constants representing inertance and resistance. This equation is deduced from the observation that the driving pressure difference precedes the flow at both peak and zero crossing indicating the existence of an inertial component. Furthermore, when the pressure gradient becomes zero, the flow decays exponentially (Fig. 2A), which is predicted by the linear relation between pressure gradient and flow. A square law relation, indicative of turbulent or disturbed flow, would result in a more rapid deceleration of flow when the gradient becomes equal to and remains at zero. If the gradient reverses (Fig. 2B) there is also a more rapid deceleration of flow, due not to increased dissipation, but to the adverse pressure difference.

Valvular compliance is negligible except at opening and closing where the release and storage of energy modifies these events in a qualitatively predictable manner. This storage and release is seen in the mitral flow traces of Fig. 1 as a closing spike of apparent backflow and a slow rise in flow preceding cross-over and valve opening. This is also evident in cine frames A, B and I, J of Fig. 3.

The mitral valve echogram reveals that the anterior cusp starts moving towards closure while flow is still accelerating (Fig. 1A, B). A calculation based on flow rate and base to apex dimension indicates that the diastolic closure movement of the mitral valve (EF slope) occurs before the advancing jet of blood has reached the apex of the ventricle. In both conditions of flow in Fig. 1, maximum valve opening occurs at about 40 msec. after the start of flow with an orifice area of approximately 3 cm^2 and a velocity of less than 40 cm/sec. Blood crossing the mitral annulus at this rate would scarcely have time to traverse the length of the anterior cusp of the mitral valve. Thus, this early diastolic closure motion can not be due to the large circulating vortex postulated by Bellhouse (4) in his model studies. These echo-flow results are consistent with those of Tsakiris et al. (5) who used cinefluorograms of implanted markers to observe mitral valve motion. They postulated a vortex which formed early in diastole and resulted in diastolic closure motion. The analysis presented in the next section will indicate a rationale for this process.

Ex vivo: A numerical method was used to solve the Navier-Stokes equations for the fluid and wall motion in a model of the left heart which preserves the normal anatomical relations, including chordae, and which possesses elastic walls with myocardial properties (Fig. 4A). Solutions are generated for the fluid and tissue motion in two dimensions representing a plane which is perpendicular to the base of the heart and bisects the two major leaflets.

When ventricular pressure falls below atrial, the valve opens rapidly resulting in considerable fluid momentum in the lateral direction (Fig. 4B). Thus, the jet does not form until later in diastole, at which time it contracts and flows toward the apex while vortices form at the cusp tips (Fig. 4C, D). Atrial systole (Fig. 4F) reinforces the jet and strengthens the vortex as the fluid finally sweeps up the walls to circulate behind the cusps. With the onset of ventricular systole (Fig. 4G) the cusps move toward closure and a stagnation point develops midway between the cusp tips and the mitral annulus, thereby minimizing backflow.

These studies serve to unite the three theories of flow patterns and valve closure: vortices, breaking jets and chordae tension. When the jet of ventricular filling decelerates, it becomes incorporated into an expanding vortex system which sweeps the valve toward closure. The valve leaflets participate in vortex formation, and tension on the chordae and commissural tissue is necessary to hold the leaflets in an appropriate position for the interaction to occur. Finally, the momentum of the fluid which has been accelerated by the atrial contraction preceding ventricular systole serves to insure an insignificant amount of backflow with valve closure. Only the fluid on the atrial side of the stagnation point will appear to regurgitate through the annulus; no retrograde flow passes the cusp tips. Finally, the effective orifice area of the jet is determined by the vena contracta, which in turn is determined by the annulus and funnel shape of the valve. Thus, the distance between the valve tips only partly influences the amount and velocity of the atrioventricular flow.

Filling patterns and valve motion are determined by a complex interaction of developed pressure, tissue constraints, and fluid dynamic forces.

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References

1. Laniado, S., Yellin, E.L., Miller, H., Frater, R.W.M. Temporal Relation of the First Heart Sound to Closure of the Mitral Valve. Circulation 47: 1006-1014, 1973.

2. Laniado, S., Yellin, E., Kotler, M., Levy, L., Stadler, J., Terdiman, R. A Study of the Dynamic Relations Between the Mitral Valve Echogram and Phasic Mitral Flow. Circulation 51: 104-113, 1975.

3. Peskin, C.S. Flow Patterns Around Heart Valves. Lecture Notes in Physics 19: 214-221, 1973.

4. Bellhouse, B.J. Fluid Mechanics of a Model Mitral Valve and Left Ventricle. Cardiovascular Research 6: 199-210,1972.

5. Tsakiris, A.G., Gordon, D.A., Mathieu, Y. and Lipton, I. Motion of Both Mitral Valve Leaflets: a Cineroentgenographic Study in Intact Dogs. J. Appl. Physiol. 39: 359-366, 1975.

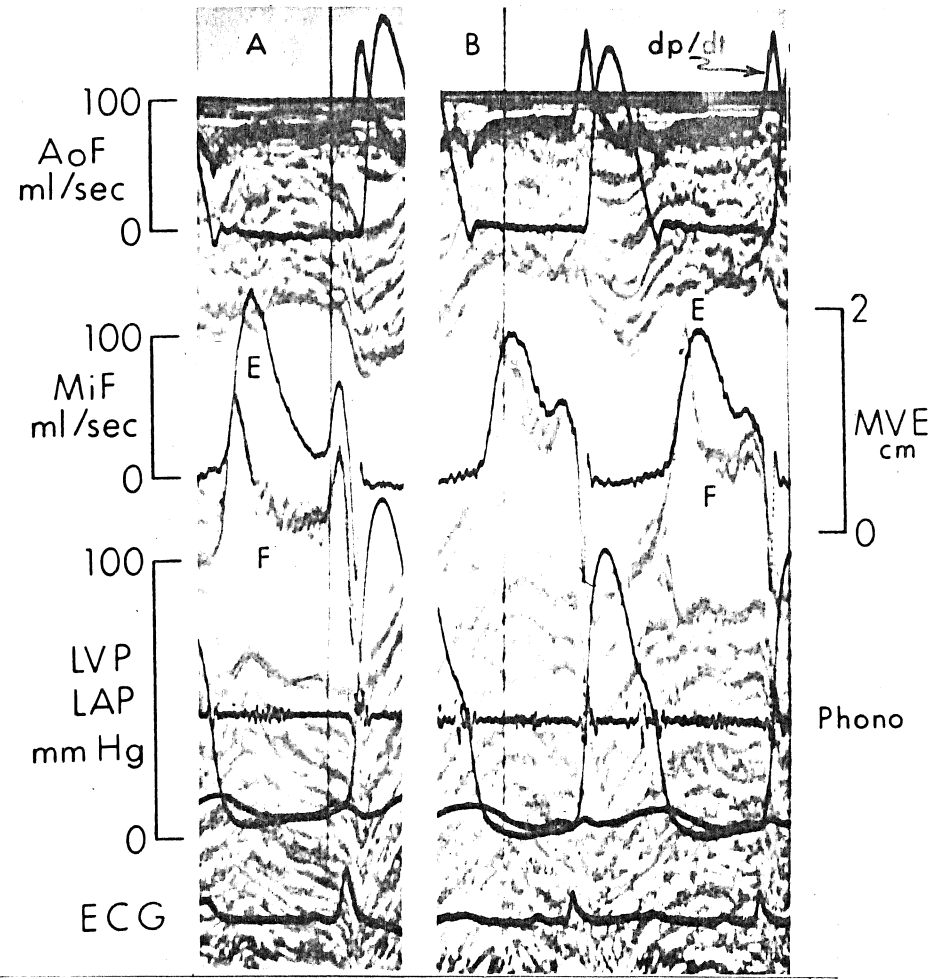
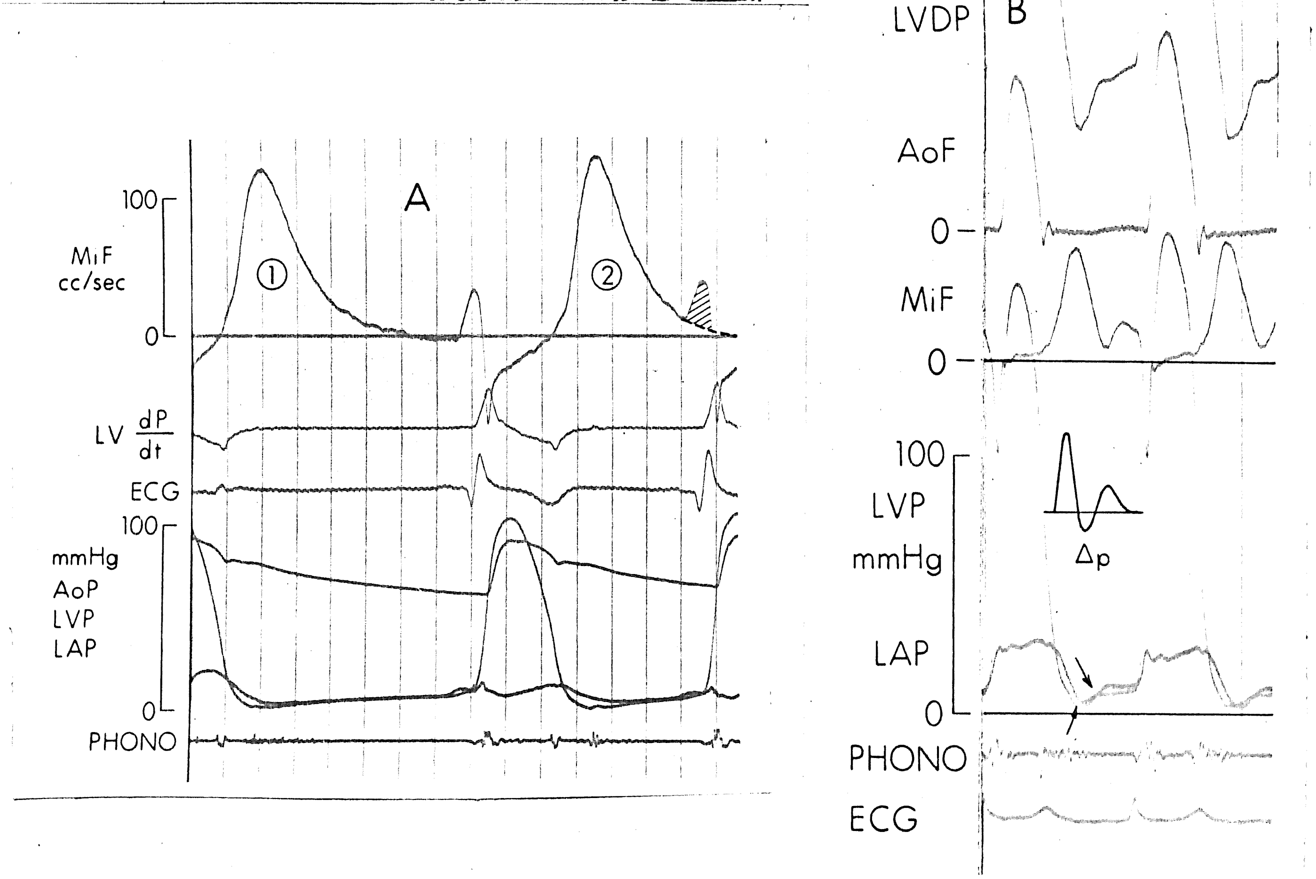


Figure 1 (Left). A record from a dog during two states of cardiac function and filling rate. In particular, note that the peak of cusp excursion (E point) precedes the peak of flow and closure movement (EF) starts while flow is still accelerating.

ECG: Electrocardiogram; LAP, LVP: Left Atrial &Left Ventricular pressure; MiF: Mitral Flow; AoF: Aortic Flow; MVE: Mitral Valve Echogram.

Figure 2 (Below). A: Illustrating the exponential decay of mitral flow in the presence of a zero pressure gradient. B: Illustrating the rapid deceleration of flow in the presence of an adverse pressure difference.



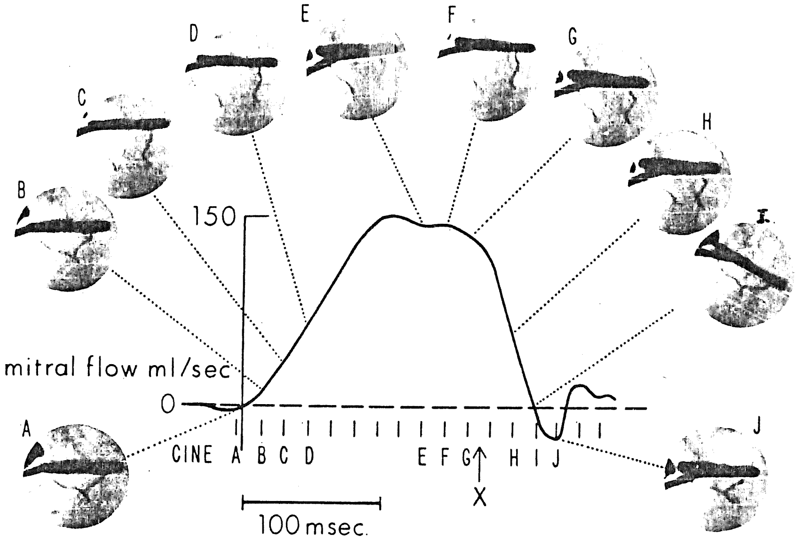


Figure 3. A record of Mitral Flow with selected frames from a cineflurogram superimposed to indicate the temporal relations. In particular, note that the first two and last two frames indicate release and storage of energy in the compliant valve cusps. At E the cusps were moving together when the atrial contraction re-opened them at F. X indicates the point of AV pressure crossover. (Reprinted from Laniado et al (1)).

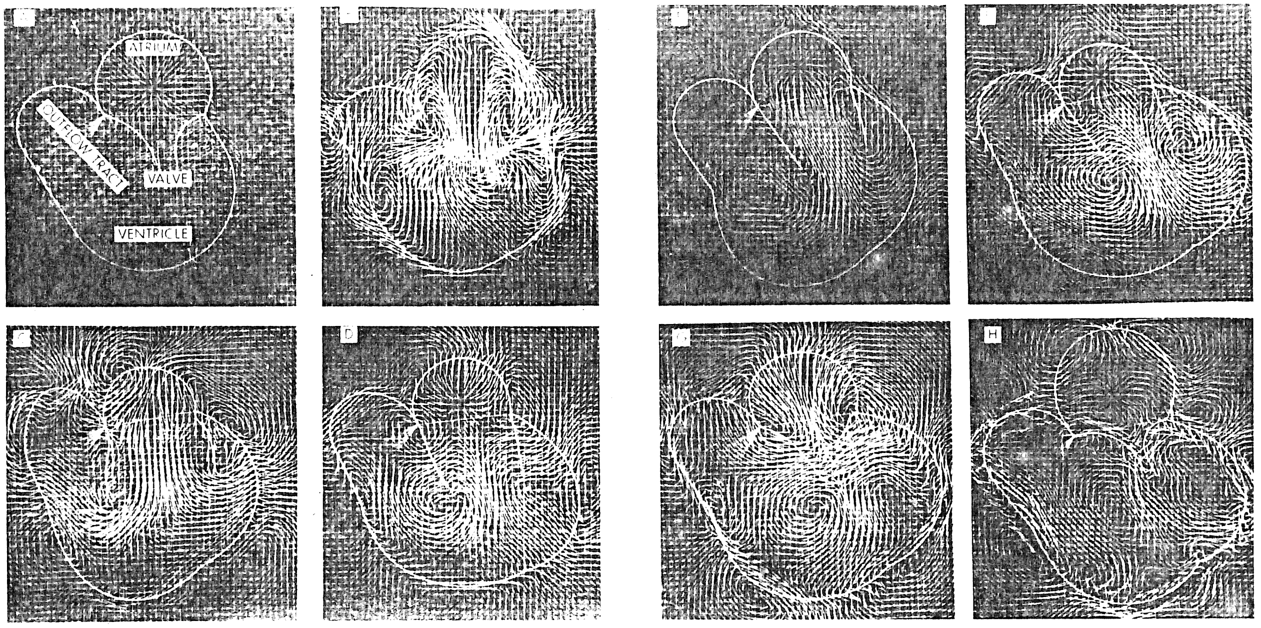


Figure 4. A computer print-out of the numerical solution to the equations of motion for the wall and fluid. Ventricular relaxation leads to rapid valve opening at B, with the dominant fluid motion in the lateral direction. From the wide open position in C, the cusps move toward closure in D where a vortex is seen to form at the cusp tips. The decaying jet in E is reinforced by an atrial contraction in F. The vortex behind the cusps facilitates closure as the ventricule contracts in G, leading to complete closure in H. Further discussion in the text. Note that vectors crossing the wall mean wall movement in that direction, not flow across the wall.