Effects of Mitral Regurgitation on Pulmonary Venous Flow and Left Atrial Pressure: An Intraoperative Transesophageal Echocardiographic Study

ALLAN L. KLEIN, MD, FACC, WILLIAM J. STEWART, MD, FACC, JAMES BARTLETT, DO, GERALD I. COHEN, MD, FRED KAHAN, MD, GREGORY PEARCE, MS, KATHLEEN HUSBANDS, RN, ALEXANDER S. BAILEY, MS, ERNESTO E. SALCEDO, MD, FACC, DELOS M. COSGROVE, MD, FACC

Cleveland, Ohio

Objectives and Background. **Pulmonary venous flows recorded by pulsed wave Doppler transesophageal echocardiography examination can be used to assess the severity of mitral regurgitation. Pulmonary venous flows are also related to left atrial pressures; however, the determinants of these flows have yet to be characterized in the presence of mitral regurgitation.**

Methods. **We simultaneously recorded intraoperative pulmonary venous flows by transesophageal echocardiography and left atrial pressures by direct left atrial puncture in 16 patients with different grades of mitral regurgitation: 2+ (n = 5), 3+ (n = 4) and 4+ (n = 7). Pulmonary venous peak systolic and diastolic flow velocities and peak reversed systolic flow velocities were compared with left atrial pressure *a* and *v* waves, *a-x* and *v-y* descent values and left atrial volumes.**

Results. **Pulmonary venous systolic to diastolic flow ratios correlated with decreases in left atrial pressure *a/v* ratios and with increases in the *v* waves of patients with higher grades of mitral regurgitation. Univariate analysis revealed that the best determinants of the pulmonary venous systolic to diastolic flow ratio were the left atrial pressure *v* wave (r = −0.76), the *v-y* descent value (r = −0.73) and the *a/v* ratio (r = 0.71). Lower correlations were found for left atrial end-systolic (r = −0.48) and end-diastolic (r = −0.42) volumes. Reversed systolic flow was present in patients with 4+ mitral regurgitation, despite left atrial enlargement.**

Conclusions. **Pulmonary venous flow can be used to assess the severity of mitral regurgitation and reflects the effects of mitral regurgitation severity on the left atrial pressure *a* and *v* waves.**

(J Am Coll Cardiol 1992;20:1345–52)

Pulmonary venous flow patterns recorded by pulsed Doppler transesophageal echocardiography have recently been used to assess the severity of mitral regurgitation (1–3). Normal biphasic systolic and diastolic flow in the pulmonary veins is altered as the severity of mitral regurgitation increases. Normal systolic flow was seen in patients with 2+ mitral regurgitation, whereas blunted and reversed systolic flows were detected in patients with 3+ and 4+ mitral regurgitation, respectively (2). Previous investigations (4–7) have shown that pulmonary venous systolic and diastolic flows may be directly related to the nadir of the left atrial pressure *a-x* and *v-y* descents. However, this relation has not been studied in the presence of mitral regurgitation. Therefore, the purpose of this study was 1) to assess the relation between pulmonary venous flow and left atrial pressure in patients with different grades of mitral regurgitation, and 2) to assess the left atrial pressure and left atrial volumetric determinants of reversed systolic flow in the pulmonary veins.

Methods

Patient group. The study group comprised 16 consecutive patients (9 women and 7 men with a mean age of 59 ± 13 years; range 37 to 83) with mitral regurgitation who were undergoing surgery, generally on the mitral valve, and had an intraoperative transesophageal echocardiogram to assess the severity of mitral regurgitation. Nine (56%) of the 16 patients had had previous open heart surgery, including 4 patients with mitral valve replacement, 1 patient with mitral balloon valvuloplasty, 3 patients with coronary artery bypass surgery and 1 patient with aortic valve surgery. Fourteen (88%) of the 16 patients subsequently had mitral valve surgery; 8 had mitral valve repair, 6 had mitral valve replacement and 2 had coronary bypass surgery. The cause of the mitral regurgitation was degenerative native valve disease (prolapse or flail chordae) in five patients (31%), prosthetic valve dysfunction in four (25%), rheumatic native valve disease in three (19%) and ischemic mitral regurgita-

From the Department of Cardiology, The Cleveland Clinic Foundation, Cleveland, Ohio.

Manuscript received February 18, 1992; revised manuscript received May 7, 1992, accepted May 27, 1992.

Address for correspondence: Allan L. Klein, MD, Desk F15, The Cleveland Clinic Foundation, 9500 Euclid Avenue, Cleveland, Ohio 44195-5064.

0735-1097/92/$5.00

JACC Vol. 20, No. 6
November 15, 1992:1345–52

tion in four (25%). All patients had chronic mitral regurgitation (duration >1 month). The protocol was approved by the Research Protocol Committee at The Cleveland Clinic Foundation and informed consent was obtained from all patients.

Anesthesia. Anesthesia was induced with a high dose narcotic technique using fentanyl (75 to 100 μg/kg body weight), diazepam (0.1 to 0.15 mg/kg) and vecuronium (0.1 to 0.2 mg/kg) (8).

Measurement protocol. To assess the influence of left atrial pressure variables on pulmonary venous flow, left atrial pressures were measured with fluid-filled catheters placed directly in the left atrium, and pulsed wave Doppler transesophageal echocardiographic recordings were made of the left upper pulmonary vein. This vein was used because transesophageal echocardiographic recordings of this vein can be easily and rapidly obtained in all patients (9). These measurements were taken after the pericardium was opened but before cannulation and cardiopulmonary bypass were instituted.

Catheter placement. To measure left atrial pressure, a 16-gauge catheter (Becton, Dickinson, Deseret) was inserted into the middle of the left atrium by direct left atrial puncture through the right upper pulmonary vein. The fluid-filled catheter was connected by 24-in. (70 cm) tubing (Spectramed) to a solid state pressure transducer (Spectramed) that was leveled at the right atrium. A resonance overshoot eliminator (Spectramed) prevented overshoot of the pressure signal. The pressure signal was magnified by a Gould amplifier (model 11-G4123-01) and connected by a stereo cable to the auxiliary input jack of the echocardiographic Doppler machine.

A pulmonary artery catheter (Spectramed) and an intraarterial catheter (Arrow International) measured standard hemodynamic variables, including cardiac output, central venous pressure, pulmonary artery systolic and diastolic pressures and mean arterial pressures.

Transesophageal echocardiographic examination. Transesophageal echocardiography was performed intraoperatively with the use of a 5-MHz monoplane transducer (Hewlett-Packard model 77020A), that was passed into the esophagus according to previously described methods (10). A basal short-axis view of the left upper pulmonary vein was obtained by positioning the probe about 30 cm from the incisors. The sample volume was placed 2 cm beyond the orifice of the left upper pulmonary vein with the left atrium. Fourteen (88%) of the 16 patients had a complete preoperative echocardiogram obtained with the use of a 2.25-MHz transducer.

Hemodynamic measurements. All hemodynamic and Doppler measurements were analyzed manually with an off-line digitizing computer (Dextra). Phasic left atrial pressure was recorded on a hard copy at a speed of 50 or 100 mm/s on a calibrated 0- to 40-mm Hg pressure scale. The left atrial pressure wave was evaluated for the amplitude of the *a* and *v* waves and the two descents (*a-x* and *v-y* [11]) except for patients in atrial fibrillation, in whom only *v* wave

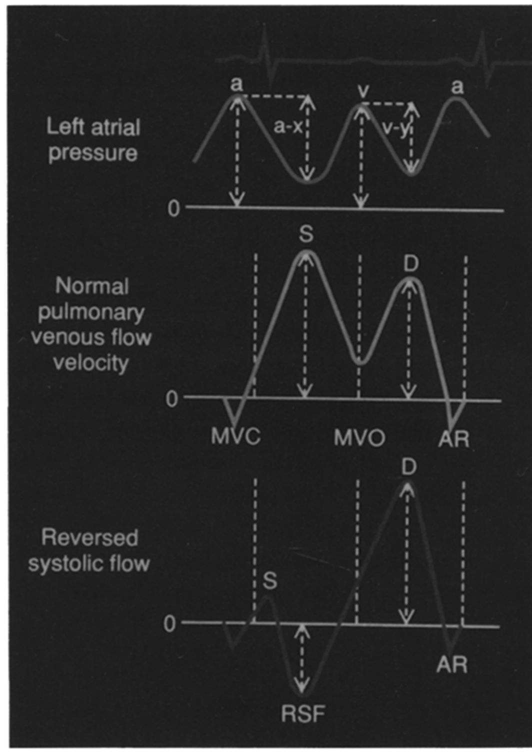

Figure 1. Electrocardiogram (**top tracing**) followed, respectively, by graphic illustrations of left atrial pressure, normal pulmonary venous flows and reversed systolic flow measurements. The left atrial pressure *a* and *v* waves are measured from the baseline (at 0) to their peaks in mm Hg, and *a-x* and *v-y* descents are measured from the peaks of the *a* and *v* waves to their troughs. Normal pulmonary venous flow consists of biphasic forward systolic (S) and diastolic (D) flow that are measured from the baseline to the peaks. Reversed systolic flow (RSF) is systolic flow occurring below the baseline and is recorded as a negative number. AR = atrial reversal flow velocity; MVC = mitral valve closure; MVO = mitral valve opening.

and *v-y* descents were measured (Fig. 1). Mean left atrial pressure and the peak *v* wave above the mean were also measured. Mean values were obtained by averaging at least 3 beats. The peak *a* and *v* waves were measured from 0 mm Hg to their peaks, and the *a-x* and *v-y* descents were measured from the peaks to their troughs (Fig. 1).

Pulmonary venous flow measurements. Pulmonary venous flows were grouped into one of three patterns as previously described (2): reversed systolic flow, blunted flow or normal flow. Reversed systolic flow is retrograde flow as indicated by a spectral Doppler profile below the baseline during most of the systole; it is expressed as a negative value (Fig. 1). If a small amount of forward systolic flow was followed by reversed systolic flow, the difference was obtained to give the total systolic flow. Blunted systolic flow is a systolic/diastolic flow ratio between 0 and 1, and normal pulmonary systolic flow is a systolic/diastolic flow ratio ≥1.

Peak pulmonary venous systolic and diastolic velocities were measured from the baseline to the peak, and a systolic to diastolic flow ratio was calculated. A negative ratio indicated reversed systolic flow. The flow-velocity integrals of the systolic, diastolic and reversed systolic flow waves were obtained by digitizing the darkest portions of the flow velocities. Reversed systolic flow as a percent of forward flow was calculated as the percent of reversed systolic flow integral to the total forward systolic and diastolic flow integrals.

Transthoracic echocardiographic measurements. Left ventricular end-systolic and end-diastolic and left atrial dimensions were derived from two-dimensional M-mode transthoracic echocardiography by using the parasternal short-axis view of the left ventricle. Ejection fraction was calculated from the left ventricular short axis at the midventricular level according to the method of Quinones et al. (12). The transthoracic study was performed an average of 6 days before the intraoperative study.

The complete left atrial area was measured with transthoracic echocardiography in orthogonal views because the full areas could not be measured by transesophageal echocardiography (13). Measurements for three to six cardiac cycles were averaged by an off-line digitizing computer (Dextra). Left atrial area was derived by planimetry of the largest end-diastolic area from the apical four- and two-chamber views. Left atrial end-diastolic and end-systolic volumes were similarly derived from these two views by using the modified biplane Simpson's rule (14).

Grading mitral regurgitation. The severity of mitral regurgitation was graded qualitatively by an independent observer who compared the maximal distribution of the mosaic portion of the regurgitant jet indicated by transesophageal echocardiographic color flow mapping with the size of the left atrium, in a procedure similar to that described for transthoracic echocardiography (15). Mitral regurgitation was graded on a scale of 1+ to 4+: mild = 1+ (<15%), moderate = 2+ (15% to 35%), moderately severe = 3+ (36% to 55%) and severe = 4+ (>55%). Eccentric 4+ regurgitant jets often showed swirling or vortex formation across the roof of the left atria.

The severity of mitral regurgitation was also assessed by nonsimultaneous cardiac catheterization in 12 (75%) of the 16 patients with the use of the classification of mitral regurgitation described by Sellers et al. (16) with grades 1+ to 4+: mild = 1+, moderate = 2+, moderately severe = 3+ and severe = 4+. The interval between the cardiac catheterization and the intraoperative Doppler study averaged 21 days (range 1 to 69 days). Four patients had 4+ mitral regurgitation, five had 3+, two had 2+ and one patient had 1+ mitral regurgitation.

Analysis of data. Statistical significance of the difference between the mean Doppler pulmonary venous systolic and diastolic variables and the different grades of mitral regurgitation was assessed by analysis of variance techniques. When overall one-way analysis of variance (ANOVA) F tests were significant ($p < 0.05$), multiple comparisons were made with repeated t tests (evaluated with Fisher's least significant difference). Univariate relations between pulmonary venous flow variables and left atrial pressure and volumetric measurements were evaluated by Pearson's correlation coefficients. A p value of <0.05 was considered significant. Values are presented as mean value ± SD.

Results

Clinical, echocardiographic and hemodynamic data. Seven patients had 4+, four had 3+ and five had 2+ mitral regurgitation as indicated by transesophageal echocardiographic color flow mapping at the time of the intraoperative study (Table 1). Three patients were in atrial fibrillation at the time of the intraoperative study. Left atrial size and left atrial end-systolic volume were larger in patients with 4+ than in those with 2+ mitral regurgitation. Jet direction was central in eight patients and eccentric (anterior or posterior) in eight patients, mainly in those with 4+ mitral regurgitation. Pulmonary artery systolic and diastolic pressures at the time of the study were mildly elevated at 43/25 mm Hg with no difference among the mitral regurgitation groups. Similarly, there was no difference in the cardiac output and mean arterial pressures among the mitral regurgitation groups.

Left atrial pressure hemodynamic measurements. Left atrial pressure data recorded at the time of the intraoperative study are shown in Table 2. In three patients with atrial fibrillation, the a wave and a-x descent were not recorded and were counted as 0. The a wave in the other 13 patients with normal sinus rhythm was 15 mm Hg and tended to be highest in patients with 3+ mitral regurgitation. Overall, the v wave was 23 mm Hg and was larger in patients with 4+ than in those with 2+ mitral regurgitation; thus the a/v ratio was smaller in patients with 4+ than in those with 2+ mitral regurgitation. The a-x descent was decreased and the v-y descent was increased in patients with 4+ compared with values in patients with 2+ mitral regurgitation; thus the a-x and v-y ratio was lower in patients with 4+ than in those with 2+ mitral regurgitation. The mean left atrial pressure and the v wave above the mean were significantly greater in patients with 4+ than in those with 2+ mitral regurgitation.

Pulmonary venous flow data. Pulmonary venous flow patterns, peak velocities and integrals for each grade of mitral regurgitation are shown in Table 3.

Flow patterns. Of the seven patients with 4+ mitral regurgitation, six (86%) had predominantly reversed systolic flow, whereas one patient (14%) had blunted systolic flow with greater forward systolic flow than reversed systolic flow. All patients with 3+ mitral regurgitation had blunted systolic flow, whereas patients with 2+ mitral regurgitation had normal systolic flow (Fig. 2 to 4).

Peak velocities and integrals. Pulsed wave Doppler recordings of the left upper pulmonary vein were obtained from all patients. The peak forward systolic velocity tended to decrease and the integrals were lower in patients with 4+ than in those with 2+ mitral regurgitation. Peak reversed systolic flow velocity and integrals were present only in patients with 4+ mitral regurgitation; thus, the total systolic

Table 1. Clinical, Echocardiographic and Hemodynamic Data From 16 Patients Undergoing Intraoperative Transesophageal Echocardiography

		Severity of Mitral Regurgitation		
	Total (n = 16)	2+ (n = 5)	3+ (n = 4)	4+ (n = 7)
Age (yr)	59 ± 13	68 ± 7*	48 ± 8	58 ± 15
Male/female patients	7/9	1/4	2/2	4/3
Heart rate (beats/min)	82 ± 18	82 ± 22	80 ± 14	83 ± 18
NYHA class (III or IV)	10	2	2	6
Previous operations	9	3	2	4
Atrial fibrillation	3	0	1	2
LV end-systolic dimension (mm)	32 ± 5	31 ± 5	34 ± 6	32 ± 6
LV end-diastolic dimension (mm)	54 ± 8	50 ± 8	57 ± 9	55 ± 9
EF (%)	64 ± 7	63 ± 4	65 ± 8	65 ± 9
LA (mm)	57 ± 10	48 ± 4	62 ± 10	58 ± 10
LA area (mm^2)	35 ± 17	21 ± 10	38 ± 11	42 ± 19
LA end-systolic volume (ml)	112 ± 82	42 ± 22	108 ± 32	155 ± 98†
LA end-diastolic volume (ml)	165 ± 110	88 ± 30	149 ± 40	218 ± 139
Eccentric MR	8	0	2	6†
CVP (mm Hg)	11 ± 4	9 ± 4	10 ± 4	13 ± 3
PA systolic pressure (mm Hg)	43 ± 25	28 ± 6	49 ± 11	53 ± 38
PA diastolic pressure (mm Hg)	20 ± 11	14 ± 3	26 ± 7	22 ± 16
CO (liters/min)	5 ± 1	4 ± 1	4 ± 1	5 ± 2
MAP (mm Hg)	81 ± 10	84 ± 11	77 ± 10	81 ± 9

*p < 0.05, 2+ versus 3+ mitral regurgitation. †p < 0.05, 4+ versus 2+ mitral regurgitation. Data are expressed as mean value ± SD or number of patients. CO = cardiac output; CVP = central venous pressure; EF = ejection fraction; LA = left atrium; LV = left ventricle; MAP = mean arterial pressure; MR = mitral regurgitation; NYHA class = New York Heart Association functional class; PA = pulmonary artery.

flow velocity and integrals were decreased in patients with 4+ compared with those with 2+ mitral regurgitation. The peak diastolic flow velocity and integrals were increased in patients with 4+ compared with those in patients with 2+ mitral regurgitation. Similarly, the peak total systolic/diastolic flow ratio and integrals were lower in patients with 4+ than in those with 2+ mitral regurgitation. Reversed systolic flow accounted for 35% of all forward flow in patients with 4+ mitral regurgitation (Fig. 2 to 4).

Univariate correlates of pulmonary venous peak systolic/diastolic flow ratio. The best correlation of the pulmonary venous systolic/diastolic flow ratio was with the left atrial pressure *v* wave (r = −0.76), the *v-y* descent (r = −0.73) and the *a/v* ratio (r = 0.71). The lowest correlations were with the left atrial end-systolic (r = −0.48) and end-diastolic volumes (r = −0.42) (Table 4, Fig. 5).

When the three patients with atrial fibrillation were excluded from the analysis, the correlations were still significant between the pulmonary venous systolic to diastolic ratio and the *a/v* ratio (r = 0.82, p = 0.0006), *v* wave (r = −0.74, p = 0.004) and *x/y* ratio (r = 0.62, p = 0.03).

Discussion

Determinants of pulmonary venous flow. Pulmonary venous flow is influenced by a multitude of factors, including

Table 2. Left Atrial Pressure Hemodynamic Data in 16 Patients With Mitral Regurgitation Measured by Direct Left Atrial Puncture

		Severity of Mitral Regurgitation		
	Total (n = 16)	2+ (n = 5)	3+ (n = 4)	4+ (n = 7)
a wave (mm Hg)	15 ± 9	16 ± 4	20 ± 14	10 ± 8
v wave (mm Hg)	23 ± 11	12 ± 3*	26 ± 6	30 ± 10†
a/v ratio	0.8 ± 0.5	1.4 ± 0.2*	0.8 ± 0.6	0.4 ± 0.3†
a-x descent (mm Hg)	6 ± 4	10 ± 3*	5 ± 4	3 ± 3†
v-y descent (mm Hg)	14 ± 8	5 ± 3*	12 ± 2‡	20 ± 7†
x/y ratio	1 ± 1	2 ± 1*	0.4 ± 0.3	0.2 ± 0.3†
mLAP (mm Hg)	19 ± 8	12 ± 5*	22 ± 5	23 ± 8†
v wave above mLAP (mm Hg)	4.5 ± 4.5	0.2 ± 3.3	4.2 ± 1.7	7.7 ± 3.8†

*p < 0.05, 2+ versus 3+ mitral regurgitation. †p < 0.05, 4+ versus 2+ mitral regurgitation. ‡p < 0.05, 3+ versus 4+ mitral regurgitation. mLAP = mean left atrial pressure.

Table 3. Pulmonary Venous Flow Patterns, Velocities and Flow-Velocity Integrals in 16 Patients With Mitral Regurgitation by Transesophageal Echocardiography

	Total (n = 16)	Severity of Mitral Regurgitation 2+ (n = 5)	3+ (n = 4)	4+ (n = 7)
Flow pattern	Systolic-to-diastolic ratio			
Normal flow	5	5	0	0
Blunted systolic flow	5	0	4	1
Reversed systolic flow	6	0	0	6
Peak velocities				
Systolic (cm/s)	30 ± 22	46 ± 12	26 ± 23	22 ± 24
Reversed systolic flow (cm/s)	−21 ± 40	0 ± 0	0 ± 0*	−49 ± 50†
Total systolic (cm/s)	9 ± 47	46 ± 12	26 ± 23*	−27 ± 48†
Diastolic (cm/s)	47 ± 24	31 ± 15	46 ± 18	60 ± 28†
Total systolic/diastolic	0.5 ± 1.0	1.7 ± 0.8‡	0.5 ± 0.3*	−0.4 ± 0.4†
Flow-velocity integrals				
Systolic (cm)	4.4 ± 4.2	7.6 ± 4.0	3.5 ± 2.4	2.6 ± 4.2†
Reversed systolic flow (cm)	−2.3 ± 4.6	0 ± 0	0 ± 0*	−5.3 ± 5.9†
Total systolic (cm)	2.1 ± 6.6	7.6 ± 4.0	3.4 ± 2.4	−2.7 ± 6.4†
Diastolic (cm)	8.1 ± 5	4.2 ± 2.4	9.3 ± 5.0	10.1 ± 5.3†
Total systolic/diastolic	0.7 ± 1.1	2.0 ± 1.0‡	0.4 ± 0.1	−0.2 ± 0.2†
% reversed systolic flow	15 ± 22	0 ± 0	0 ± 0*	35 ± 21†

*$p < 0.05$, 3+ versus 4+ mitral regurgitation. †$p < 0.05$, 4+ versus 2+ mitral regurgitation. ‡$p < 0.05$, 2+ versus 3+ mitral regurgitation. Data are expressed as number of patients or mean value ± SD. Diastolic = forward diastolic flow; % reversed systolic flow = percent of reversed systolic flow-velocity integral compared with forward systolic and diastolic flow-velocity integrals; Systolic = forward systolic flow; Total systolic = forward systolic flow minus reversed systolic flow; Total systolic/diastolic = (forward systolic flow minus reversed systolic flow) divided by diastolic flow.

left atrial function, left atrial pressure and compliance and left ventricular function (1). This study shows that a major determinant of pulmonary venous flow in patients with different grades of mitral regurgitation is left atrial pressure (17) (Fig. 6). We found a progressive decrease in the pulmonary venous velocity systolic/diastolic flow ratio in patients with grade 2+ to 4+ mitral regurgitation. In patients with 4+ mitral regurgitation, the systolic/diastolic ratio became negative because of the presence of reversed systolic flow. Similarly, the left atrial pressure profile showed a progressive increase in *v* wave, *v* wave above the mean left atrial pressure, mean left atrial pressure and the *v-y* descent, and showed a decrease in the *a/v* and *a-x/v-y* ratio with increased grades of mitral regurgitation. The decrease in the systolic/diastolic flow ratio in patients with different grades of mitral regurgitation paralleled the increase in the *v* wave in the left atrial pressure tracing (r = −0.76).

The mechanism for these changes in pulmonary venous flow are complex (1) but reflect the effect of mitral regurgitation on left atrial pressure hemodynamics. Previous studies (4–7,18,19) have found that peak pulmonary venous systolic and diastolic flows are directly related to the nadirs of the *a-x* and *v-y* descents of the left atrial pressure profile. In our study, the *v* wave increased from 12 mm Hg in patients with 2+ mitral regurgitation to 26 mm Hg in those with 3+ to 30 mm Hg in patients with 4+ mitral regurgitation. Similarly, the pulmonary venous flow pattern changed from a normal to a blunted pattern, to a reversed systolic flow pattern in those patients with 2+, 3+ and 4+ mitral regurgitation respectively. We have previously demonstrated that the presence of reversed systolic flow is a sensitive and specific physiologic marker of 4+ mitral regurgitation by transesophageal echocardiographic color flow mapping or by cardiac catheterization. Blunted systolic flow shows some overlap between 2+ and 3+ mitral regurgitation; however, the combination of reversed systolic flow and blunted systolic flow was useful in distinguishing between patients with 3+ and 4+ from patients with 2+ regurgitation (2).

Previous studies (20,21) have shown that large *v* waves in the pulmonary capillary wedge pressure (≥10 mm Hg above the mean capillary wedge pressure) are neither sensitive nor specific for 4+ mitral regurgitation. For example, large *v* waves in the pulmonary capillary wedge pressure were detected in patients without mitral regurgitation but with mitral stenosis or ventricular septal defect. The presence of *v* waves in these conditions may be related to the nonlinearity of the left atrial pressure-volume curve. The factors influencing the *v* wave included not only the effect of mitral regurgitation (increasing the volume of regurgitating blood into the left atrium) but also the shape and position of the left atrial pressure-volume curve, left atrial size and function (20,21). In our study, we did not record pulmonary capillary wedge pressures but, rather, direct left atrial pressures, which may be more accurate predictors of left atrial pressure hemodynamics (22,23). Meticulous direct left atrial pressure

JACC Vol. 20, No. 6
November 15, 1992:1345–52

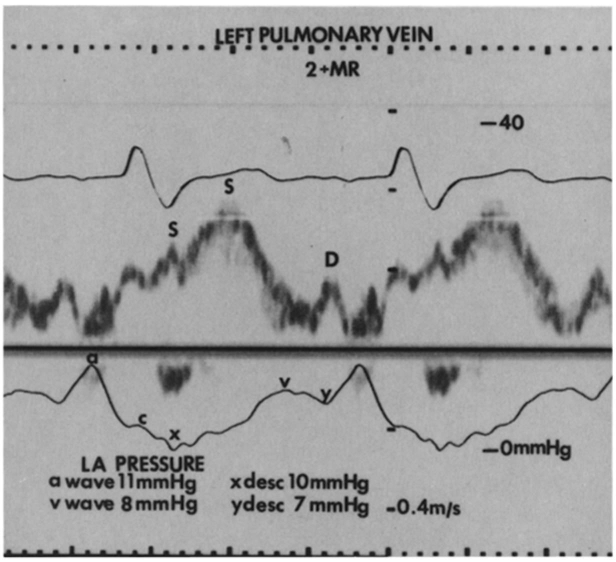

Figure 2. Simultaneous left atrial (LA) pressure and pulsed wave Doppler transesophageal recordings of the left upper pulmonary vein in a 75-year old woman with 2+ mitral regurgitation (MR). The left atrial pressure recording shows a greater *a* wave (11 mm Hg) than *v* wave (8 mm Hg), with an *a/v* ratio of 1.4 as well as a greater *a-x* (10 mm Hg) to *v-y* descent (desc) (7 mm Hg) with an *x/y* ratio of 1.4. Similarly, the pulmonary venous flow recording shows a biphasic pulmonary venous flow with a greater systolic (S)/diastolic (D) flow ratio of 1.9. The peak systolic and diastolic flow in the pulmonary veins closely corresponds to the nadirs of *a-x* and *v-y* descent in the left atrial pressure tracing; however, slight delay may be caused by the fluid-filled catheter that measured left atrial pressure. Note also the presence of an early systolic wave in the pulmonary venous flow tracing coincident with a *c* wave in the left atrial pressure tracing, which can be detected when the mean left atrial pressure is decreased (6 mm Hg).

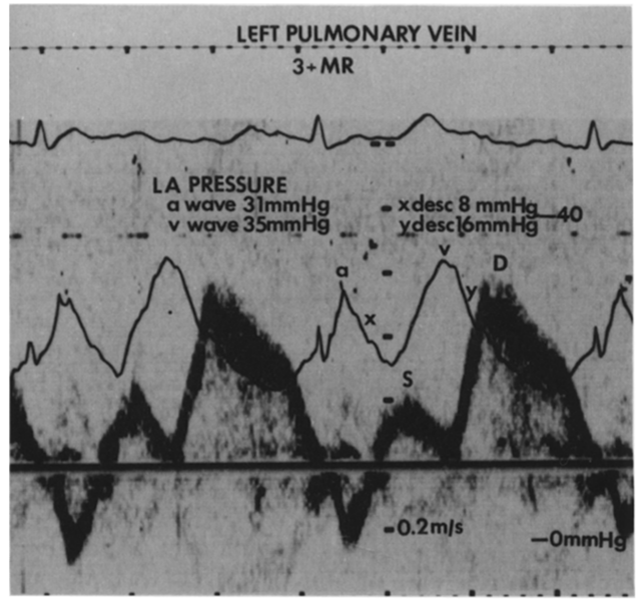

Figure 3. Simultaneous left atrial pressure and pulsed wave Doppler transesophageal recordings of the left upper pulmonary vein in a 37-year old woman with 3+ mitral regurgitation. The left atrial pressure *a* wave (31 mm Hg) is smaller than that of the *v* wave (35 mm Hg) and the *a/v* wave ratio of 0.8 and the *a-x* descent (8 mm Hg) are smaller than the *v-y* descent (16 mm Hg) and the *x/y* ratio of 0.5. The pulmonary venous recording now shows a decreased or blunted systolic flow compared with diastolic flow with a decreased ratio of 0.3. The *v-y* descent is prolonged, coincident with the pulmonary venous diastolic flow, which suggests an element of mitral stenosis. Abbreviations as in Figure 2.

recordings better correlated with mitral regurgitation severity. In addition, we did not use just the height of the *v* wave, but the contour of the left atrial pressure profile, including the *a/v* ratio and their descents.

A recent study (3) demonstrated the influence of severe mitral regurgitation on pulmonary venous flow; however, left atrial pressure measurements were not reported. Similarly, another study of pulmonary venous flow with left atrial pressure recordings in patients without mitral regurgitation undergoing coronary bypass surgery with left atrial pressure recording suggested that blunted systolic flow was the result of an elevated mean left atrial pressure, which was operating on a steep portion of the left atrial pressure-volume curve (24). This observation suggests that the pulmonary venous flow is not uniquely influenced by the mitral regurgitant volume but is also affected by the operating left atrial compliance. Also, previous studies (1) have noted that diseases with impaired left ventricular compliance, such as restrictive cardiomyopathy, may show blunted systolic flow in the absence of 3+ mitral regurgitation and probably reflect elevated left atrial pressure.

Influence of left atrial size. We found that our study patients with 4+ mitral regurgitation had larger left atrial volumes than did patients with 2+ mitral regurgitation (Table 1). The patients with 4+ mitral regurgitation had decreased pulmonary venous systolic/diastolic ratios and reversed systolic flow; thus, reversed systolic flow was present despite a large left atrium. Our findings suggest that a decreased left atrial pressure *a/v* wave ratio and increased *v* waves do occur in the presence of large left atria. The large left atrium in patients with 4+ mitral regurgitation indirectly reflects the chronicity of the mitral regurgitation in our study patients (25).

Left atrial volume definitely influences the pulmonary venous systolic/diastolic flow ratio but not as strongly as the left atrial pressure hemodynamic profile.

Limitations of the study. Limitations of this study include the small number of patients and the heterogeneity of the patients studied. It is difficult to control all the potential factors affecting pulmonary venous flow, including the different mechanisms of mitral regurgitation, the effect of left ventricular compliance, mitral stenosis and arrhythmias, that could influence pulmonary venous flow (1). Other factors of the mitral regurgitant jet could also influence pulmonary venous flow, including the eccentricity of the jet with the Coanda effect and jet momentum (26). Left atrial compliance could have played a major role in influencing both pulmonary venous flow and left atrial pressure patterns in our study, especially in poorly compliant left atria. In our

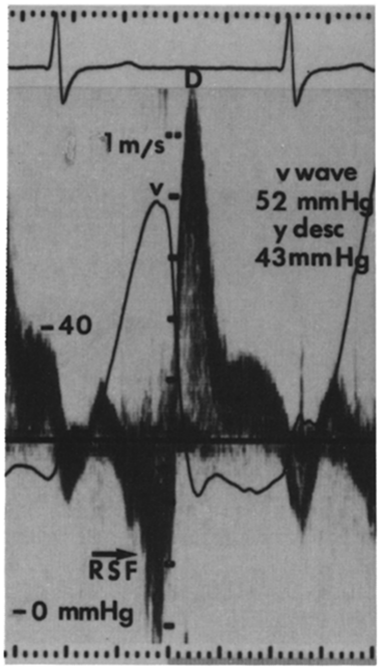

Figure 4. Simultaneous left atrial pressure and pulsed wave Doppler transesophageal recordings of the left upper pulmonary vein in a 62-year old woman with 4+ mitral regurgitation and atrial fibrillation. The left atrial pressure shows a markedly increased *v* wave of 52 mm Hg and a *v-y* descent (desc) of 43 mm Hg. The pulmonary venous flow now shows reversed systolic flow (RSF) coincident with the *v* wave, and increased diastolic (D) flow.

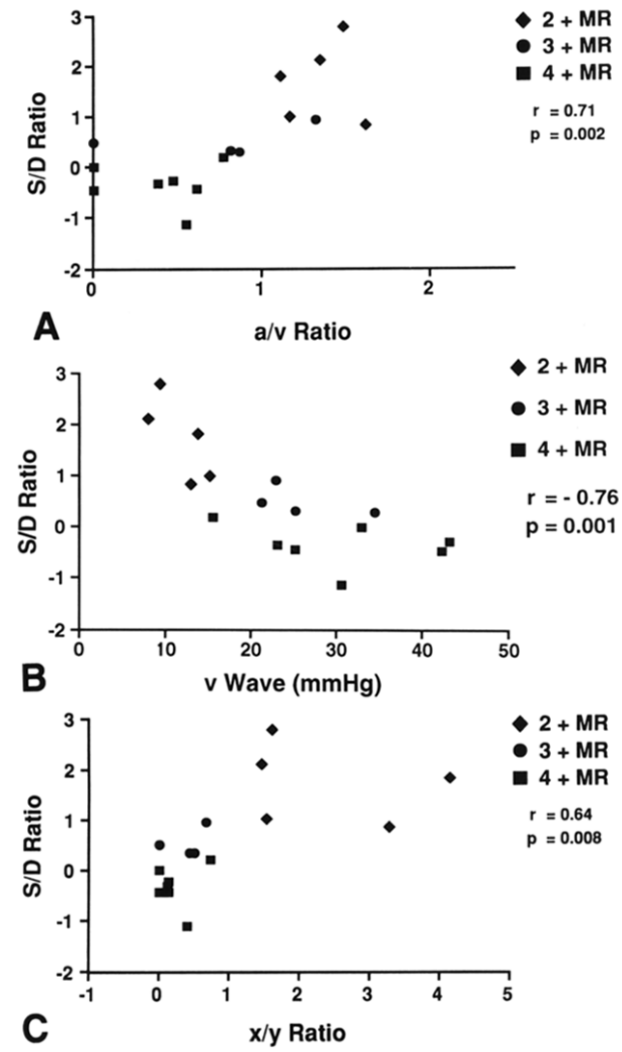

Figure 5. Comparison of pulmonary venous Doppler variables and left atrial pressure hemodynamics in patients with 2+ (n = 5), 3+ (n = 4) and 4+ (n = 7) mitral regurgitation (MR). Correlation between the pulmonary venous systolic (S)/diastolic (D) flow ratio and the left atrial pressure *a/v* ratio (A), the left atrial pressure *v* wave (B) and the left atrial *a-x/v-y* ratio (C) in patients with different grades of mitral regurgitation.

study, we did not measure simultaneous left atrial pressure and volume to generate pressure-volume loops, which would have been important in assessing the influence of poorly compliant left atria. This result would be particularly important in patients with acute mitral regurgitation with small "stiff" left atria; however, none of our patients had acute mitral regurgitation in this study. Despite these limitations, there was a very good correlation between the left atrial pressure and hemodynamic determinants and pulmonary venous flow in various diseases. The presence of atrial fibrillation in three (19%) of the patients may have also influenced our results because the *a* wave and the *a-x* descent could not be measured, and with atrial fibrillation, the systolic to diastolic velocity ratio is usually decreased because of the lack of atrial relaxation (2,27,28). Even when these patients with atrial fibrillation were excluded from analysis, a good correlation existed between pulmonary venous flow and left atrial pressure with increasing severity of mitral regurgitation.

Table 4. Univariate Correlates of Pulmonary Venous Peak Systolic/Diastolic Velocity Ratios

	r Value	p Value
v wave	−0.76	0.001
v-y descent	−0.73	0.002
a/v ratio	0.71	0.002
x/y ratio	0.64	0.008
ESV	−0.48	0.07
EDV	−0.42	0.12

EDV = end-diastolic volume; ESV = end-systolic volume.

Unfortunately, in this study, we did not measure right upper pulmonary vein tracings but rather the left upper pulmonary vein tracing, which was more reliably and easily obtained than the right upper pulmonary vein tracings in the operating room setting; thus, the issues concerning the mechanism of discordance between right and left pulmonary venous flow could not be addressed in this study (2). The primary focus of our study was to show the major determinants of pulmonary venous flow in the setting of mitral regurgitation.

Finally, we used a fluid-filled rather than a pressure-

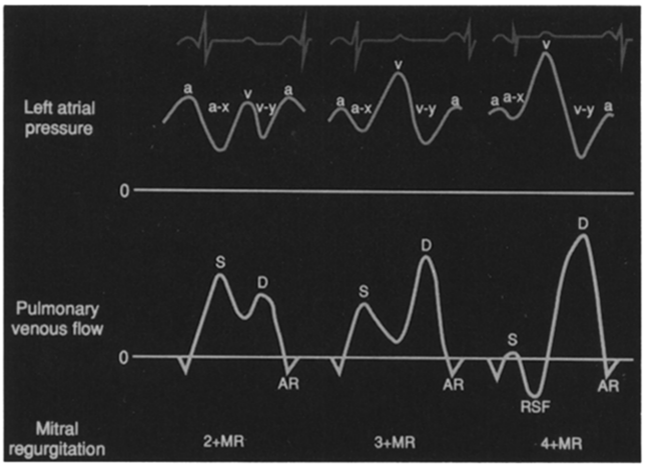

Figure 6. Summary of relation between left atrial pressure hemodynamic and pulmonary venous flow Doppler profiles in 2+, 3+ and 4+ mitral regurgitation (MR). As mitral regurgitation increases, the *v* wave and *v-y* descent increase and the *a* wave and *x-y* descent decrease, which is coincident with decreased pulmonary venous systolic (S) flow, increased diastolic (D) flow and reversed systolic flow (RSF) in 4+ mitral regurgitation. Electrocardiograms are shown at **top**. AR = atrial reversed flow velocity.

tipped catheter system, and thus there may be a confounding variable of a time delay in the simultaneous recording of the left atrial pressure and the Doppler recordings (29).

Conclusions. This study shows that a major determinant of pulmonary venous flow in patients with mitral regurgitation is left atrial pressure. A decreased pulmonary venous systolic/diastolic flow ratio and reversed systolic flow reflect the increasing amplitude of the *v* wave and the decreasing left atrial pressure *a/v* ratio in patients with severe mitral regurgitation.

We acknowledge the secretarial assistance of Patricia J. Goldean.

References

1. Klein AL, Tajik AJ. Doppler assessment of pulmonary venous flow in healthy subjects and in patients with heart disease. J Am Soc Echocardiogr 1991;4:379–92.
2. Klein AL, Obarski TP, Stewart WJ, et al. Transesophageal Doppler echocardiography of pulmonary venous flow: a new marker of mitral regurgitation severity. J Am Coll Cardiol 1991;18:518–26.
3. Castello R, Pearson AC, Lenzen P, Labovitz RJ. Effect of mitral regurgitation on pulmonary venous flow velocities derived from transesophageal echocardiography color guided pulsed-Doppler imaging. J Am Coll Cardiol 1991;17:1499–506.
4. Rajagopalan B, Friend JA, Stallard T, Lee G de J. Blood flow in pulmonary veins: I. Studies in dog and man. Cardiovasc Res 1979;13:667–76.
5. Rajagopalan B, Friend JA, Stallard T, Lee G de J. Blood flow in pulmonary veins: II. The influence of events transmitted from the right sides of the heart. Cardiovasc Res 1979;13:677–83.
6. Rajagopalan B, Friend JA, Stallard T, Lee G de J. Blood flow in pulmonary veins: III. Simultaneous measurements of their dimension, intervascular pressure and flow. Cardiovasc Res 1979;13:684–92.
7. Smallhorn JF, Freedom RM, Olley PM. Pulsed Doppler echocardiographic assessment of extra parenchymal pulmonary vein flow. J Am Coll Cardiol 1987;9:573–9.
8. Stanley TH, Webster LR. Anesthetic requirements and cardiovascular effects of fentanyl-oxygen and fentanyl-diazepam, oxygen anesthesia in man. Anesth Analg 1978;57:411–6.
9. Orihashi K, Goldiner PL, Oka Y. Intraoperative assessment of pulmonary vein flow. Echocardiography 1990;7:261–71.
10. Seward JB, Khandheria BK, Oh JK, et al. Transesophageal echocardiography: technique, anatomic correlations, implementation and clinical applications. Mayo Clin Proc 1980;63:649–80.
11. Braunwald E, Brockenbrough EC, Frahm C, Ross J. Left atrial and left ventricular pressures in subjects without cardiovascular disease. Circulation 1961;24:267–9.
12. Quinones MA, Waggoner AD, Reduto LA, et al. A new simplified and accurate method for determining ejection fraction with two-dimensional echocardiography. Circulation 1981;64:744–53.
13. Drexler M, Erbel R, Miller V, Wittlich N, Mohr-Kahaly S, Meyer J. Measurement of intracardiac dimensions and structures in normal young adult subjects by transesophageal echocardiography. Am J Cardiol 1990;65:1491–6.
14. Gutman J, Wang YS, Wahr D, Schiller NB. Normal left atrial function by 2-dimensional echocardiography. Am J Cardiol 1983;51:336–40.
15. Stewart WJ, Currie PJ, Salcedo EE, et al. Intraoperative Doppler color flow mapping for decision-making in valve repair for mitral regurgitation: techniques and results in 100 patients. Circulation 1990;81:556–66.
16. Sellers RD, Levy MJ, Amplatz K, Lillehei CW. Left retrograde cardioangiography in acquired cardiac disease: technical limitations and interpretation in 700 cases. Am J Cardiol 1964;14:437–47.
17. Klein AL, Stewart WJ, Litowitz H, et al. Pulmonary venous flow assessment of mitral regurgitation: a simultaneous left atrial pressure and transesophageal echo-Doppler study (abstr). Circulation 1990;82(suppl III):III-552.
18. Dixon SH Jr, Nolan SP, Morrow AG. Pulmonary venous blood flow. The effects of alteration in left atrial pressure, pulmonary artery occlusion and mitral regurgitation in the dog. Ann Surg 1971;174:944–9.
19. Keren G, Sherez J, Megidish R, Levitt B, Laniado S. Pulmonary venous flow pattern, its relationship to cardiac dynamics—a pulsed Doppler echocardiographic study. Circulation 1985;71:1105–12.
20. Fuchs RM, Heuser RR, Vin FCP, Brinker JA. Limitations of pulmonary wedge v waves in diagnosing mitral regurgitation. Am J Cardiol 1982:49:849–54.
21. Pichard AD, Kay R, Smith H, Rentrop P, Holt J, Gerlin R. Large v waves in the pulmonary wedge pressure tracing in the absence of mitral regurgitation. Am J Cardiol 1982;50:1044–50.
22. Luchsinger PC, Seipp HW, Patel DJ. Relationship of pulmonary artery wedge pressure to left atrial pressure in man. Circ Res 1962;11:315–8.
23. Haskell RJ, French WJ. Accuracy of left atrial and pulmonary artery wedge pressure in pure mitral regurgitation in predicting left ventricular end-diastolic pressure. Am J Cardiol 1988;61:136–41.
24. Kuecherer HF, Muhiudeen IA, Kusomoto FM, et al. Estimation of mean left atrial pressure from transesophageal pulsed-Doppler echocardiography of pulmonary venous flow. Circulation 1990;82:1127–39.
25. Hawley RR, Dodge HT, Graham TP. Left atrial volume and its changes in heart disease. Circulation 1966;34:989–96.
26. Cape EG, Skovfis EG, Weyman AE, Yoganathan AP, Levine RA. A new method for noninvasive quantification of valvular regurgitation based on conservation of momentum. In vitro validation. Circulation 1989;79:1343–53.
27. Keren G, Sonnenblick EH, LeJentel TH. Mitral annulus motion-relation to pulmonary venous and transmitral flow in normal subjects and in patients with dilated cardiomyopathy. Circulation 1988;78:621–9.
28. Keren A, Bier A, Sherez J, Miura D, Keefe D, LeJemtel T. Atrial contraction is an important determinant of pulmonary venous flow. J Am Coll Cardiol 1986;7:693–5.
29. Grossman W. Cardiac catheterization. In: Braunwald E, ed. Heart Disease. A Textbook of Cardiovascular Medicine. 4th ed. Philadelphia: WB Saunders, 1992:185–6.