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Simultaneous Measurement of Pulmonary Venous Flow by Intravascular Catheter Doppler Velocimetry and Transesophageal Doppler Echocardiography: Relation to Left Atrial Pressure and Left Atrial and Left Ventricular Function

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Objectives. **The aim of our study was to compare measurements of pulmonary venous flow velocity obtained either by transesophageal Doppler echocardiography or by intravascular catheter Doppler velocimetry. Furthermore, the relation among pulmonary venous flow velocity, left atrial compliance and left atrial pressure was evaluated.**

Background. **Data about the relation between left atrial pressure and pulmonary venous flow velocity are controversial.**

Methods. **A total of 32 patients undergoing elective open heart surgery for coronary artery bypass grafting were included prospectively in the study. Pulmonary venous flow velocity (Doppler catheter) and left atrial pressure (microtip pressure transducer) were recorded simultaneously with recordings of pulmonary venous flow velocity obtained by transesophageal Doppler echocardiography.**

Results. **Agreement between Doppler catheter and Doppler echocardiographic measurements of pulmonary venous flow velocity (n = 18 patients) was analyzed using the Bland-Altmann technique. The 95% limits of agreement were −0.16 to +0.11 m/s for systolic peak velocity, −0.14 to +0.09 m/s for diastolic peak velocity and −0.12 to +0.10 m/s for atrial peak velocity. The closest agreement between both methods was found for the ratio of systolic to diastolic peak velocity, the ratio of systolic to diastolic flow duration and the time from Q deflection on the electrocardiogram to maximal flow velocity. Mean left atrial pressure was strongly correlated with the ratio of systolic to diastolic peak velocity (r = −0.829), systolic velocity–time integral (r = −0.653), time to maximal flow velocity (r = 0.844) and the ratio of systolic to diastolic flow duration (r = −0.556). The ratio of systolic to diastolic peak velocity and the time to maximal flow velocity were identified as strong independent predictors of mean left atrial pressure. Left atrial compliance was not found to be an independent predictor of mean left atrial pressure.**

Conclusions. **Flow velocity in the left upper pulmonary vein can be reliably recorded by transesophageal pulsed wave Doppler echocardiography. Our data reveal further evidence that mean left atrial pressure can be estimated by the pattern of pulmonary venous flow velocity.**

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Pulmonary venous flow velocity recorded by Doppler echocardiography has been used in addition to mitral flow velocity to study systolic and diastolic function of the left atrium and ventricle. Pulmonary venous flow velocity is influenced by left atrial pressure, left atrial contraction and relaxation, left atrial compliance, mitral annular displacement, cardiac output, left ventricular compliance and left ventricular relaxation (1–9). Recent studies (10,11) have demonstrated a significant correlation between pulmonary venous flow velocity and pulmonary capillary wedge pressure in patients with coronary heart disease, suggesting that left atrial pressure can be predicted by recording pulmonary venous flow velocity in a clinical setting. Pulmonary venous flow velocity recorded by transesophageal echocardiography has been shown to be strongly correlated with pulmonary venous volume flow obtained with an ultrasound transmit time flow probe in the dog (12). However, to our knowledge the recording of pulmonary venous flow velocity by transesophageal Doppler echocardiography has not yet been compared with any other method in humans.

The aim of our study was to compare measurements of pulmonary venous flow velocity obtained by either transesophageal Doppler echocardiography and by an intravascular Doppler catheter method. Furthermore, the relation between pulmonary venous flow velocity, left atrial compliance and left atrial pressure was evaluated.

Methods

Patients. A total of 32 patients undergoing elective open heart surgery for coronary artery bypass grafting were included

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Table 1. Clinical and Hemodynamic Characteristics of 32 Patients

Pt No.	Age (yr)/ Gender	MI	EF (%)	Heart Rate (beats/min)	BP (mm Hg)	Mean LAP (mm Hg)	LAC (mm/mm Hg)	Spec LAC (1/mm Hg)	SV (ml)	FAS (%)	LA-SF (%)	PV Diam (mm)
1	65/M	Ant	46	85	103/61	19.9	1.090	0.035	46	37	42	13
2	56/F	Ant	48	81	94/59	18.1	0.753	0.020	35	28	35	12
3	63/M	None	64	97	102/74	8.0	2.721	0.078	51	30	25	8
4	66/F	Ant	40	105	83/50	19.3	0.647	0.020	55	36	26	16
5	71/M	None	55	107	79/48	13.3	2.464	0.073	56	37	38	13
6	69/F	None	70	76	140/69	12.3	2.705	0.090	51	52	25	13
7	72/M	None	81	70	89/51	10.1	1.185	0.028	36	41	28	14
8	68/M	Ant	49	107	96/71	19.7	0.647	0.014	45	32	36	11
9	71/M	Post	58	118	94/69	13.0	0.720	0.020	31	30	28	11
10	69/M	None	69	111	75/50	10.7	0.798	0.019	64	38	44	10
11	53/M	Ant/Post	50	88	91/67	12.4	0.498	0.015	40	24	32	9
12	70/F	None	70	103	89/66	9.1	2.953	0.081	35	38	27	11
13	52/M	Post	65	74	101/78	15.2	0.646	0.024	55	33	31	8
14	66/F	Ant	44	112	88/63	22.2	0.532	0.017	27	33	23	7
15	58/M	None	72	97	88/54	5.9	3.504	0.084	48	42	23	11
16	59/M	Post	69	75	100/61	9.3	0.699	0.019	83	41	26	10
17	64/F	Ant	41	65	105/71	19.9	0.491	0.017	42	41	27	14
18	78/M	None	60	82	86/51	11.8	0.637	0.024	33	34	16	12
19	72/M	Ant	21	127	91/56	10.5	0.360	0.017	43	33	32	10
20	76/F	None	45	71	113/48	10.5	0.754	0.021	32	38	24	11
21	72/F	None	55	98	100/54	4.4	1.614	0.037	41	32	22	11
22	72/M	None	57	85	97/59	16.0	3.120	0.079	39	32	28	11
23	55/M	Post	49	103	100/52	9.8	1.030	0.028	36	43	23	10
24	72/M	Ant	74	71	86/57	8.7	1.415	0.036	60	45	18	11
25	74/M	None	58	110	98/52	13.2	2.578	0.012	46	14	43	11
26	73/F	None	60	108	140/73	14.1	1.649	0.023	45	45	45	8
27	68/F	Ant	59	91	98/59	9.6	1.170	0.047	52	9	37	7
28	64/M	Ant	71	105	114/62	13.2	0.716	0.022	54	45	42	9
29	71/M	None	64	95	124/61	13.3	1.708	0.059	70	41	39	9
30	59/M	Post	56	89	96/61	9.2	0.618	0.020	42	15	32	7
31	74/F	None	59	112	99/60	5.2	1.223	0.049	43	23	40	10
32	70/M	Post	51	96	107/65	10.6	0.844	0.025	49	19	31	9

Ant = anterior; BP = systolic/diastolic arterial blood pressure; EF = left ventricular ejection fraction during diagnostic cardiac catheterization; F = female; FAS = left ventricular fractional area shortening; LAC = left atrial compliance; LA-SF = left atrial shortening fraction; M = male; Mean LAP = mean left atrial pressure; MI = myocardial infarction; Post = posterior; Pt = patient; PV Diam = diameter of left upper pulmonary vein; Spec = specific; SV = stroke volume.

prospectively in the study (21 men, and 11 women; mean [±SD] age 66.9 ± 6.8 years, range 52 to 78). Patients with aortic or mitral valve disease (regurgitation of grade II or more, aortic valve opening area <1.5 cm^2 or mitral valve opening area <1.8 cm^2) were excluded. All patients underwent coronary artery bypass grafting for multivessel coronary artery disease. Seventeen patients had evidence of previous myocardial infarction (anterior wall infarction, n = 12; posterior wall infarction, n = 6). The ejection fraction at diagnostic cardiac catheterization before operation ranged from 21% to 81% (mean 58.2 ± 12.8%), left ventricular end-diastolic pressure ranged from 0 to 35 mm Hg (mean 12.4 ± 10.3 mm Hg). Clinical and hemodynamic characteristics are summarized in Table 1.

All patients had given written informed consent to participate in the study. The study protocol was approved by the ethical committee of the Ärztekammer and the University of Hamburg.

Experimental procedures. *Pulmonary artery flotation catheter.* In all patients a Swan–Ganz flotation catheter was inserted in the pulmonary artery through the left internal jugular vein before induction of anesthesia. The catheter was connected to a strain gauge pressure transducer (Hewlett-Packard) to obtain pulmonary artery pressure and mean pulmonary capillary wedge pressure. Cardiac output was determined using iced saline solution according to the thermodilution method. Pulmonary pressure measurements were performed simultaneously with the registration of left atrial pressure and pulmonary venous flow velocity.

Recording of pulmonary venous flow velocity with a Doppler catheter. In the first 24 patients, a 3F Doppler catheter (Millar Micro Tip Doppler catheter DC 201, Millar Instruments) was introduced into the left upper pulmonary vein immediately before termination of the extracorporal circulation near the end of the bypass operation. The catheter was inserted through the left atrial wall near the orifice of the right pulmonary vein.

The insertion procedure was guided by transesophageal echocardiography. The tip of the Doppler catheter was placed 1.5 cm distal to the junction of the pulmonary vein into the left atrium in the center of the vascular lumen. The catheter was connected to a pulsed Doppler velocimeter (Velocimeter MDV 20, Millar Instruments) operating with a frequency of 20 MHz. The Doppler signal was optimized by altering the range settings (1 to 10 mm) and the final position of the Doppler catheter tip to obtain a clear signal with maximal amplitudes of anterograde flow velocity. The Doppler signals were recorded simultaneously with an electrocardiogram (ECG) and left atrial pressure signals at a paper speed of 50 and 100 mm/s (thermal printer) on a multichannel physiologic recorder (Gould Windograf, Gould Inc.). Additionally, all recordings were stored on a personal computer disk. The recordings started 5 min after complete termination of the extracorporal circulation.

The flow velocity tracings were analyzed using the computer disk recordings and the View II software package (Gould Instruments).

Recording of left atrial pressure. In all patients, a 2F Millar microtip catheter pressure transducer was inserted into the left atrium simultaneously with the Doppler catheter, using the same insertion site. The tip of the catheter was placed in the cavum of the left atrium. The position was controlled by transesophageal echocardiography. The catheter pressure transducer was connected to a bridge amplifier (Gould Inc.), and the tracings were recorded on a multichannel recorder as previously described. Analysis was performed using the View II software package.

Electrocardiographic recording. A single-lead ECG was recorded simultaneously with the echocardiographic equipment and the previously described multichannel recorder. For both recordings the same electrode positions were used. Electrode positions were optimized to allow a clear identification of the beginning of the Q wave, the termination of the T wave and the onset of the P wave.

Transesophageal echocardiography. We used a Hewlett-Packard Sonos 1000 with a commercially available monoplane esophagus transducer (5 MHz, phased array, horizontal planes). The transducer was inserted after induction of complete anesthesia in the operation preparation room. The insertion procedure was guided by a laryngoscope. The tip of the instrument was placed ~35 cm beyond the row of the teeth.

The positions of the Doppler and pressure catheters were controlled as previously described. The left upper pulmonary vein was visualized adjacent to the left atrial appendage. The sample volume of the pulsed wave Doppler system was placed into the left upper pulmonary vein ~1.5 cm (at end-diastole) distal to the junction of the vessel into the left atrium. Color Doppler and acoustic control were useful in optimizing the position of the sample volume to obtain maximal anterograde flow velocities with sharp contours on the fast Fourier transform display.

The echocardiographic recordings were started simultaneously with the recordings of pulmonary venous flow velocity (Doppler catheter) and of left atrial pressure. The single-lead ECG that was recorded simultaneously by both methods was used for exact synchronization of the flow signals in the subsequent analysis.

Thereafter, we recorded mitral flow velocities at the level of the mitral valve leaflet tips in a standard four-chamber view, where leaflet excursions were maximal. None of the patients had mitral regurgitation of grade II or more during the registration period. Additionally, we recorded flow velocity in the main stem of the pulmonary artery, proximal to the branching into left and right pulmonary arteries.

The aortic valve was imaged in a cross-sectional view with proper angulation of the tip of the esophagus transducer (13). An M-mode beam was directed through the center of the aortic orifice to image both aortic valve motion and motion of the posterior and anterior left atrial wall. A cross-sectional view of the left ventricle at the level of the tips of the papillary muscles was obtained finally. All measurements were finished after 3.9 ± 0.9 min (range 3 to 6). During the registration period, all patients were in stable hemodynamic condition. None of the patients had mitral regurgitation of grade II or more. The change in mean left atrial pressure during the complete examination period was <3 mm Hg. Mean left atrial pressure during the registration period showed a strong correlation with left ventricular end-diastolic pressure obtained during diagnostic cardiac catheterization performed 7 to 56 days before operation ($r = 0.763$). There were no changes in respiration variables or any changes in pharmaceutical therapy. None of the patients was ventilated with positive end-expiratory pressure. Catecholamines were not given before or during the registration period.

All recordings were stored on videotape (S-VHS) for subsequent analysis. Representative tracings were stored on a personal computer using the Screen Machine video digitizer (Fast Electronics). The contours of the tracings were hand digitized on the screen of the personal computer. All calculations were performed using the digitized tracings.

Measurements. *Pulmonary venous flow velocity.* Pulmonary venous flow waveforms were analyzed for peak systolic, diastolic and atrial velocities and the area under each component of the flow velocity curve. In 25 of 32 patients the systolic flow velocity curve was biphasic with an early and a late systolic peak (Fig. 1). In all patients the late systolic peak was higher than the early systolic peak. In addition, the following time intervals were calculated, using the onset of the Q wave in the ECG as a point of reference: t_1 = onset of systolic flow; t_2 = late peak of systolic flow; t_3 = onset of diastolic flow; t_4 = peak of diastolic flow; t_5 = onset of retrograde atrial flow; t_6 = peak of atrial flow; t_7 = onset of systolic flow of the subsequent cardiac cycle. With these intervals the timing of the different phases of pulmonary venous flow velocity could be calculated: duration of systolic flow (t_{sys}) = $t_3 - t_1$; duration of diastolic flow (t_{dia}) = $t_5 - t_3$; duration of retrograde atrial flow = $t_7 - t_5$. In addition, the time interval from the Q wave to maximal anterograde flow velocity was calculated ($t\text{-}v_{max}$) and expressed in percent of cardiac cycle length.

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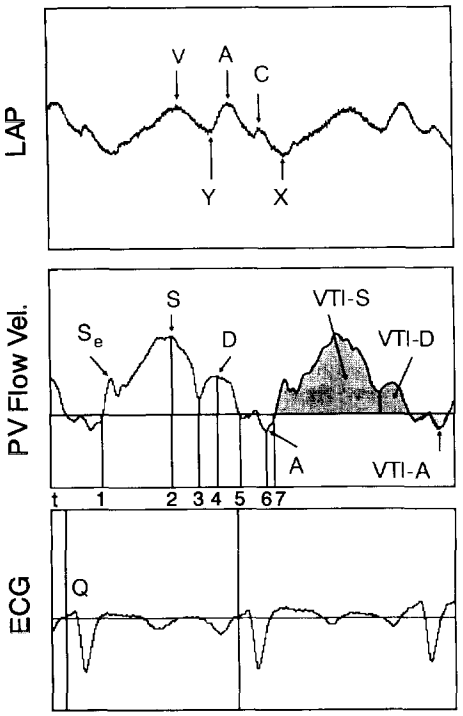

Figure 1. Correlation of left atrial pressure (LAP) (**top**) with pulmonary venous flow velocity (PVFlow Vel.) (**middle**) and the electrocardiogram (ECG) (**bottom**). Tracings were obtained by Doppler catheter recordings. **Top:** V = *v* wave; Y = y descent; A = *a* wave; C = *c* wave; X = x descent. **Middle:** A (D, S) = atrial (diastolic, systolic) peak of pulmonary venous flow velocity: S_e = early peak of systolic pulmonary venous flow velocity; VTI-A (VTI-D, VTI-S) = velocity–time integral of atrial (diastolic, systolic) phase. Compare text for definition of the time intervals of pulmonary venous flow velocity. **Bottom:** Q = Q deflection on the ECG.

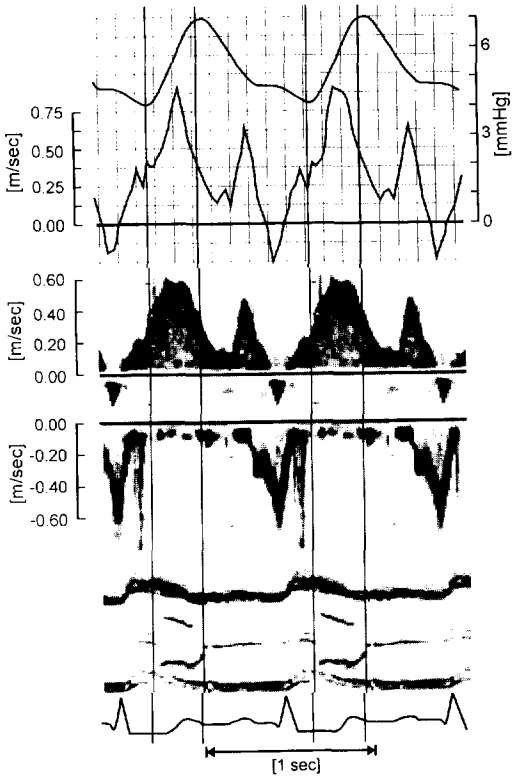

Figure 2. Correlation of left atrial pressure with pulmonary venous flow velocity obtained by Doppler catheter registrations, pulmonary venous flow velocity obtained by transesophageal Doppler echocardiography, mitral flow velocity, motion of the aortic valve (M-mode) and the electrocardiogram (specification from top to bottom).

From transesophageal Doppler echocardiography and Doppler catheter velocimetry, respectively, intraobserver variability was 4.7 ± 2.6% (vs. 2.0 ± 1.4%) for systolic peak velocity, 4.8 ± 2.4% (vs. 2.2 ± 1.2%) for diastolic peak velocity and 5.1 ± 2.7% (vs. 1.9 ± 1.4%) for atrial peak velocity. Interobserver variability was 6.1 ± 2.7% (vs. 3.7 ± 2.0%) for systolic peak velocity, 5.0 ± 3.2% (vs. 3.5 ± 1.9%) for diastolic peak velocity and 7.5 ± 3.7% (vs. 3.5 ± 2.2%) for atrial peak velocity. The values for intraobserver and interobserver variability for velocity–time integrals and time-based variables were in the same range.

Furthermore, we determined the angle between the Doppler beam and the longitudinal axis of the pulmonary vein.

Displacement of the Doppler sample volume. Maximal displacement of the Doppler sample volume ($\Delta_{distance}$) was calculated as the difference of maximal to minimal distance of the sample volume to the orifice of the pulmonary vein during one cardiac cycle.

Left atrial pressure. Left atrial pressure tracings were evaluated for both phasic and mean pressure values using the View II software as previously described. We measured the *a* wave (positive peak from atrial systole), the *v* wave (from atrial diastole) as well as the pressure at the nadir of the x and y troughs (compare Fig. 2). In some cases an additional *c* wave occurred from mitral valve closure. Mean left atrial pressure was measured as mean pressure during one cardiac cycle.

Left atrial compliance. The x nadir and the *v* peak were identified in the left atrial pressure tracing. Left atrial diameter (M-mode recording) and left atrial pressure were calculated at intervals of 10 ms beginning at the x nadir until the *v* peak was reached. Left atrial compliance was defined by fitting left atrial pressure–diameter data to the monoexponential curve equation p = a × exp(b × Left atrial diameter) using a Marquardt-Levenberg algorithm (SigmaPlot, Jandel Scientific), where a = elastic constant; and b = passive elastic chamber stiffness constant. Correlation coefficients between observed and predicted pressure data using the equation above ranged from 0.932 to 0.998 (mean 0.965 ± 0.025). Instantenous left atrial diastolic compliance (LAC) and specific instantenous left atrial diastolic compliance (S-LAC) at the peak of the *v* wave were calculated as follows: LAC (mm/mm Hg = $1/(b \times p_{v\ wave})$; S-LAC (1/mm Hg) = $LAC/Diameter_{v\ wave}$, where $p_{v\ wave}$ = left atrial pressure at the peak of the *v* wave; $Diameter_{v\ wave}$ = left atrial diameter at the peak of the *v* wave.

Mitral flow velocity. We calculated the peak velocity of early (MV-E) and late diastolic filling (MV-A), as well as their ratio (MV-E/MV-A).

Pulmonary flow velocity. Stroke volume (SV) was calculated according to the formula $SV = \pi(\frac{1}{2}Dia_{PA})^2 \times VTI_{PA}$ (ml),

where Dia_{PA} = diameter of the main stem of the pulmonary artery measured at the location of the Doppler sample volume (inner edge to inner edge); and VTI_{PA} = systolic velocity–time integral of pulmonary artery flow.

Left ventricular fractional area shortening. We measured the area of the left ventricular cavum at end-diastole (LVA_{dia}) and end-systole (LVA_{sys}) using a transesophageal short-axis view at the level of the papillary muscles (14). Left ventricular fractional area shorting (FAS) was calculated according to the following formula: $FAS = [(LVA_{dia} - LVA_{sys})/LVA_{dia}] \times 100\%$.

Left atrial shortening. From left ventricular four-chamber views we measured maximal (LA_{max}) and minimal left atrial diameters (LA_{min}). Left atrial shortening fraction (LA-SF) was calculated as follows: $LA\text{-}SF = [(LA_{max} - LA_{min})/LA_{max}] \times 100\%$.

Statistical analysis. All measurements were performed by averaging five consecutive cardiac cycles. Results are expressed as mean value ± 1 SD. All statistical calculations were performed using SPSS for Windows, Release 5.0.1. For all variables a normal probability plot and the Shapiro-Wilks test were performed to test for normality. All variables used in this study were approximately normally distributed. Mean values of variables derived from pulmonary venous flow tracings obtained by either transesophageal Doppler echocardiography or Doppler catheter measurements were compared with a *t* test for paired data. Mean values between different groups were compared by either *t* test statistics or an analysis of variance when appropriate. The correlation between two variables was evaluated by linear regression analysis. To evaluate the agreement between transesophageal Doppler echocardiography (TDE) and Doppler catheter (DC) measurements of pulmonary venous flow velocity, data were processed by the Bland-Altman method (15). The 95% limits of agreement were expressed in absolute values [$\Sigma(x_{TDE} - x_{DC})/n \pm 2$ SD] and as percent of the mean value [$\Sigma(x_{TDE} + x_{DC})/2]/n$. Interobserver and intraobserver variability were calculated as the coefficient of variation.

The relation among mean left atrial pressure, variables derived from pulmonary venous flow velocity tracings (systolic peak velocity [S], diastolic peak velocity [D], S/D ratio, $t\text{–}v_{max}$, t_{sys}/t_{dia}), hemodynamic variables (stroke volume, systolic blood pressure, left ventricular fractional area shortening, left atrial shortening fraction, specific left atrial compliance), the ratio of early to late diastolic mitral flow velocity and age were tested using stepwise multiple linear regression analysis. The same set of variables was used to look for independent predictors of the variables S/D ratio, $t\text{–}v_{max}$ and t_{sys}/t_{dia}.

Results

Correlation between measurements of pulmonary venous flow velocity obtained by Doppler catheter and Doppler transesophageal echocardiography. In all 32 patients high quality recordings of pulmonary venous flow velocity could be obtained by transesophageal Doppler echocardiography. In seven patients the velocity pattern was triphasic, with one positive peak related to ventricular systole, one positive peak related to ventricular diastole and one negative peak related to atrial systole. In 25 patients the velocity pattern was quadriphasic with two positive peaks during ventricular systole. The first of these peaks was related to atrial relaxation (x descent of the left atrial pressure pulse). In all of those 19 patients the early systolic peak velocity was less than the late systolic peak velocity. Thus, for calculation of systolic peak velocity, in all patients the late systolic peak was used. In none of the patients was significant spectral broadening of the Doppler signal observed. Figure 2 shows the temporal relation among left atrial pressure, pulmonary venous flow velocity, mitral flow velocity, aortic valve opening and closure and the ECG.

Doppler catheter registrations of similar quality could be obtained in 18 of the first 24 consecutive study patients (75%). In six patients a stable position of the Doppler catheter could not be achieved. Thus, for the comparison of both methods only 18 patients could be included.

We used the Bland-Altman technique to assess agreement between the two techniques by plotting the arithmetic difference (Variable TDE − Variable DC) on the ordinate against the arithmetic average [(variable TDE + variable DC)/2] (TDE = transesophageal Doppler echocardiography; DC = Doppler catheter). The results are summarized in Figures 3 to 5. The 95% limits of agreement were −0.16 to +0.11 ml for systolic peak velocity and −0.12 to +0.10 ml for atrial peak velocity. For none of the variables tested could a significant difference be detected between the two methods of measuring pulmonary venous flow velocity (*t* test for paired samples). The angle between the Doppler beam (transesophageal echocardiography) and the longitudinal axis of the pulmonary vein ranged from 0° to 20° (mean 6.1 ± 3.5°). Angle correction of systolic and diastolic peak velocities slightly improved the agreement between both methods. Ninety-five percent limits of agreement after angle correction were −18% to +13% (−0.092 to +0.068 m/s) for systolic peak velocity and −21% to +18% (−0.100 to +0.084 m/s) for diastolic peak velocity. The agreement for the other variables did not improve significantly.

The maximal displacement of the Doppler sample volume relative to the orifice of the pulmonary vein ($\Delta_{distance}$) ranged from 0.1 to 0.7 cm (mean 0.21 ± 0.24 cm). In 10 patients with a $\Delta_{distance} \leq 0.3$ cm, the 95% limits of agreement were −8.2 to +8.4% for systolic peak velocity, −7.9 to +8.1% for diastolic peak velocity and −53.2 to +92.1% for atrial peak velocity.

Relation between pulmonary venous flow velocity and left atrial pressure. *Univariate regression analysis.* In all 32 patients pulmonary venous flow velocity data obtained by transesophageal Doppler echocardiography could be compared with left atrial pressure tracings. Table 2 summarizes the correlation coefficients between mean left atrial pressure and several echocardiographic variables. The strongest correlation with mean left atrial pressure was found for the S/D ratio (r = −0.829), $t\text{–}v_{max}$ (r = 0.844), systolic velocity time integral (r = −0.653) and t_{sys}/t_{dia} (r = −0.556).

The peaks and nadirs of the left atrial pressure tracing showed a strong temporal relation to corresponding peaks of

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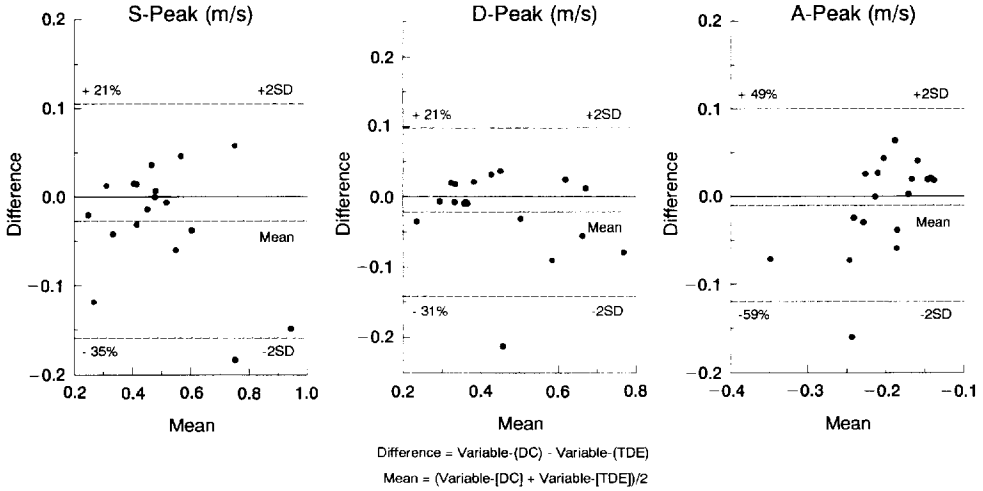

Figure 3. Difference between Doppler catheter (DC) and transesophageal Doppler echocardiographic (TDE) measurements of pulmonary venous flow velocity. A-Peak (D-Peak, S-Peak) = atrial (diastolic, systolic) peak velocity.

the pulmonary venous flow velocity tracings. However, no significant correlations could be found between relative or absolute heights of atrial *a* and *v* waves and maxima or minima of pulmonary venous flow velocity.

Left atrial compliance and specific left atrial compliance showed a significant hyperbolic relation to mean left atrial pressure ($r = 0.423$ and $r = 0.434$, respectively). Furthermore, specific left atrial compliance was correlated to pulmonary venous systolic peak velocity ($r = 0.580$), to the S/D ratio ($r = 0.395$), to $t-v_{max}$ ($r = -0.449$) and to t_{sys}/t_{dia} ($r = 0.435$).

Left atrial shortening fraction was significantly related to mean left atrial pressure ($r = 0.354$) but to none of the variables derived from pulmonary venous flow velocity tracings. Left ventricular fractional area shortening was not related to mean left atrial pressure.

Stepwise linear regression analysis. Stepwise linear regression analysis detected the S/D ratio, $t - v_{max}$ and the left atrial shortening fraction as independent predictors of mean left atrial pressure. All variables together could explain 89% of the variability of the left atrial pressure data (Table 3). Furthermore, we looked for independent predictors of the S/D ratio, $t-v_{max}$ and t_{sys}/t_{dia}. The only independent predictor of the S/D ratio was mean left atrial pressure, which could explain 69% of the variability of the data. The variable $t-v_{max}$ was independently influenced by mean left atrial pressure and the left atrial shortening fraction. The variable t_{sys}/t_{dia} was correlated to the S/D ratio only ($r^2 = 0.388$). Left atrial compliance as well as specific left atrial compliance were not found to be independent predictors of mean left atrial pressure.

Discussion

Correlation between transesophageal Doppler and catheter Doppler registrations of pulmonary venous flow velocity. Hoit et al. (12) previously showed in the dog that pulmonary venous flow velocity obtained by transesophageal Doppler echocardiography is strongly correlated to pulmonary venous volume flow. In human beings this has not yet been proved.

When pulmonary venous flow velocity is recorded by transesophageal Doppler echocardiography, only minor adjust-

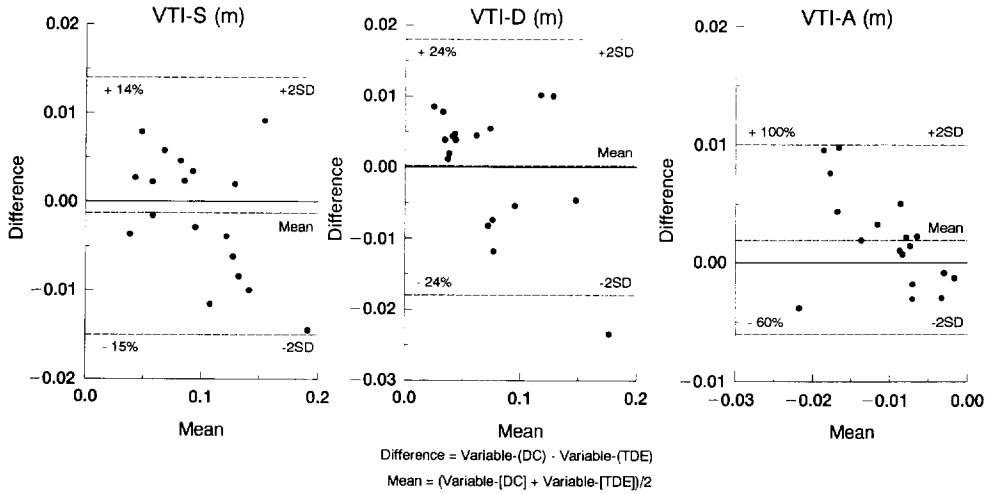

Figure 4. Difference between Doppler catheter (DC) and transesophageal Doppler echocardiographic (TDE) measurements of pulmonary venous flow velocity. VTI-A (VTI-D, VTI-S) = velocity–time integral of atrial (diastolic, systolic) flow velocity.

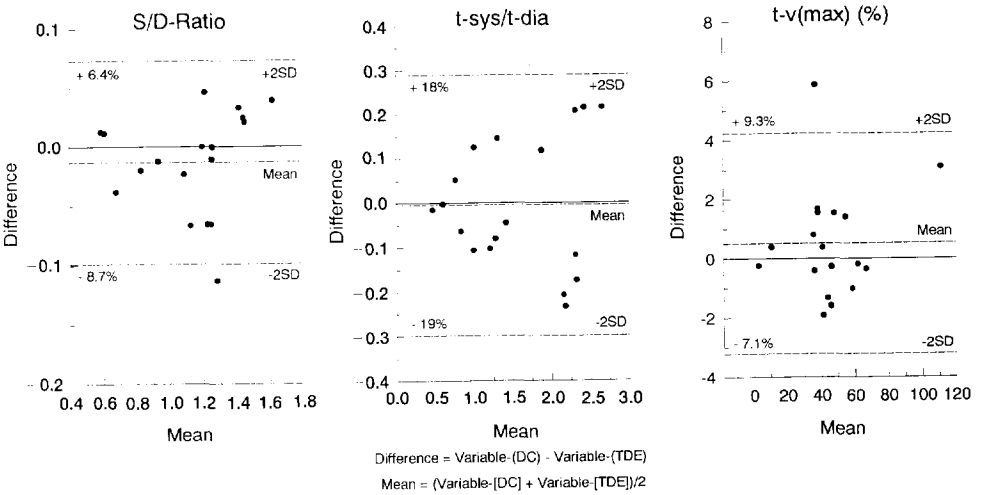

Figure 5. Difference between Doppler catheter (DC) and transesophageal Doppler echocardiographic (TDE) measurements of pulmonary venous flow velocity. S/D-Ratio = ratio of systolic to diastolic peak velocity; t-sys/ t-dia = duration of systolic phase/duration of diastolic phase of pulmonary venous flow; $t-v_{(max)}$ = time from Q deflection (electrocardiogram) to maximal anterograde flow velocity.

ments of the position and the angulation of the esophagus transducer are possible to optimize the quality of the Doppler signal. Failure of proper alignment of the Doppler beam with the direction of flow could lead to significant underestimation of flow velocities. By contrast, the sample volume of the pulsed wave Doppler changes its position relative to the pulmonary vein during the cardiac cycle because of movements of the heart. Because flow patterns in the pulmonary vein are strongly influenced by the position of the Doppler sample volume, distortions of flow velocity patterns are likely to occur in cases with significant movement of the heart relative to the transducer position. These issues have not yet been studied in humans. One objective of our study was to validate the recording of pulmonary venous flow velocity by transesophageal Doppler echocardiography in humans. Because of ethical and technical problems in recording pulmonary venous flow directly using an electromagnetic flow probe (prolongation of the operative procedure, increased intraoperative risk), we decided to compare our transesophageal Doppler tracings with intravascular measurements of pulmonary venous flow velocity, using a Doppler catheter. Although this device has not yet been used in the pulmonary vein, there is much experience in recording blood flow in the major coronary arteries (16–19). However, it must be considered that the pulmonary vein diameter is about three to four times larger than a major coronary artery and that the velocity profile may be quite different.

We found a strong agreement between pulmonary venous flow velocity obtained by transesophageal Doppler and by catheter Doppler measurements. The agreement between the two methods was excellent for measurements of time intervals (t_{sys}/t_{dia}, $t-v_{max}$) and for the S/D ratio. Variability was somewhat larger for velocity–time integrals and was largest for the

Table 2. Correlation of Mean Left Atrial Pressure With Hemodynamic and Echocardiographic Variables

Variables	r Value	SEE	p Value
S-Peak	−0.4769	4.014	0.0058
D-Peak	−0.0789	4.550	NS
A-Peak	0.0829	4.551	NS
S/D ratio	−0.8289	2.554	< 0.0001
$t-v_{max}$	0.8438	2.450	< 0.0001
t_{sys}/t_{dia}	−0.5557	3.797	0.001
VTI-S	−0.6525	3.756	0.0004
VTI-D	0.4623	4.391	0.0255
VTI-A	0.0327	5.165	NS
LA-SF	0.3543	4.270	0.047
1/LAC	0.4229	4.138	0.016
1/Specific LAC	0.4814	4.003	0.005
FAS	−0.2783	4.386	NS
MV-E/MV-A	−0.0105	4.566	NS
SV	−0.1069	4.541	NS
PV Diam	0.2043	4.470	NS

A-Peak (D-Peak, S-Peak) = atrial (diastolic, systolic) peak velocity; MV-E/MV-A = ratio of early to late diastolic mitral flow velocity; S/D ratio = ratio of systolic to diastolic peak velocity; t_{sys}/t_{dia} = duration of systolic phase/duration of diastolic phase of pulmonary venous flow; $t-v_{max}$ = time from Q deflection (electrocardiogram) to maximal pulmonary venous flow velocity; VTI-A (VTI-D, VTI-S) = velocity time integral of atrial (diastolic, systolic) flow velocity; other abbreviations as in Table 1.

Table 3. Results of Stepwise Multiple Linear Regression Analysis

Step	Variable	B Value	Cumulative Correlation of Determination (r^2)	Partial F Ratio	p Value (F ratio)
1	$t-v_{max}$	0.1036	0.7121	74.188	< 0.0001
2	S/D ratio	−6.5255	0.8314	20.534	< 0.0001
3	LA-SF	0.1207	0.8910	15.315	< 0.001
...	Intercept	11.4474	...	...	...

Dependent variable: mean left atrial pressure. Variables used: stroke volume, systolic and diastolic blood pressures, left ventricular fractional area shortening, left atrial shortening fraction (LA-SF), left atrial compliance, ratio of early to late diastolic peak velocity of mitral flow, pulmonary venous systolic and diastolic peak velocities, ratio of systolic to diastolic peak of pulmonary venous flow velocity (S/D ratio), time from Q deflection (electrocardiogram) to maximal pulmonary venous flow velocity ($t-v_{max}$), duration of systolic phase/duration of diastolic phase of pulmonary venous flow.

determination of peak velocities. Correction for the angle between the Doppler beam and the longitudinal axis of the pulmonary vein improved the agreement between both methods only slightly for systolic and diastolic peak velocity. There was no evidence of systematic overestimation or underestimation of variables of pulmonary venous flow velocity obtained by both Doppler methods.

There was considerable variability for atrial peak velocity and velocity time integral. This may be explained in part by the fact that the Doppler catheter was positioned to record maximal anterograde flow velocities. However, for the recording of optimal retrograde flow velocities another position of the tip of the catheter might have been chosen. One possible cause of scattering of peak velocities might be explained by the fact that the Doppler catheter tip moved in parallel with the pulmonary vein during the cardiac cycle, which could be visualized by monitoring the distance of the catheter tip relative to the orifice of the pulmonary vein by transesophageal echocardiography. By contrast, the position of the sample volume of the transesophageal pulsed-wave Doppler was spatially fixed during the cardiac cycle, whereas the orifice of the pulmonary vein was moving relative to the sample volume. The variation of the position of the sample volume relative to the pulmonary venous junction with the left atrium was correlated with the amount of scattering of systolic and diastolic peak velocities of pulmonary venous flow. In patients with small displacement of the sample volume ($\leq$0.3 cm), the agreement for the measurement of systolic and diastolic peak velocities of pulmonary venous flow was found to be remarkably better.

These data indicate that pulmonary venous flow velocity can be reliably determined by transesophageal Doppler echocardiography. However, peak velocities must be interpreted with caution in the case of significant movement of the pulmonary vein during the cardiac cycle relative to the pulsed-wave Doppler sample volume.

In our study we used a zero-crossing detector to determine pulmonary venous flow velocity using a Doppler catheter, and transesophageal recordings were performed using a fast Fourier transformation of the Doppler signal. Zero-crossing detectors can accurately measure velocity only when all red blood cells in the sample volume move with the same velocity (19). With a nonuniform flow profile, the true peak velocity cannot be measured, and the technique is inaccurate (16,20,21). Especially in the coronary circulation, high amplitude artifacts that can occur when the wall of the coronary artery moves within the Doppler beam can lead to significant errors when a zero-crossing detector is used (16,18,21). Although we have not ruled out these possible limitations in detail, these problems are rather unlikely to occur in the pulmonary veins. The wall motion artifact in the coronary arteries is mainly caused by the small diameter of the coronary artery in relation to the diameter of the Doppler catheter and by the bending of the coronary arteries. In contrast, the pulmonary vein is significantly larger in diameter and is straight. Furthermore, transesophageal recordings of pulmonary venous flow velocity using fast Fourier transformation of the Doppler signal typically show only minor spectral broadening when the sample volume is located ~1.5 cm distal to the junction of the pulmonary vein with the left atrium. These findings may be interpreted as evidence of a highly laminar and undisturbed flow within the pulmonary vein.

Relation between pulmonary venous flow velocity and hemodynamic variables. Pulmonary venous systolic flow is believed to be strongly related to left atrial relaxation and to the descent of the atrioventricular groove associated with left ventricular systole (6,7,22,23). Pulmonary venous diastolic flow has been reported to be correlated with peak mitral flow in early diastole. Both of the latter variables have been shown to be related to left atrial maximal diameter, left atrial maximal volume and to left ventricular end-diastolic pressure (6,7,11,22–26). Similar results could be obtained in our investigation.

We found an inverse relation between mean left atrial pressure and left ventricular ejection time ($r = -0.559$). As a consequence of the shortening of left ventricular ejection time, the duration of the systolic phase of pulmonary venous flow decreases with increasing mean left atrial pressure. This leads to an increase in the relative duration of the diastolic phase. We found a significant correlation between t_{sys}/t_{dia} and mean left atrial pressure. Furthermore, with increasing mean left atrial pressure, systolic peak velocity and systolic velocity–time integral decreased, whereas diastolic peak velocity was unchanged and diastolic velocity–time integral was slightly increased. The S/D ratio was one of the best single predictors of mean left atrial pressure. Twenty-four of 25 patients with a mean left atrial pressure <15 mm Hg had an S/D ratio >1, and all patients with a mean left atrial pressure >15 mm Hg ($n = 7$) had an S/D ratio <1. These data confirm the results of Kuecherer et al. (10,11), who proposed to use the systolic fraction of pulmonary venous flow velocity (Systolic velocity time integral/[Systolic + Diastolic velocity time integral]) as an "eyeball index" to predict mean left atrial pressure. Similar results have been published by others (27,28).

The best predictor of mean left atrial pressure in our study was the time interval from the Q deflection (ECG) to the occurrence of maximal peak velocity during either the systolic or the diastolic phase of pulmonary venous flow (expressed in percent of the cardiac cycle length). When mean left atrial pressure is low, the maximal peak velocity occurs in the first half of the cardiac cycle, whereas with increasing mean left atrial pressure the maximal shifts to the end. Furthermore, this variable was found to be an independent predictor of mean left atrial pressure in stepwise linear regression analysis. However, in univariate analysis, we found a correlation between $t-v_{max}$ and the S/D ratio ($r = -0.690$).

The third independent predictor of mean left atrial pressure was the left atrial shortening fraction. These three variables together could explain 89% of the variability of mean left atrial pressure. Systolic left ventricular function (expressed as fractional area shortening), stroke volume, left ventricular or right ventricular systolic time intervals, age, heart rate or systolic

blood pressure were not related to mean left atrial pressure nor to S/D ratio, $t-v_{max}$ or left atrial shortening fraction.

The relation between left atrial compliance and pulmonary venous flow has not yet been systematically studied in humans. Because volume expansion was not possible for ethical reasons in the present study design, atrial pressure–diameter data were obtained during the atrial filling phase, which corresponds to the ascending limb of the *v* loop. The method of calculating instantaneous left atrial diastolic compliance has been described previously (29,30). For calculations of atrial compliance we used atrial diameter derived from m-mode tracings rather than volume data. However, similar techniques have been used in other studies, which demonstrated good correlations between changes in left atrial diameters and changes in left atrial volume (31–33). To calculate the passive elastic chamber stiffness constant and the elastic constant, we fitted our pressure–diameter data to a monoexponential equation. This type of equation is widely accepted as representing the passive properties of the left atrium (29,30,34–36). We found significant positive correlations between left atrial compliance and pulmonary venous systolic peak velocity but not with diastolic or atrial peak velocity. With increasing left atrial compliance, the S/D ratio and the duration of systolic to diastolic flow decrease, whereas the time from Q deflection to maximal flow velocity increases. However, these changes of pulmonary venous flow velocities can be explained mainly by corresponding changes in mean left atrial pressure. A similar hyperbolic relation between left atrial compliance and mean left atrial pressure has been described previously (37,38). Left atrial compliance was not found to be an independent predictor of mean left atrial pressure in multivariate analysis.

A close relation between left atrial pressure and the systolic fraction of pulmonary venous flow velocity could be clearly demonstrated in our study and in the study of Kuecherer et al. (10,11). Although Kuecherer et al. (10) found a weak but significant correlation between systolic fraction and left ventricular fractional area shortening in multiple stepwise regression analysis, this relation did not reach statistic significance in our study. However, these relations between left atrial pressure and pulmonary venous flow waveforms seem not to be applicable in conditions with abrupt changes in left atrial pressure (12,39). Studies of Hoit et al. (12) and Appleton et al. (39) could show that abrupt increases in left atrial pressure induced by volume expansion in the dog increase left atrial shortening fraction and the proportion of systolic pulmonary venous flow, a finding opposite to our results and to the results of others studying patients with chronic cardiac disease (10,11). Clinical studies in humans describing the relation between abrupt changes in left atrial pressure and pulmonary venous flow are lacking, but the animal models demonstrate that the findings obtained in patients with chronic cardiac disease cannot be extrapolated to conditions with abrupt changes of left atrial pressure.

The relation between the S/D ratio and left atrial pressure in patients under clinical conditions has not yet been completely studied. In patients with mitral regurgitation, a decrease in the S/D ratio was reported with increasing severity of mitral regurgitation (40). This effect may be explained at least in part by an increase in mean left atrial pressure with increasing mitral regurgitation. An increase in the S/D ratio after valvulotomy of the mitral valve has been described previously (41–43). The decrease in the S/D ratio in patients undergoing mitral valvulotomy is accompanied by an abrupt reduction in left atrial pressure, suggesting a correlation between these variables.

In our observations early systolic peak velocity (if present) was smaller than late systolic peak velocity. These findings are consistent with previous studies (28,44,45). Although the early systolic peak is related to atrial relaxation and is often timed before aortic valve opening, the late systolic peak is temporally related to ventricular ejection (44,45). In our study late systolic peak velocity was used to calculate the S/D ratio.

Limitations of the study. *Comparison between measurements of pulmonary venous flow velocity.* Although we found a close correlation between measurements of pulmonary venous flow velocity, it must be kept in mind that different techniques were applied to analyze the Doppler spectrum. It can be argued that the application of fast Fourier transform analysis on the signals obtained by catheter Doppler measurements might have detected higher flow velocities. Similar results have been described when fast Fourier transform and zero-counting devices were compared in the coronary circulation. These differences in maximal flow velocities could be explained mainly by the presence of turbulent flow, nonuniform flow distribution in the vessel and by motion artifacts of the vessel walls (16,19–21). As previously discussed, these problems are unlikely to occur in the pulmonary vein. By contrast, catheter Doppler velocity values were scattered with a symmetric distribution around the Doppler echocardiographic values, thus ruling out a systematic bias with underestimation of Doppler catheter velocities. Furthermore, these potential limitations would not have influenced the measurement of variables that are not dependent on absolute values of pulmonary venous flow velocity (S/D ratio, t_{sys}/t_{dia}, $t-v_{max}$).

Relation between patterns of pulmonary venous flow velocity and hemodynamic variables. In our study left atrial pressure was recorded directly, which has considerable advantages over the measurement of pulmonary capillary wedge pressure. Pulmonary capillary wedge pressure has a waveform similar to that of the left atrial pressure but is both damped and delayed by transmission through the capillary vessels. By contrast, measurements were performed in an artificial environment shortly after termination of the extracorporal circulation and with an open pericardium. Mean left atrial pressure during the registration period showed a strong correlation with left ventricular end-diastolic pressure obtained during diagnostic cardiac catheterization. All patients with a mean left atrial pressure during the study >15 mm Hg had a left ventricular end-diastolic pressure at cardiac catheterization >15 mm Hg as well. Thus, with respect to mean left atrial pressure, the patients studied were in a hemodynamic condition similar to the preoperative situation.

Future studies must be undertaken to prove whether these results can be generalized to predict left atrial pressure under clinical conditions.

Measurements were performed only once and interventions to change preload and afterload or the state of myocardial contractility were not performed. However, all of those procedures would have prolonged the operation time and would have increased the operation risk, which could not be tolerated for ethical reasons.

Small increases in pulmonary venous systolic peak velocity with inspiration have been described previously (46). Although measurements of pulmonary venous flow velocity were not controlled for the respiratory cycle, the averaging of five consecutive cardiac cycles is likely to eliminate respiratory effects. None of the patients was ventilated with positive end-expiratory pressure during the measurement period.

Clinical implications. Our results confirm that pulmonary venous flow velocity tracings can be obtained reliably by transesophageal Doppler echocardiography. However, if peak velocities of pulmonary venous flow are studied, significant error can occur from movements of the orifice of the pulmonary vein relative to the position of the Doppler sample volume. Our data reveal further evidence that left atrial pressure might be estimated by the pattern of pulmonary venous flow velocity. Left atrial compliance is related to pulmonary venous flow waveforms, but this effect can be explained mainly by the decrease in left atrial compliance with increasing left atrial pressure. Further clinical studies in patients with cardiac disease with different underlying mechanisms must be performed to prove the clinical applicability of this method.

References

1. Klein AL, Tajik AJ. Doppler assessment of pulmonary venous flow in healthy subjects and in patients with heart diseases. J Am Soc Echocardiogr 1991;4:379–92.
2. 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.
3. Rajagopalan B, Friend JA, Stallard T, Lee G de J. Blood flow in pulmonary veins: II. The influence of events transmitted from the right to the left sides of the heart. Cardiovasc Res 1979;13:677–83.
4. Rajagopalan B, Friend JA, Stallard T, Lee G de J. Blood flow in pulmonary veins: III. Simultaneous measurements of their dimensions, intravascular pressure and flow. Cardiovasc Res 1979;13:684–92.
5. Keren G, Meisner JS, Sherez J, Yellin EL, Laniado S. Interrelationship of mid-diastolic mitral motion, pulmonary venous flow and transmitral flow. Circulation 1986;74:36–44.
6. 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.
7. Keren G, Sonnenblick EH, LeJentel TH. Mitral annular motion—relation to pulmonary venous and transmitral flow in normal subjects and in patients with dilated cardiomyopathy. Circulation 1988;78:621–9.
8. Klein AL, Hatle L, Burstow DJ, et al. Doppler characterization of left ventricular diastolic function in cardiac amyloidosis. J Am Coll Cardiol 1989;13:1017–26.
9. Klein AL, Oh JK, Miller FA, Seward JB, Tajik AJ. Two-dimensional and Doppler echocardiographic assessment of infiltrative cardiomyopathy. J Am Soc Echocardiogr 1988;1:48–59.
10. Kuecherer HF, Kusumoto F, Muhiudeen IA, Cahalan, MK, Schiller NB. Pulmonary venous flow patterns by transesophageal pulsed Doppler echocardiography: relation to parameters of left ventricular systolic and diastolic function. Am Heart J 1991;122:1683–93.
11. Kuecherer HF, Muhiudeen IA, Kusumoto FM, Lee E, Cahalan MK, Schiller NB. Estimation of mean left atrial pressure from transesophageal pulsed Doppler echocardiography of pulmonary venous flow. Circulation 1990;82: 1127–39.
12. Hoit BD, Shao Y, Gabel M, Walsh RA. Influence of loading conditions and contractile state on pulmonary venous flow. Validation of Doppler velocimetry. Circulation 1992;86:651–9.
13. Hofmann T, Kasper W, Meinertz T, Spiller G, Schlosser V, Just H. Determination of aortic valve orifice area in aortic stenosis by two-dimensional transesophageal echocardiography. Am J Cardiol 1987;59: 330–5.
14. Schiller NB, Cahalan MK, Lee E. Intraoperative assessment of left ventricular function and wall motion by transesophageal echocardiography. Echocardiography 1989;6:79–86.
15. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307–10.
16. Grayburn PA, Willard JE, Haagen DR, Brickner ME, Alvarez MG, Eichhorn EJ. Measurement of coronary flow using high-frequency intravascular ultrasound imaging and pulsed Doppler velocimetry: in vitro feasibility study. J Am Soc Echocardiogr 1992;5:5–12.
17. Tatineni S, Kern MJ, Aguirre F. The effect of ergonovine on coronary vasodilatory reserve in patients with angiographically normal coronary arteries. Am Heart J 1992;123:617–20.
18. Yamagishi M, Hotta D, Tamai J, Nakatani S, Miyatake K. Validity of catheter-tip Doppler technique in assessment of coronary flow velocity and application of spectrum analysis method. Am J Cardiol 1991;67:758–62.
19. Sudhir K, Hargrave VK, Johnson EL, et al. Measurement of volumetric coronary blood flow with a Doppler catheter: validation in an animal model. Am Heart J 1992;124:870–5.
20. Kajiya F, Tsujioka K, Ogasawara Y, et al. Analysis of flow characteristics in poststenotic regions of the human coronary artery during bypass graft surgery. Circulation 1987;76:1092–100.
21. Lunt MJ. Accuracy and limitations of the ultrasonic Doppler velocimeter and zero crossing detector. Ultrasound Med Biol 1975;2:1–10.
22. Basnight MA, Gonzalez MS, Kershenovich SC, Appleton CP. Pulmonary venous flow velocity: relation to hemodynamics, mitral flow velocity and left atrial volume, and ejection fraction. J Am Soc Echocardiogr 1991;4:547–58.
23. Keren G, Bier A, Sherez J, Miura D, Keefe B, LeJemtel T. Atrial contraction is an important determinant of pulmonary venous flow. J Am Coll Cardiol 1986;7:693–5.
24. Nishimura RA, Abel MD, Hatle LK, Tajik AJ. Relation of pulmonary vein to mitral flow velocities by transesophageal Doppler echocardiography. Effect of different loading conditions. Circulation 1990;81:1488–97.
25. Ishida Y, Meisner JS, Tsujioka K. Left ventricular filling dynamics: influence of left ventricular relaxation and left atrial pressure. Circulation 1986;74: 187–96.
26. Appleton CP, Hatle LK, Popp RL. Relation of transmitral flow velocity patterns to left ventricular diastolic function: new insights from a combined hemodynamic and Doppler echocardiographic study. J Am Coll Cardiol 1988;12:426–40.
27. Masuyama T, Lee J-M, Yamamoto K, Tanouchi J, Hori M, Kamada T. Analysis of pulmonary venous flow velocity patterns in hypertensive hearts: its complementary value in the interpretation of mitral flow velocity patterns. Am Heart J 1992;124:983–94.
28. Smallhorn JF, Freedom RM, Olley PM. Pulsed Doppler echocardiographic assessment of extraparenchymal pulmonary vein flow. J Am Coll Cardiol 1987;9:573–9.
29. Nagano T, Arakawa M, Tanaka T, et al. Diastolic compliance of the left atrium in man: a determinant of preload of the left ventricle. Heart Vessels 1989;5:25–32.
30. Leistad E, Christensen G, Ilebekk A. Effects of atrial fibrillation on left and right atrial dimensions, pressures, and compliances. Am J Physiol 1993;264: H1093–7.
31. Yabek SM, Isabel-Jones J, Bhatt DR, Nakazawa M, Marks RA, Jarmakani JM. Echocardiographic determination of left atrial volumes in children with congenital heart disease. Circulation 1976;53:268–72.
32. Tsakiris AG, Padiyar R, Gordon DA, Lipton I. Left atrial size and geometry in the intact dog. Am J Physiol 1977;232:H167–72.
33. Goldman S, Olajos M, Morkin E. Comparison of left atrial and left ventricular performance in conscious dogs. Cardiovasc Res 1984;18:604–12.
34. Hoit BD, Shao Y, Tsai LM, Patel R, Gabel M, Walsh RA. Altered left atrial compliance after atrial appendectomy. Influence on left atrial and ventricular filling. Circ Res 1993;72:167–75.

35. Hoit BD, Shao Y, Gabel M, Walsh RA. Influence of pericardium of left atrial compliance and pulmonary venous flow. Am J Physiol 1993;264: H1781–7.
36. Booth DC, Wisenbaugh T, Smith M, DeMaria AN. Left ventricular distensibility and passive elastic stiffness in atrial septal defect. J Am Coll Cardiol 1988;12:1231–6.
37. Sato S, Kawashima Y, Hirose H, Nakano S, Matsuda H, Shimasaki Y. Clinical study of left atrial compliance and left atrial volume in mitral stenosis. Jpn Circ J 1991;55:481–6.
38. Pichard AD, Diaz R, Marchant E, Casanegra P. Large v waves in the pulmonary capillary wedge pressure tracing without mitral regurgitation: the influence of the pressure/volume relationship on the v wave size. Clin Cardiol 1983;6:534–41.
39. Appleton CP, Gonzalez MS, Basnight MA. Relationship of left atrial pressure and pulmonary venous flow velocities: importance of baseline mitral and pulmonary venous flow velocity patterns studied in lightly sedated dogs. J Am Soc Echocardiogr 1994;7:264–75.
40. 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.
41. Natarajan D, Sharma VP, Chandra S, Dhar SK, Gaba M, Caroli B. Effects of percutaneous balloon mitral valvulotomy on pulmonary venous flow in severe mitral stenosis. Am J Cardiol 1992;69:810–2.
42. Jolly N, Arora R, Mohan JC, Khalilullah M. Pulmonary venous flow dynamics before and after balloon mitral valvuloplasty as determined by transesophageal Doppler echocardiography. Am J Cardiol 1992;70:780–4.
43. Chen Y, Kan M, Lee AY, Chen J, Chiang BN. Pulmonary venous flow: its relationship to left atrial and mitral valve motion. J Am Soc Echocardiogr 1993;6:387–94.
44. Castello R, Pearson AC, Lenzen P, Labovitz AJ. Evaluation of pulmonary venous flow by transesophageal echocardiography in subjects with a normal heart: comparison with transthoracic echocardiography. J Am Coll Cardiol 1991;18:65–71.
45. Castello R, Pearson AC, Lenzen P, Labovitz AJ. Effect of mitral regurgitation on pulmonary venous velocities derived from transesophageal echocardiography color-guided pulsed Doppler imaging. J Am Coll Cardiol 1991; 17:1499–506.
46. Meijburg HWJ, Visser CA, Westerhof PW, Kasteleyn I, van der Tweel I, Robles de Medina EO. Normal pulmonary venous flow characteristics as assessed by transesophageal pulsed Doppler echocardiography. J Am Soc Echocardiogr 1992;5:588–97.