Atrial Contribution to Ventricular Filling in Mitral Stenosis

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Background. The importance of the contribution of atrial systole to ventricular filling in mitral stenosis is controversial. The cause of reduced cardiac output following the onset of atrial fibrillation may be due to an increased heart rate, a loss of booster pump function, or both.

Methods and Results. We studied the atrial contribution to filling under a variety of conditions by combining noninvasive studies of patients with computer modeling. Thirty patients in sinus rhythm with mild-to-severe stenosis were studied with two-dimensional and Doppler echocardiography for measurement of mitral flow velocity and mitral valve area (MVA). The mean±SD atrial contribution to left ventricular filling volume was 18±10% and varied inversely with mitral resistance. Patients with mild mitral stenosis (MVA, 1.8±0.7 cm²) and severe mitral stenosis (MVA, 0.9±0.2 cm²) had atrial contributions of 29±4% and 9±5%, respectively. The pathophysiological mechanisms responsible for these trends were further investigated by the computer model. In modeled severe mitral stenosis, increasing heart rate from 75 to 150 beats/min caused an increase of 5.2 mm Hg in mean left atrial pressure, whereas loss of atrial contraction at a heart rate of 150 beats/min caused only a 1.3 mm Hg increase.

Conclusions. The atrial booster pump contributes less to ventricular filling in mitral stenosis than in the normal heart, and the loss of atrial pump function is less important than the effect of increasing heart rate as the cause of decompensation during atrial fibrillation. (Circulation 1991;84:1469-1480)

Loss of the atrial contribution to ventricular filling (FV-A) occurs in mitral stenosis with the onset of atrial fibrillation. Both the loss of atrial “booster-pump” function and the decrease in diastolic filling time resulting from increased heart rate contribute to the decrease in cardiac output and the increase in mean left atrial pressure.1 However, neither the absolute nor the relative contributions of these factors have been well established.

A number of clinical studies have attempted to quantify FV-A in mitral stenosis. They have measured progressively more direct indexes of ventricular filling from ventricular pressures2 to cineangio-

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We used two-dimensional and Doppler echocardiography to determine the mitral orifice area and FV-A in patients with mitral stenosis of varying severities. Both the absolute atrial contribution and its dependence on orifice area were studied. The findings of the clinical study were extended with a computational model of ventricular filling dynamics. The model assessed the effects of independently varying heart rate and eliminating atrial pump function on ventricular filling. The model was also used to study ventricular filling dynamics in mitral stenosis more fully than is ethically and methodologically possible in the clinical setting. Finally, a canine model of mitral stenosis with directly measured mitral flow was examined.

Methods

Patient Study

Thirty patients with mitral stenosis in normal sinus rhythm were studied. Their ages ranged from 38 to 69 years. Left ventricular ejection fraction estimated by echocardiography was 60±9%.

An ultrasound imaging system (Model 77020AC, Hewlett-Packard) was used for both imaging and Doppler flow studies. The system has a phased-array sector scanner and a movable Doppler cursor that allows volume sampling directed by two-dimensional echocardiographic imaging in the pulsed Doppler mode. A continuous wave Doppler transducer (Model 21220A, Hewlett-Packard) was also used, and it was oriented by maximizing the Doppler frequency shifts.

M-mode echocardiograms were spatially oriented from the two-dimensional image, preferably from the short-axis view. The two-dimensional echocardiograms included several cross-sectional views of the heart. The long-axis view was obtained by orienting the sector plane parallel to the longitudinal axis of the left ventricle. Short-axis views were obtained by orienting the sector plane perpendicular to the long axis. The largest mitral valve area (MVA) was obtained with a Doppler echocardiographic analyzer (Microsonics Echo Doppler Analyzer, Indianapolis, Ind.) programmed for area computation.

Flow velocity across the mitral valve was obtained by pulsed and continuous wave Doppler echocardiography from the apex. We attempted to maximize the Doppler shifts by making small adjustments in transducer angulations. Flow velocities were calculated assuming a Doppler angle of 0°. The analyzer was used to measure peak mitral flow velocity (Vmean), mean mitral flow velocity (Vmean), peak mitral valve pressure gradient (ΔPmean), and diastolic filling period (DFP).

Filling volume entering the left ventricle through the mitral valve is the product of the flow velocity and the mitral orifice area integrated over the DFP. FV-A is defined as the increment in filling volume resulting from atrial contraction (Figure 1). Thus, FV-A does not include atrial conduit or reservoir function. Note that this defines the contribution as the difference between filling volume associated with sinus rhythm and filling volume of the first cycle without an atrial contraction. The percentage FV-A (%FV-A) is defined as FV-A divided by filling volume.

Mitrval valve resistance (R) is derived as follows. The mean pressure gradient across a stenotic valve (ΔP [mm Hg]) equals the product of the square of flow (Q [ml/sec]) and R (mm Hg/ml²/sec²):

\[ \Delta P = Q^2 \cdot R \]  

From the Bernoulli relation, ΔP also equals the square of the mean flow velocity (Vmean [m/sec]) multiplied by 4:

\[ \Delta P = 4 \cdot V_{\text{mean}}^2 \]  

Assuming that MVA (cm²) does not vary during diastole, an assumption that is reasonable for moderate-to-severe stenosis, the following equation can be written:

\[ Q = V_{\text{mean}} \cdot \text{MVA} \]  

Equations 1–3 can be combined to yield:

\[ R = 4 \times 10^{-4}/\text{MVA}^2 \]  

Model Study

The computational model is a lumped hydraulic analog of the pulmonary bed, left atrium, mitral orifice and valve, left ventricle, aortic valve, aorta, and systemic periphery. The analog schematic appears in Figure 2. Parametric values are chosen to represent the 15-kg dog. The details of the model rationale and design and the parametric values can be found in previously published reports. In brief, the pulmonary bed comprises serial compliances feeding into the left atrium through a conduit with properties of resistance and inductance. The left atrium is represented by a linear time-varying compliance. The mitral orifice and valve are modeled in a complex fashion to simulate forward flow such that the atrioventricular pressure gradient is proportional to the square of mitral flow. Retrograde flow simulates the bulging of the mitral valve leaflets into the left atrium during ventricular systole. The left ventricle is simulated by a complex compliance that provides a diastolic exponential pressure–volume relation and systolic pressure generation by increasing elastance. The aorta and periphery are simulated by a simple Windkessel model with peripheral runoff resistance. Differential equations based on the above scheme are solved on a microcomputer, and the results are given numerically and graphically (Figure 3).

For the present study, mitral stenoses of varying grades were simulated by successively doubling the mitral resistance (R2 in Figure 2) above its control value of 0.0008 mm Hg/ml²/sec². The effects of increasing mitral resistance on filling volume, atrial contribution to filling volume, peak mitral flow, and duration of DFP were studied at heart rates of 75 and 120 beats/min. At a heart rate of 75 beats/min, the experiment was repeated with an increased left atrial
contractility to simulate left atrial hypertrophy produced by chronic mitral stenosis. As in the patient study, FV-A is defined as the increment in filling resulting from the atrial contraction. Using the model, this value is obtained by subtracting from the actual filling volume the filling volume that would have occurred had the atrium not contracted.

A fixed cardiac output mode is also used. In this mode, the pressure input to the pulmonary bed is automatically adjusted to achieve a predetermined cardiac output. When cardiac output is fixed, mean left atrial pressure can be used as an index of the efficiency of blood transfer from the pulmonary bed into the left ventricle. An increase in mean left atrial pressure for any given cardiac output denotes reduced efficiency of blood transfer and would be associated with increased likelihood of pulmonary vascular congestion in vivo.

The fixed cardiac output mode is applied to varying degrees of mitral stenosis, both with and without atrial contraction, and at varying heart rates (75, 120, and 150 beats/min). This allows determination of the effect of loss of atrial contraction versus increases in heart rate on mean left atrial pressure in atrial fibrillation.

Results

Patient Study

Table 1 presents the echocardiographic results of both the patients with mitral stenosis and the control subjects. The mean MVA for the stenosis group was $1.4\pm0.6$ cm$^2$, which corresponds to a resistance of $3.4\pm3.0\times10^{-4}$ mm Hg/ml/sec$^2$. The peak and mean atrioventricular pressure gradients estimated from the Doppler data were $14\pm7$ and $8\pm5$ mm Hg, respectively. $V_{\text{mean}}$ including the atrial contraction was $121\pm47$ cm/sec, and $V_{\text{mean}}$ without the atrial contraction was $104\pm45$ cm/sec. The calculated total filling volume was $75\pm13$ ml, FV-A was $14\pm8$ ml, and %FV-A was $18\pm10\%$.

Ten patients had mild stenosis (valve area, more than 1.5 cm$^2$) with mean valve area of $2.0\pm0.4$ cm$^2$, resistance of $1.1\pm0.4\times10^{-4}$ mm Hg/ml$^2$/sec$^2$, and FV-A% of $29\pm4\%$. Nine patients with moderate stenosis (MVA, more than 1 cm$^2$ and equal to or less than 1.5 cm$^2$) had a mean valve area of $1.4\pm0.1$ cm$^2$, a resistance of $2.2\pm0.4\times10^{-4}$ mm Hg/ml$^2$/sec$^2$, and FV-A% of $19\pm5\%$. In the 11 patients with severe stenosis (MVA, less than 1 cm$^2$), mean valve area was $0.9\pm0.2$ cm$^2$, resistance was $6.5\pm3.1\times10^{-4}$ mm Hg/ml$^2$/sec$^2$, and FV-A% was only $9\pm5\%$.

Early diastolic $V_{\text{max}}$ correlated weakly with mitral resistance ($r=0.41$, $p=0.024$).

Figure 4 shows that FV-A% is inversely related to valve resistance. Linear regression analysis between these two variables yields a correlation coefficient of $-0.81$ ($p<0.001$).

In the normal group, $V_{\text{mean}}$ was $31\pm3$ cm/sec. Filling volume was $95\pm24$ ml, FV-A was $23\pm7$ ml, and %FV-A was $25\pm7\%$. 
Model Study

Further insight is provided by the computational model, which allows independent variation of heart rate, mitral resistance, and atrial contractility and prediction of cardiac output, left atrial pressure, left ventricular pressure, and pulmonary venous flow. This helps determine the effect of changing heart rate with and without loss of atrial pump function, thus facilitating an understanding of the effects of atrial fibrillation in mitral stenosis. It also allows us to clarify the compensatory mechanisms that come into play when the atrial contraction is lost.19

Plots of the modeled hemodynamic data versus time at heart rates of 75 and 120 beats/min appear in Figure 3. Data are presented in vertical panels, each representing one cardiac cycle beginning during ventricular isovolumic relaxation and continuing through diastole and the subsequent systole. The first panel at each rate corresponds to a mitral resistance of 0.0008 mm Hg/ml/sec^2, which is the control (nonstenotic) value for the computer simulation. Subsequent panels correspond to successive doubling of mitral resistance to a maximum of 0.0256 mm Hg/ml/sec^2. Note that the control mitral flow waveform is similar to that seen in normal subjects.18,20

As mitral resistance increases, the mitral flow waveform takes on the shape associated with mitral stenosis in Doppler echocardiographic studies of mitral velocity (Figure 1).18,20 A characteristic feature is the progressive decrease in the rate of flow deceleration after peak early diastolic flow. The absolute FV-A (difference in area between the two traces of mitral flow in each panel) clearly decreases with increasing mitral resistance. With increasing stenosis, the pressure gradient from left atrium to left ventricle increases. The increase in gradient is due to an increase in left atrial pressure as well as to a decrease in left ventricular pressure. The increase in left atrial pressure during atrial contraction (a wave) is larger and the increment in left ventricular volume due to atrial contraction is smaller as mitral resistance increases, particularly at the higher heart rate. During atrial systole, there is a short period of retrograde pulmonary vein flow that increases as mitral resistance and the magnitude of the a wave in left atrial pressure increase.

Mid-diastolic atrioventricular pressure gradient reversal associated with rapid mitral flow deceleration is present only at the control mitral resistance of 0.0008 mm Hg/ml/sec^2 at a heart rate of 75 beats/min. Any increase in mitral resistance above control effectively prevents this phenomenon from occurring.

The percent FV-A values at heart rates of 75 and 120 beats/min is plotted versus mitral resistance in Figure 5 (left). Note the similarity in trends between these model results and the patient data of Figure 4. At a heart rate of 75 beats/min, %FV-A decreases from 20.7% at control to 5.5% at the highest mitral resistance as a result of a greater decrease in FV-A than in total filling volume. At the control resistance,
filling volume is 18.5 ml and FV-A is 3.8 ml, whereas at the highest mitral resistance, filling volume decreases by 29% to 13.2 ml and FV-A decreases by 82% to 0.7 ml. FV-A% decreases to 6% at the highest mitral resistance when filling volume is 13.2 ml and FV-A is 0.7 ml. The effects of mitral resistance on %FV-A are similar at the two heart rates. The resistance values of the patient study are less than those of the model. This is because resistance is inversely proportional to the square of orifice area, which is significantly greater in the human subjects than in the model based on the 15-kg dog.

When left atrial contractility is doubled, the relation between FV-A% and mitral resistance is shifted upward. Thus, enhancement of atrial contractility can in part compensate for the loss of atrial contribution in mitral stenosis. For example, when mitral resistance is increased from 0.0008 to 0.0016 mm Hg/ml²/sec², enhanced atrial contractility is capable of completely restoring the FV-A%. However, the increase in atrial contribution cannot compensate for the loss of early diastolic filling volume, and total filling volume remains low.

The decrease of peak mitral flow (PMF) with increasing mitral stenosis is seen clearly in Figure 3 and plotted in Figure 5 (middle panel). PMF decreases to as low as 20% of control flow at maximum mitral resistance where it is actually less than the flow associated with atrial contraction (see Figure 3, upper panel). As seen in Figure 3 at a heart rate of 75 beats/min, the flow associated with atrial contraction begins to exceed early diastolic PMF at a mitral resistance of approximately 0.0128 mm Hg/ml²/sec². At the higher heart rate of 120 beats/min, this occurs at lower resistances.
Because atrial contractility has only a minimal effect on PMF, the velocity of atrial systolic flow will also exceed the early peak at even lower resistance values with enhanced atrial contractility.

The loss of filling volume in mitral stenosis is minimally compensated for by an increase in DFP that is related to the degree of stenosis. This is illustrated in Figure 5 (bottom), a plot of DFP normalized to cardiac cycle duration versus mitral resistance. The increase in time available for filling is due to earlier mitral valve opening as well as to later mitral valve closure. The former is secondary to increased left atrial pressure; the latter is secondary to increased left atrial pressure and decreased left ventricular pressure. When mitral resistance is large, the mitral flow waveform is relatively flat, and the volume entering the ventricle is approximately proportional to the diastolic filling time. At maximal mitral resistance, the DFP and therefore the filling volume are increased by approximately 7% over the values that would have been obtained had the filling period not increased. This small increase in filling time only blunts the effect on the filling volume of increased resistance. The effect of resistance on DFP is even less important at high heart rates when there is a progressively smaller compensation for the decrease in cardiac output resulting from increased resistance.

Plots of mean left atrial pressure versus mitral resistance for heart rates of 75, 120, and 150 beats/min, both with and without atrial contraction, are presented in Figure 6. These data are from the computational model with cardiac output fixed at 1.4 I/min.

Mean left atrial pressure is always greater when the atrial contraction is absent, implying a loss of efficiency of atrioventricular blood transfer. In this simulation, loss of atrial contraction in the absence of mitral stenosis increases mean left atrial pressure by 7.8 mm Hg (from 10.6 to 18.4 mm Hg) at a heart rate of 75 beats/min. When heart rate is 150 beats/min, the increase is only 1.4 mm Hg (from 4.4 to 5.8 mm Hg). At the highest mitral resistance, loss of atrial contraction increases mean left atrial pressure by 1.9 mm Hg (from 29 to 30.9 mm Hg) at a heart rate of 75 beats/min and by 1.3 mm Hg (from 34.8 to 36.1 mm Hg) at a heart rate of 150 beats/min. Thus, the effect of loss of atrial contraction on mean left atrial pressure is greatest at lower mitral resistances and slower heart rates.

Increases in heart rate tend to lower mean left atrial pressure at low mitral resistances and raise this pressure at higher mitral resistances. This is because at low mitral resistances, increases in heart rate cause the left ventricle to operate at low end-systolic and end-diastolic volumes. This results in a lower mean

### Table 1. Echocardiographic Results of Patients and Control Subjects

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HR, heart rate; MVA, mitral valve area; DFP, diastolic filling period; V_mean, mean flow velocity; V^*_mean, mean flow velocity without atrial contribution; FV, filling volume; FV-A, filling volume due to atrial contribution; %FV-A, atrial contribution as a percent of filling volume; V_max, peak mitral flow velocity; Δ P_max, peak atrioventricular pressure gradient; Δ P_mean, mean atrioventricular pressure gradient; R, resistance of mitral valve/orifice.

Group 1, mitral valve area less than 1.5 cm²; group 2, mitral valve area greater than 1.0 cm² but less than or equal to 1.5 cm²; group 3, mitral valve area less than or equal to 1.0 cm².

left atrial pressure. However, the combination of mitral stenosis and shortened DFP associated with higher heart rates impedes left ventricular filling and mean left atrial pressure increases. Thus, at the highest mitral resistance, mean left atrial pressure increases from 29.0 to 34.8 mm Hg when heart rate increases from 75 to 150 beats/min.

In the absence of mitral stenosis (mitral resistance, 0.0008 mm Hg/ml²/sec²) and at a heart rate of 150 beats/min, loss of atrial conduction causes an increase in mean left atrial pressure of only 1.4 mm Hg (from 4.5 to 5.8 mm Hg). At this mitral resistance, the effect of increasing heart rate from 75 to 150 beats/min in the presence of atrial conduction actually decreases mean left atrial pressure by 6.2 mm Hg (from 10.6 to 4.4 mm Hg). A similar decrease in mean left atrial pressure is seen when heart rate increases from 75 to 120 beats/min. Thus, both the loss of atrial contraction and the increase in heart

Figure 4. Scatterplot of percent atrial systolic contribution to ventricular filling in 30 patients with varying degrees of mitral stenosis, represented by R² (calculated resistance of mitral valve). Correlation coefficient, -0.81; p<0.001.
FIGURE 5. Plots of model results. Top panel: Percent atrial contribution to filling (FV-A/FV) as a function of resistance at two heart rates (HRs) and two levels of atrial contractility at lower rate. Note similarity to data from patients in Figure 4 and from dogs in Figure 7. Middle panel: Peak mitral flow (PMF), normalized to control, with increasing resistance at HR of 75 beats/min. Bottom panel: Diastolic filling period (DFP), as a fraction of RR interval, with increasing mitral resistance at HR of 75 beats/min. Note small effect of enhanced atrial contractility and its decreased influence in severe stenosis. R2, calculated resistance of mitral valve.

rate associated with the onset of atrial fibrillation are well tolerated in the absence of mitral stenosis.

In the presence of mitral stenosis (mitral resistance, 0.0256 mm Hg/ml2/sec2) and heart rate of 150 beats/min, loss of atrial contraction causes a small increase in mean left atrial pressure of 1.3 mm Hg (from 34.8 to 36.1 mm Hg). However, an increase in heart rate alone from 75 to 150 beats/min in the presence of atrial contraction causes a more significant increase of 5.2 mm Hg (from 29.0 to 34.8 mm Hg). Thus, in mitral stenosis, most of the increase in mean left atrial pressure from simulated atrial fibrillation is due to the increase in heart rate, with only a small fraction of the increase due to loss of the atrial contraction per se.

Discussion

Attempts to quantify FV-A in mitral stenosis have used measurement of ventricular pressures, cineangiograms, atrioventricular pressure gradients, M-mode echocardiographic indexes, and Doppler echocardiographic indexes. Carleton and Graettinger varied the paced atrioventricular interval from 150 to less than 10 msec and found no change in left ventricular systolic pressure in mitral stenosis, implying that the atrial contribution is small. Kendall et al estimated filling volume from the atrioventricular pressure gradient and found that an effective atrial contraction increased filling volume from 8% to 24% with the percent increase generally greater with milder degrees of stenosis. Using similar techniques, Thompson et al attributed 19% of cardiac output to the effect of atrial contraction in mitral stenosis, whereas Heidenreich et al found that peak left ventricular pressure increased by 24% when atrioventricular delay was optimal. Stott et al used cineangiography and found FV-A% to be 26% in controls and 24% in mitral stenosis—an insignificant difference.

Yamaguchi et al estimated phasic left ventricular volume from M-mode echocardiography and calculated atrial contribution from the end-diastolic portion of the curve. Unfortunately, this technique fails to subtract atrial conduit function from pump function (see below) and yields artificially large atrial contributions to ventricular filling of 37% and 26% for mild (orifice area, more than 1.5 cm2) and moderate (orifice area, more than 1.0 cm2 and less than 1.5 cm2) stenosis, respectively. With severe stenosis (orifice area, less than 1.0 cm2), atrial contribution was 14%, which is not significantly different than the control value of 18%. Although their technique overestimates the atrial contribution in mitral stenosis, the basic trend is for atrial contribution to increase with increasing orifice area. Parris et al used pulsed and continuous wave Doppler echocardiography to estimate mitral flow velocity in patients with mild-to-moderate mitral stenosis. They found that the FV-A% ranged from 2% to 37% and decreased with increasing degrees of stenosis. Jaffe and Roche used continuous wave Doppler echocardiography to arrive at a value of 11% for the atrial contribution in severe mitral stenosis. Unfortunately, in neither of these two reports are their methods applied to a normal population to provide a baseline for comparison.

Thus, previous reports of the importance of atrial contraction in mitral stenosis have reached differing conclusions. By directly measuring mitral flow velocity in patients with a spectrum of mitral orifice areas.
ranging from normal to severely stenotic and by complementing and supplementing these findings with an established computational model of the left heart, we can draw definitive conclusions about the absolute and relative effects of atrial pump function in mitral stenosis.

In the clinical component of the present study, we have shown that FV-A% varies inversely with the degree of stenosis. For mitral resistances less than 0.00016 mm Hg/ml²/sec², FV-A% ranges from 21% to 34% with a mean value of 29%; for resistances from 0.00016 to 0.0003 mm Hg/ml²/sec², the range is 11% to 25% with a mean value of 19%; and for resistances of more than 0.0006 mm Hg/ml²/sec², the range is 1% to 17% with a mean value of 9%. These resistances correspond to our definitions of mild, moderate, and severe stenosis by valve area (see above). The range of atrial contribution in the normal subjects was 17–36% with a mean value of 25%. The trend toward a smaller atrial contribution with increasing degree of stenosis is consistent with the predictions of our computational model in which the atrial contribution decreased to 16%, and to 7% when mitral resistance progressively increased. Both the trend and magnitude of the percent contribution differ with commonly held views of the importance of the atrial contraction in filling the ventricle through a narrowed orifice.9,11

The model allows us to compare the effects of increasing heart rate in mitral stenosis with and without loss of atrial function. This facilitates an understanding of the effect of atrial fibrillation, which is common in mitral stenosis. Figure 6 predicts that in the absence of mitral stenosis, loss of the atrial contraction causes a trivial increase in mean left atrial pressure (1.4 mm Hg), whereas an increase in heart rate from 75 to 150 beats/min actually decreases mean left atrial pressure. Thus, the normal heart can maintain cardiac output without a significant increase in mean left atrial pressure in the setting of atrial fibrillation with a ventricular rate of 150. However, when the mitral valve is severely stenotic, loss of atrial contraction causes an increase in mean left atrial pressure of 1.3 mm Hg and an increase in heart rate causes an increase of 5.2 mm Hg. Thus, a substantial increase in mean left atrial pressure is required to maintain cardiac output. Most of the increase in mean left atrial pressure is required to offset the effect of increased heart rate rather than the effect of loss of atrial contraction.

**Canine Studies**

To accurately model the clinical setting in which left atrial hypertrophy develops with mitral stenosis, an attempt was made to create chronic mitral stenosis in three dogs. A stenotic (1.25 cm²) electromagnetic flow probe was inserted into the mitral annulus. Because of technical limitations, the chronic studies failed to live up to expectations. A retrospective analysis was undertaken of data from three dogs acutely or chronically instrumented with normalized electromagnetic flow probes on the mitral annulus. In these dogs, functional stenosis inadvertently resulted from probe interference with the valve, fibrin deposition and tissue in-growth on the probe leading to a reduced orifice area, and/or from atriotomy resulting in interference with atrial inflow. Severity of the stenosis was derived from the atrioventricular pressure gradient and the shape of the mitral flow curve. Only FV-A% could be readily calculated. Because we can only infer the degree of stenosis from the shape of the flow waveform, we have limited the presentation of results to a qualitative description of the records and a report of %FV-A.
Figure 7 (left) shows a normal mitral flow trace along with high-gain atrial and ventricular pressures. FV-A% (dark shaded area) is 25%. In contrast, the moderate and severe stenoses shown in Figure 7 (middle and right) illustrate atrial contributions of 11% and 12%, respectively. In a previously published study of severe stenosis with a measured valve area of 0.8 cm², FV-A% was 9%.²¹

**Filling Dynamics in Mitral Stenosis**

We have demonstrated that the pattern of ventricular filling is grossly disturbed in mitral stenosis. The pattern of mitral flow in the normal heart (Figures 1, 3, and 7) is 1) very rapid acceleration to an early diastolic peak after mitral valve opening; 2) rapid flow deceleration to a minimal flow rate by mid-diastole due to a decreasing, and often reversing, atrioventricular pressure gradient; 3) relatively low oscillatory flow as the atrial and ventricular pressure oscillations decay and ultimately equilibrate; 4) a second rapid acceleration to a second peak due to atrial contraction; and 5) deceleration in late diastole due to atrial relaxation and emptying and/or to ventricular activation.¹²,²²–²⁵ In Figures 3 and 7, it can be seen that all five phases of filling are distorted by mitral stenosis to a degree proportional to the degree of stenosis. By phase, 1) early diastolic PMF is reduced while flow velocity is increased, 2) rates of atrioventricular pressure gradient reduction and flow deceleration are reduced, 3) and there is an absence of oscillatory flow, 4) a reduction in second peak flow, and 5) slow flow deceleration.

The reduction in peak flow of the first phase is due to increased mitral resistance, which limits mitral flow for any given atrioventricular pressure gradient. Although the pressure gradient is raised by compensatory mechanisms that increase atrial pressure at the time of mitral valve opening and decrease minimum ventricular pressure,¹⁹ PMF remains depressed. In the patient study, Vₘₐₓ increased with increased severity of stenosis. This is not unexpected because mitral orifice area decreases in mitral stenosis. An increase in Vₘₐₓ is well accepted in mitral stenosis.¹⁸

Under normal conditions in the second phase of diastole, mitral flow decreases atrial pressure and increases ventricular pressure so that the atrioventricular pressure gradient very rapidly approaches zero and, because of flow inertia, becomes negative.¹²,²³ The rapid decrease and reversal of the gradient cause rapid flow deceleration. In mitral stenosis, there is a decrease in the flow rate, the rate of atrial pressure fall, and the rate of ventricular pressure rise. Thus, the decrease in the atrioventricular pressure gradient is slow, and the gradient never reverses. This directly causes a reduction of the rate of deceleration of mitral flow. This effect, clearly seen in the modeled data, is the basis for the "pressure half-time" method of calculating mitral orifice area in mitral stenosis.

Phase 3 of diastole can occur only after rapid flow deceleration.²³ In mitral stenosis, flow deceleration is sufficiently slow so that significant mitral flow is maintained until atrial contraction or the end of diastole. In phase 4 of diastole, atrial contraction causes a second increase in the atrioventricular pressure gradient, which reaccelerates mitral flow. As in phase 1, the resulting PMF is less in mitral stenosis than in the normal heart, despite a larger developed atrial pressure. Finally, in phase 5, the rate of flow deceleration is slowed because of increased resistance to atrial emptying and consequent prolongation of the pressure gradient enhancement by atrial systole. Even if the FR interval is short and ventricular systole intervenes, diastole is prolonged because it takes longer for ventricular pressure to rise to the increased atrial pressure.

The systolic function of the left ventricle was within normal limits in the patients studied with mitral stenosis. Similarly, the computational model assumed normal function and size of the left ventri-
The conclusions regarding the relative insensitivity of FV-A apply only to subjects with these characteristics. The effect of atrial fibrillation on atrioventricular blood transfer is not due solely to loss of atrial contraction and loss of time available for ventricular filling. Other factors influencing the efficiency of blood transfer include increase in left atrial size and change of left atrial compliance, mitral annulus motion, and changes in phasic pulmonary flow patterns, all of which may change in patients with atrial fibrillation.

The diastolic (K) phase of pulmonary venous flow takes on a continuous low-velocity shape in mild-to-moderate mitral stenosis and is of very low velocity in severe mitral stenosis. The systolic (J) phase remains with approximately the same flow velocity as in normal subjects. With the onset of atrial fibrillation, the systolic pulmonary venous flow is significantly diminished, and there is a relative increase in the diastolic velocity. Normally, the atrium operates as a reservoir of blood awaiting the opening of the mitral valve in diastole and maintaining left atrial pressure despite high rates of left ventricular filling. The loss of the systolic flow component of pulmonary venous flow in atrial fibrillation impedes this reservoir function. However, in mitral stenosis, the rate of left ventricular filling (mitral flow) is low, and there is little need for atrial reservoir function to buffer the early diastolic left ventricular filling. Thus, in mitral stenosis, the left atrium acts primarily as a conduit rather than as a reservoir or pump.

**Effect of Method of Computation of FV-A**

At any point in diastole, mitral flow may be divided into atrial conduit, reservoir, and pump function. In early diastole, more blood leaves the atrium than enters it from the pulmonary veins. Thus, mitral flow is due exclusively to atrial conduit and reservoir function. In late diastole, after the onset of atrial systole, mitral flow equals the sum of the flow due to atrial contraction (pump function) and the flow that would have occurred even in the absence of atrial systole (conduit/reservoir function).

Most previously reported methods of analysis of FV-A assume that all mitral flow after the onset of atrial systole is due to atrial systole (i.e., pump function). These methods overestimate the atrial contribution by also including atrial conduit and reservoir function. This error is especially significant in two conditions: tachycardia and mitral stenosis. To illustrate with Figure 1, the assumption that all mitral flow after the onset of atrial systole is due to the atrial contraction yields FV-A% equal to area ABCA divided by area DEFACT (the crosshatched area is included). The method used in our analysis yields area AFGA divided by area DEFACT (the crosshatched area is not included). For the stenotic waveform in the left panel, the first method yields FV-A% of 37%, whereas our method yields a value of only 4%. The values for the less stenotic pattern in the right panel are 36% and 21%, respectively. Thus, methods that include atrial conduit and reservoir function overestimate FV-A most profoundly in high-grade mitral stenosis.

FV-A decreases in mitral stenosis. By Doppler echocardiography, FV-A is 29%, 19%, and 9% in mild, moderate, and severe mitral stenosis, respectively. A computational model has shown that there also is a progressive loss of early diastolic mitral flow rate and a small increase in DFP, which serves to minimally compensate for loss of atrial pump function. The model allows independent variation of heart rate and simulation of loss of atrial contraction, facilitating study of these effects of atrial fibrillation. When the model is run with fixed cardiac output, the effect of loss of atrial contraction is seen to be less important in increasing mean left atrial pressure than is an increase in heart rate.

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