Estimation of Mean Left Atrial Pressure From Transesophageal Pulsed Doppler Echocardiography of Pulmonary Venous Flow

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To determine whether pulmonary venous flow and mitral inflow measured by transesophageal pulsed Doppler echocardiography can be used to estimate mean left atrial pressure (LAP), we prospectively studied 47 consecutive patients undergoing cardiovascular surgery. We correlated Doppler variables of pulmonary venous flow and mitral inflow with simultaneously obtained mean LAP and changes in pressure measured by left atrial or pulmonary artery catheters. Among the pulmonary venous flow variables, the systolic fraction (i.e., the systolic velocity-time integral expressed as a fraction of the sum of systolic and early diastolic velocity-time integrals) correlated most strongly with mean LAP \((r = -0.88)\). Of the mitral inflow variables, the ratio of peak early diastolic to peak late diastolic mitral flow velocity correlated most strongly with mean LAP \((r = 0.43)\), but this correlation was not as strong as that with the systolic fraction of pulmonary venous flow. Similarly, changes in the systolic fraction correlated more strongly with changes in mean LAP \((r = -0.78)\) than did changes in the ratio of peak early diastolic to peak late diastolic mitral inflow velocity \((r = 0.68)\). We conclude that in the surgical setting observed, pulmonary venous flow from transesophageal pulsed Doppler echocardiography can be used to estimate mean LAP. This technique may provide a rapid, simple, and relatively noninvasive means of gauging this variable in patients undergoing intraoperative transesophageal echocardiography. (Circulation 1990;82:1127–1139)

In patients with heart disease, left ventricular diastolic performance is often clinically evaluated by using a flow-directed balloon-tipped catheter to measure pulmonary capillary wedge pressure (PCWP) as an estimate of mean left atrial pressure (LAP) and thus as an indicator of left ventricular filling pressure. In an attempt to find a noninvasive method of assessing left ventricular diastolic performance, pulsed Doppler echocardiography of mitral inflow has recently been investigated.\(^1\)\(^-\)\(^3\) However, quantitation of mitral inflow characteristics as a means of estimating left ventricular filling pressure has been frustrated by such factors as left ventricular relaxation,\(^1\)\(^,\)\(^2\)\(^,\)\(^4\) chamber compliance,\(^1\)\(^,\)\(^2\)\(^,\)\(^5\) left ventricular loading conditions,\(^6\)\(^,\)\(^7\) ventricular interaction,\(^5\) pericardial restraint,\(^5\) and left atrial function,\(^8\) variables that significantly affect mitral inflow.

Left atrial pressure dynamics has been shown to be inversely related to pulmonary venous flow in dogs\(^9\)\(^-\)\(^11\) and humans\(^9\)\(^,\)\(^12\) and also to influence mitral inflow.\(^13\) Therefore, we designed this study to determine whether pulmonary venous flow and mitral inflow measured by transesophageal pulsed Doppler echocardiography can be used to estimate mean LAP. In patients undergoing cardiovascular surgery, we correlated Doppler variables of pulmonary venous flow and mitral inflow with simultaneously measured mean LAP. In addition, we investigated whether elevated mean LAP alters the pattern of pulmonary venous flow and mitral inflow. Finally, we determined whether changes in Doppler variables of pulmonary venous flow and mitral inflow reflect changes in LAP in individual patients by correlating changes in these variables with changes in mean LAP.

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Patient Population

We prospectively performed transesophageal Doppler echocardiography in 52 consecutive patients (38 men and 14 women; age range, 35–78 years) undergoing elective cardiovascular surgery. Five patients were excluded from the study—two because of moderate mitral regurgitation, two because pulmonary wedge pressure tracings could not be obtained, and one because Doppler measurements could not be obtained. Therefore, 47 patients (40 with coronary artery bypass grafting, three with aortic valve replacement, two with aortofemoral bypass, and two with abdominal aortic aneurysm; Table 1) were included in the study. The study protocol was approved by the Committee on Human Research at the University of California, San Francisco. Written informed consent was obtained from all patients.

Anesthesia

Anesthesia was induced with sufentanil (10–15 μg/kg) or fentanyl (75–100 μg/kg) and maintained with isoflurane, oxygen, and nitrous oxide. Anesthetic adjuvants, other medications, and fluids were administered according to the patient’s clinical status.

Experimental Approach

To determine whether pulmonary venous flow and mitral inflow velocities can be used to estimate mean LAP, we monitored mean LAP and other hemodynamic variables and concurrently performed transesophageal Doppler echocardiography of pulmonary venous flow and mitral inflow. To determine whether elevated mean LAP alters the patterns of pulmonary venous flow and mitral inflow velocities, we monitored these variables in patients prospectively divided into two groups—those with normal mean LAP (<15 mm Hg) and those with elevated mean LAP (≥15 mm Hg). To investigate whether changes in pulmonary venous flow and mitral inflow velocities reflect changes in LAP in individual patients, we performed transesophageal echocardiographic measurements during four 3-minute study periods—after induction of anesthesia and intubation, after opening of the pericardium, after cardiopulmonary bypass, and after closing the sternum, constituting a subgroup of 28 consecutive patients. In addition, we measured left ventricular short-axis dimensions throughout the study to determine whether Doppler variables of pulmonary venous flow and mitral inflow are related not only to LAP but also to left ventricular systolic function.

Experimental Procedures

Mean LAP either was measured directly using fluid-filled left atrial catheters (The Desert Company, Sandy, Utah) placed by the surgeon or was estimated from mean PCWP. The left atrial catheters (0.7 mm in diameter, 20.3 cm in length) were connected to strain-gauge pressure transducers (Ameri-

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Patient} & \text{Age (yr)} & \text{Sex} & \text{Surgical procedure} & \text{Coronary artery disease} & \text{Myocardial infarction} \\
\hline
1 & 77 & M & CABG & 2 & AMI \\
2 & 56 & M & AVR & 0 & \ldots \\
3 & 67 & M & CABG & LM & \ldots \\
4 & 68 & F & CABG & 3 & \ldots \\
5 & 67 & M & AFB & 0 & \ldots \\
6 & 65 & F & AVR & 0 & \ldots \\
7 & 67 & M & CABG & LM & \ldots \\
8 & 64 & M & CABG & 1 & \ldots \\
9 & 73 & F & CABG & 3 & \ldots \\
10 & 65 & F & CABG & 1 & \ldots \\
11 & 72 & M & CABG & 2 & IMI \\
12 & 60 & M & CABG & 3 & IMI \\
13 & 66 & M & CABG & 2 & \ldots \\
14 & 73 & M & CABG & 1 & IMI \\
15 & 62 & M & CABG & 2 & \ldots \\
16 & 65 & M & CABG & 2 & \ldots \\
17 & 67 & M & CABG & 1 & IMI \\
18 & 63 & M & CABG & 2 & IMI \\
19 & 64 & M & CABG & 3 & \ldots \\
20 & 64 & F & CABG & 2 & \ldots \\
21 & 65 & M & CABG & 2 & \ldots \\
22 & 62 & M & CABG & 3 & \ldots \\
23 & 58 & M & CABG & 2 & IMI \\
24 & 60 & F & CABG & 1 & AMI \\
25 & 53 & M & CABG & 2 & IMI \\
26 & 62 & M & CABG & 1 & \ldots \\
27 & 35 & M & AVR & 0 & \ldots \\
28 & 61 & M & CABG & 3 & IMI \\
29 & 65 & M & CABG & 3 & \ldots \\
30 & 57 & F & CABG & 2 & IMI \\
31 & 77 & M & CABG & 3 & IMI \\
32 & 73 & F & CABG & 2 & \ldots \\
33 & 44 & F & CABG & 2 & IMI \\
34 & 63 & M & CABG & 3 & IMI \\
35 & 69 & M & AAA & 2 & \ldots \\
36 & 71 & M & CABG & 3 & IMI \\
37 & 72 & F & AAA & 0 & \ldots \\
38 & 63 & M & CABG & 2 & \ldots \\
39 & 63 & M & CABG & 3 & \ldots \\
40 & 54 & M & CABG & 3 & IMI \\
41 & 64 & M & CABG & 3 & AMI,IMI \\
42 & 78 & M & CABG & 1 & AMI \\
43 & 72 & M & CABG & 3 & \ldots \\
44 & 67 & F & CABG & 3 & \ldots \\
45 & 63 & F & AFB & 2 & \ldots \\
46 & 63 & M & CABG & 3 & AMI \\
47 & 60 & M & CABG & 3 & IMI \\
\hline
\end{array}
\]

M, male; F, female; CABG, coronary artery bypass grafting; AVR, aortic valve replacement; AFB, aortofemoral bypass; AAA, abdominal aortic aneurysm; 0, no coronary artery disease; 1, one-vessel disease; 2, two-vessel disease; 3, three-vessel disease; LM, left main disease; AMI, anterior myocardial infarction; IMI, inferior myocardial infarction; \ldots, no myocardial infarction.
can Edwards Laboratories, Irvine, Calif.), which were visually leveled to the right atrium. We used 7.5F pulmonary artery catheters (American Edwards Laboratories) to measure PCWPs. In addition, to detect a possible effect of arterial blood pressure and heart rate on the Doppler variables, we continuously monitored systolic and diastolic arterial pressure using a catheter in the radial artery and derived heart rate from an electrocardiogram that was displayed on the screen of the ultrasonograph.

We performed transesophageal echocardiography using one of three commercially available transesophageal echo probes (Hewlett-Packard Co., Andover, Mass.; Advanced Technology Laboratories Inc., Bellevue, Wash.; Aloka Corometrics Inc., Wallingford, Conn.). After induction of anesthesia, we inserted the transesophageal probe and evaluated Doppler and two-dimensional variables in the following sequence. First, we measured pulmonary venous flow velocities by positioning the Doppler sample in either the upper or lower left pulmonary vein approximately 2 cm proximal to its entrance into the left atrium, where the audio signal was maximal, color Doppler flow indicated maximal forward flow, and the Doppler beam of interrogation was as parallel as possible to its long axis. Second, we measured mitral inflow velocities at the level of the mitral leaflet tips, where leaflet excursions were maximal and color flow indicated maximal flow, in a standard four-chamber view. An angle correction was not employed. Still frames of Doppler tracings were recorded on videotape at end expiration to minimize the possible influence of ventilation on these tracings. Third, we determined left ventricular systolic function by recording cross-sectional views of the left ventricle at the level of the papillary muscles. Images in this sequence could be acquired within 3 minutes. Doppler tracings of pulmonary venous flow and mitral inflow were acquired within the first 30–60 seconds of each study period, concurrent with measurements of mean LAP or PCWP. Color flow Doppler imaging was used to evaluate mitral valve function at each time period to exclude greater-than-mild mitral regurgitation. The severity of mitral regurgitation was semiquantitatively estimated as previously described.14

Two independent observers were used: One recorded invasive hemodynamic variables and the other, blinded to the hemodynamic data, recorded the pulsed Doppler and two-dimensional echocardiographic images.

Measurements and Calculations

Hemodynamic variables were obtained directly from a digital display (Squibb Vitatek Inc., Hillsboro, Ore.) at end expiration by averaging at least three cardiac cycles. Positive end-expiratory pressure ventilation was avoided during the study periods.

Transesophageal Doppler and two-dimensional echocardiographic variables were measured from recordings that were digitized off-line using a phantom-calibrated computerized video analysis system (Cine View, Freeland Medical Division, Indianapolis, Ind.). Measurements were made in a manner randomizing the sequence of acquisition. Three cardiac cycles were averaged for quantitation.

The following variables were derived from Doppler tracings of pulmonary venous flow and mitral inflow and from two-dimensional cross sections of left ventricular short-axis views. From pulmonary venous flow velocity tracings we measured peak systolic and peak early diastolic flow velocities; peak velocities of flow reversal at atrial contraction; and velocity-time integrals of the systolic, early diastolic, and atrial contraction phases. The systolic velocity-time integral was also expressed as a fraction of the sum of systolic and early diastolic velocity-time integrals (systolic fraction). According to the three phases of pulmonary venous flow, velocity-time integrals were measured as follows (Figure 1). The systolic velocity-time integral (X) was measured from the onset of forward flow after the peak R wave on the electrocardiogram to the crossover of that wave with the zero-line. The early diastolic velocity-time integral (Y) was measured from the onset of the second wave to its crossover with the zero-line. The velocity-time integral of flow reversal due to atrial contraction (Z) was measured from onset to termination of negative flow velocities in late diastole. Ratios of peak and integrated flow velocities (peak X/Y and VTI-X/Y) were calculated.

From Doppler tracings of mitral inflow, we measured peak early diastolic and peak late diastolic filling velocities, velocity-time integrals of early and late diastole, deceleration, and deceleration time of early diastolic mitral inflow. Ratios between peak early and peak late diastolic filling velocities and between early and late diastolic velocity-time integrals were calculated. Early and late diastolic velocity-time integrals were normalized for the total velocity-time integral as previously described.15 From left ventricular short-axis views, we measured left ventricular end-diastolic and end-systolic short-axis area and calculated fractional area shortening as previously described.16

Sample Size

To limit potentially confounding variables, five of the 47 patients in whom measurements were obtained after induction of anesthesia had to be excluded: one because of junctional rhythm, two because of atrial fibrillation, and two because PCWP could not be obtained. In addition, 44 of the 112 possible study periods in the first 28 consecutive patients were necessarily excluded from data analysis for the following reasons: 14 for hemodynamic instability, defined as increases or decreases in arterial blood pressure or changes in volume status requiring pharmacological intervention or rapid infusion of fluid; eight for first-degree atrioventricular block; 12 for paced rhythm; three for Doppler tracings of pulmonary venous flow with ill-defined or incomplete
envelopes, and seven because PCWP was unobtainable. Thus, 68 of the 112 possible study periods in this subgroup could be analyzed. LAP was measured using left atrial catheters in 23 of these periods and was derived from PCWP tracings in the remaining 45 periods. During the study periods, all patients were in sinus rhythm (heart rate, 44–117 beats/min).

**Data Analysis**

To determine the relations of pulmonary venous flow and mitral inflow to mean LAP, Doppler variables were correlated with PCWP using a multiple stepwise linear regression analysis that allowed detection of the possible effects of age, heart rate, and systolic and diastolic arterial blood pressures.

In addition, we correlated changes in Doppler variables with changes in PCWP or mean LAP using multiple stepwise regression analysis, including changes in heart rate and systolic and diastolic arterial blood pressure.

To test whether correlation of the systolic fraction with indirectly measured mean LAP differs from that with directly measured mean LAP, we compared correlation of the systolic fraction with mean PCWP to that with directly measured mean LAP.

Hemodynamic and Doppler variables for all study periods during which mean LAP was elevated were compared with the corresponding variables for all study periods during which mean LAP was normal using a two-tailed Student's t test for unpaired variables.

To determine interobserver and intraobserver variability of Doppler echocardiographic measurements, variables in 10 randomly selected patients were analyzed by two independent observers (interobserver variability) and by one observer on two different occasions (intraobserver variability). For determination of interobserver and intraobserver variability, the mean of the percent differences between the two observers and that of the percent differences between the two occasions were calculated.

In addition, by means of a paired Student's t test, time periods during which the patient's chest was opened were compared with those during which the chest was closed to rule out a difference in transthoracic pressure as a confounding variable.

To investigate whether acute increases in mean LAP have a different effect than chronic increases on Doppler variables, we compared time periods in patients who developed an increased LAP ($\geq$15 mm Hg) during surgery with time periods in those who had an increased mean LAP after induction of anesthesia.

Values are given as mean±SD.

**Results**

**Correlation of Doppler Variables With Mean Left Atrial Pressure**

Doppler variables of pulmonary venous flow correlated more strongly with mean LAP (Table 2) and its changes (Table 3) than did Doppler variables of mitral inflow. Of the Doppler variables of pulmonary venous flow, the systolic fraction correlated most strongly with mean LAP ($r=-0.88$) (Figure 2). Mitral inflow variables correlated less well with mean LAP than did pulmonary venous flow variables.
TABLE 2. Correlation of Doppler Variables With Pulmonary Capillary Wedge Pressure in Patients After Induction of Anesthesia

<table>
<thead>
<tr>
<th>Doppler variables</th>
<th>r</th>
<th>SEE (mm Hg)</th>
<th>Slope</th>
<th>Intercept (mm Hg)</th>
<th>F ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary venous flow (n=42)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systolic VTI (cm)</td>
<td>0.57</td>
<td>6.2</td>
<td>1.00</td>
<td>20.8</td>
<td>18.7</td>
</tr>
<tr>
<td>Early diastolic VTI (cm)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;4.0</td>
</tr>
<tr>
<td>Late diastolic VTI (cm)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;4.0</td>
</tr>
<tr>
<td>Systolic fraction (%)</td>
<td>-0.88</td>
<td>3.5</td>
<td>-0.39</td>
<td>34.9</td>
<td>141.4</td>
</tr>
<tr>
<td>Peak systolic velocity (cm/sec)</td>
<td>-0.52</td>
<td>6.5</td>
<td>-0.29</td>
<td>23.1</td>
<td>14.1</td>
</tr>
<tr>
<td>Peak early diastolic velocity (cm/sec)</td>
<td>0.52</td>
<td>6.5</td>
<td>0.20</td>
<td>5.5</td>
<td>14.3</td>
</tr>
<tr>
<td>Peak late diastolic velocity (cm/sec)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;4.0</td>
</tr>
<tr>
<td>Mitral inflow (n=40)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak early diastolic velocity (cm/sec)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;4.0</td>
</tr>
<tr>
<td>Peak late diastolic velocity (cm/sec)</td>
<td>0.40</td>
<td>5.4</td>
<td>0.12</td>
<td>18.7</td>
<td>6.9</td>
</tr>
<tr>
<td>Peak early/late diastolic velocity</td>
<td>0.43</td>
<td>5.3</td>
<td>0.29</td>
<td>23.9</td>
<td>8.8</td>
</tr>
<tr>
<td>Normalized early diastolic VTI (%)</td>
<td>0.40</td>
<td>5.4</td>
<td>0.15</td>
<td>2.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Normalized late diastolic VTI (%)</td>
<td>-0.41</td>
<td>5.4</td>
<td>-0.14</td>
<td>17.2</td>
<td>7.4</td>
</tr>
<tr>
<td>Ratio of early/late diastolic VTI</td>
<td>0.34</td>
<td>5.6</td>
<td>0.78</td>
<td>10.2</td>
<td>4.8</td>
</tr>
<tr>
<td>Deceleration of early velocity (m/sec²)</td>
<td>0.35</td>
<td>5.5</td>
<td>0.85</td>
<td>8.7</td>
<td>5.1</td>
</tr>
<tr>
<td>Deceleration time (msec)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;4.0</td>
</tr>
</tbody>
</table>

A stepwise linear regression analysis was performed to test for possible influences of heart rate, systolic and diastolic arterial blood pressure, and age. Variables with an F ratio ≥ 4.0 entered the regression equation.

SEE, standard error of the estimate; n, number of patients; VTI, velocity-time integral.

Among the mitral inflow variables, the ratio of peak early diastolic to peak late diastolic flow velocity correlated most strongly with mean left atrial pressure (r=0.43) (Table 2). In addition, changes in the systolic fraction of pulmonary venous flow in individual patients correlated better with changes in mean LAP (r= -0.78) than did changes in the ratio of peak early diastolic to peak late diastolic mitral flow velocity (r=0.68) (Figure 3). Baseline values of hemodynamic and Doppler variables in all patients are summarized in Tables 4 and 5.

TABLE 3. Correlation of Changes in Doppler Variables With Changes in Mean Left Atrial Pressure* in Patients During Cardiovascular Surgery

<table>
<thead>
<tr>
<th>Doppler variables</th>
<th>r</th>
<th>SEE (mm Hg)</th>
<th>Slope due to Doppler variable</th>
<th>Slope due to SBP or HR</th>
<th>Intercept (mm Hg)</th>
<th>F ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary venous flow (n=42)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systolic VTI (cm)</td>
<td>0.44</td>
<td>5.7</td>
<td>0.64</td>
<td>...</td>
<td>0.71</td>
<td>9.1</td>
</tr>
<tr>
<td>Early diastolic VTI (cm)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;4.0</td>
</tr>
<tr>
<td>Late diastolic VTI (cm)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;4.0</td>
</tr>
<tr>
<td>Systolic fraction (%)</td>
<td>-0.78</td>
<td>3.9</td>
<td>0.24</td>
<td>...</td>
<td>-0.38</td>
<td>59.1</td>
</tr>
<tr>
<td>Peak systolic velocity (cm/sec)</td>
<td>-0.42</td>
<td>5.7</td>
<td>0.14</td>
<td>...</td>
<td>-0.84</td>
<td>8.3</td>
</tr>
<tr>
<td>Peak early diastolic velocity (cm/sec)</td>
<td>0.52</td>
<td>5.4</td>
<td>0.16</td>
<td>...</td>
<td>-1.27</td>
<td>14.9</td>
</tr>
<tr>
<td>Peak late diastolic velocity (cm/sec)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;4.0</td>
<td></td>
</tr>
<tr>
<td>Mitral inflow (n=34)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak early diastolic velocity (cm/sec)</td>
<td>0.56</td>
<td>4.9</td>
<td>0.12</td>
<td>...</td>
<td>-0.91</td>
<td>14.3</td>
</tr>
<tr>
<td>Peak late diastolic velocity (cm/sec)</td>
<td>-0.61†</td>
<td>4.7</td>
<td>-0.16</td>
<td>0.08‡</td>
<td>0.05</td>
<td>17.1</td>
</tr>
<tr>
<td>Peak early/late diastolic velocity</td>
<td>0.68</td>
<td>4.4</td>
<td>3.6</td>
<td>...</td>
<td>-0.35</td>
<td>27.0</td>
</tr>
<tr>
<td>Normalized early diastolic VTI (%)</td>
<td>0.58‡</td>
<td>4.9</td>
<td>0.18</td>
<td>0.10‡</td>
<td>-1.50</td>
<td>14.4</td>
</tr>
<tr>
<td>Normalized late diastolic VTI (%)</td>
<td>-0.52</td>
<td>5.0</td>
<td>-0.16</td>
<td>...</td>
<td>-0.01</td>
<td>12.3</td>
</tr>
<tr>
<td>Ratio of early/late diastolic VTI</td>
<td>0.50</td>
<td>5.1</td>
<td>1.35</td>
<td>...</td>
<td>-0.19</td>
<td>10.6</td>
</tr>
<tr>
<td>Deceleration of early velocity (m/sec²)</td>
<td>0.60</td>
<td>4.7</td>
<td>1.40</td>
<td>...</td>
<td>-0.44</td>
<td>18.8</td>
</tr>
<tr>
<td>Deceleration time (msec)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>&lt;4.0</td>
<td></td>
</tr>
</tbody>
</table>

A stepwise regression analysis was performed to correlate changes in Doppler variables with changes in left atrial pressure.
*Mean left atrial pressure was measured indirectly, using pulmonary artery flotation catheters, or directly, using left atrial catheters. A cumulative correlation coefficient (†) is given where either heart rate (HR) or systolic blood pressure (SBP) entered the regression equation. Slopes for SBP‡ and HR§ changes are also given. Variables with an F ratio ≥ 4.0 entered the regression equation.

VTI, velocity-time integral; n, number of directional changes analyzed.
The correlation of the systolic fraction with PCWP \((r=-0.85, \text{SEE}=0.12, n=42)\) was similar to that of the systolic fraction with directly measured LAP \((r=0.80, \text{SEE}=0.13, n=23)\).

**Effect of Elevated Mean Left Atrial Pressure on Pulmonary Venous Flow and Mitral Inflow**

When mean LAP was normal, higher pulmonary venous flow velocities were predominant during systole. When mean LAP was elevated, both pulmonary venous flow and mitral inflow patterns were altered, but variables of left ventricular systolic function were not (Table 6). For pulmonary venous flow, peak systolic velocities and systolic velocity-time integrals were decreased and peak early diastolic velocities and early diastolic velocity-time integrals were increased, resulting in a shift of high flow velocities toward early diastole (Figure 4). However, peak velocities and velocity-time integrals after atrial contraction were not influenced by the level of atrial pressure.

Left ventricular systolic function as estimated from fractional shortening of cross-sectional short-axis areas was not different between the two groups (Table 6).

For mitral inflow, peak early diastolic flow velocities were increased and late diastolic flow velocities were decreased with elevation of mean LAP, thus increasing the ratio of peak early diastolic to peak late diastolic flow velocity and resulting in a shift of flow velocities toward early diastole (Figure 5). Similarly, early and late diastolic velocity-time integrals were increased and decreased, respectively, thus increasing the ratio of early to late diastolic velocity-time integrals, again shifting flow velocities toward early diastole.

The deceleration rate of early diastolic mitral inflow was increased at higher mean LAP (Table 3). Deceleration time was not altered in patients with elevated mean LAP.

**Effects of Age, Arterial Blood Pressure, and Heart Rate on Pulmonary Venous Flow and Mitral Inflow**

Neither age, arterial blood pressure, nor heart rate affected Doppler variables of pulmonary venous flow. However, systolic arterial blood pressure and heart rate affected mitral inflow. Changes in systolic blood pressure altered the correlation of changes in peak late diastolic filling velocity with changes in mean LAP (Table 3). With increasing systolic arterial blood pressure, peak late diastolic filling velocity decreased. In addition, heart rate significantly altered the correlation of changes in mitral inflow with changes in mean LAP. Changes in the normalized peak early diastolic velocity-time integral decreased with increasing heart rate.

**Effects of Sternotomy and Opening of Pericardium on Pulmonary Venous Flow and Mitral Inflow**

We compared 25 periods with opened pericardium (seven after sternotomy and opening of the pericardium and 18 after bypass) with 25 periods with the chest closed (seven with chest closed and 18 after induction of anesthesia). Doppler and hemodynamic variables did not differ between these two groups. The systolic fraction was 51.4±27% in open-chest versus 52.9±21% in closed-chest periods, and peak of early diastolic-to-atrial contraction (E/A) ratio was 1.54±0.88 in open-chest versus 1.68±1.38 in closed-chest periods. In both situations, mean LAP was similar (13.1±9.7 mm Hg in open-chest periods versus 12.9±9.5 mm Hg in closed-chest periods).

**Effects of Acute and Chronic Left Atrial Pressure Elevation on Pulmonary Venous Flow and Mitral Inflow**

Acute increases in LAP resulted in a higher peak early filling velocity than did chronic pressure elevations (acute, 96.3±13.5 cm/sec; chronic, 73.0±15.7 cm/sec; \(p<0.006\)) and hence in a higher deceleration
of early filling velocities (acute, 7.96±1.3 m/sec²; chronic, 5.18±3.4 m/sec²; p<0.006). Systolic fraction and peak E/A ratio were not different between acute and chronic pressure elevations (systolic fraction: Acute, 28.7±20.9%; chronic, 36.8±18.2%; p=NS; peak E/A: Acute, 2.8±0.9; chronic, 2.4±1.7; p=0.52). LAP elevation was not significantly different in the two groups (acute, 24±6 mm Hg; chronic, 22±7 mm Hg; p=0.45).

**Reproducibility of Transesophageal Doppler Measurements**

For pulmonary venous flow velocities, interobserver variability was 1.7±4.5% for peak systolic
pulmonary venous flow velocities and 2.3±4.0% for the systolic fraction. The corresponding values for intraobserver variability were 0.7±6.0% and 0.3±2.6%, respectively. For mitral inflow variables, interobserver variability was 0.3±2.6% for peak early diastolic mitral inflow velocities, 3.0±7.0% for peak late diastolic mitral inflow velocities, and 0.6±5.0% for the ratio of the two. Intraobserver variability values were 1.5±3.0%, 2.5±5.0%, and 0.5±4.0%, respectively.

**Discussion**

The results of the present study indicate that both pulmonary venous flow and mitral inflow measured
TABLE 6. Hemodynamic, Doppler, and Two-dimensional Echocardiographic Variables in Patients With Normal and Elevated Mean Left Atrial Pressure

<table>
<thead>
<tr>
<th>Variable</th>
<th>Normal mean LAP (n=60)</th>
<th>Elevated mean LAP (n=27)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemodynamic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean LAP (mm Hg)</td>
<td>8.5±3.4</td>
<td>22.7±7.3*</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>71±16</td>
<td>78±23</td>
</tr>
<tr>
<td>SBP (mm Hg)</td>
<td>119±19</td>
<td>115±15</td>
</tr>
<tr>
<td>DBP (mm Hg)</td>
<td>58±9</td>
<td>61±12</td>
</tr>
<tr>
<td>Systolic PA pressure (mm Hg)</td>
<td>22±6</td>
<td>45±15*</td>
</tr>
<tr>
<td>Diastolic PA pressure (mm Hg)</td>
<td>11±5</td>
<td>23±7*</td>
</tr>
<tr>
<td>Cardiac output (l/min)</td>
<td>4.5±1.5</td>
<td>4.0±1.3</td>
</tr>
<tr>
<td>Doppler (pulmonary venous flow)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak systolic flow velocity (cm/sec)</td>
<td>41.1±12.8</td>
<td>24.4±16.5*</td>
</tr>
<tr>
<td>Peak early diastolic flow velocity (cm/sec)</td>
<td>32.0±14.5</td>
<td>56.3±23.1*</td>
</tr>
<tr>
<td>Peak late diastolic flow velocity (cm/sec)</td>
<td>−18.8±8.1</td>
<td>−19.4±7.4</td>
</tr>
<tr>
<td>Systolic VTI (cm)</td>
<td>9.2±3.9</td>
<td>3.9±2.8*</td>
</tr>
<tr>
<td>Early diastolic VTI (cm)</td>
<td>5.2±2.9</td>
<td>7.5±3.2†</td>
</tr>
<tr>
<td>Late diastolic VTI (cm)</td>
<td>1.3±0.9</td>
<td>1.4±0.6</td>
</tr>
<tr>
<td>Systolic fraction of VTI (%)</td>
<td>66±12.7</td>
<td>32±18.5†</td>
</tr>
<tr>
<td>Doppler (mitral inflow)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak early diastolic velocity (cm/sec)</td>
<td>54.6±19.6</td>
<td>81.5±19.8*</td>
</tr>
<tr>
<td>Peak late diastolic velocity (cm/sec)</td>
<td>58.5±17.5</td>
<td>40.3±17.7*</td>
</tr>
<tr>
<td>Peak early/late diastolic velocity</td>
<td>1.0±0.6</td>
<td>2.4±1.4†</td>
</tr>
<tr>
<td>Normalized early diastolic VTI (%)</td>
<td>57.3±14.2</td>
<td>75.1±12.9*</td>
</tr>
<tr>
<td>Normalized late diastolic VTI (%)</td>
<td>44.3±17.0</td>
<td>22.6±13.0*</td>
</tr>
<tr>
<td>Early/late diastolic VTI</td>
<td>1.7±1.4</td>
<td>4.0±1.6*</td>
</tr>
<tr>
<td>Deceleration of early flow velocity (m/sec^2)</td>
<td>3.3±1.7</td>
<td>6.5±2.9†</td>
</tr>
<tr>
<td>Deceleration Time (msec)</td>
<td>134±62</td>
<td>132±43</td>
</tr>
<tr>
<td>Two-dimensional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End-diastolic short-axis area (cm^2)</td>
<td>21.3±5.5</td>
<td>21.8±4.0</td>
</tr>
<tr>
<td>End-systolic short-axis area (cm^2)</td>
<td>10.2±4.3</td>
<td>11.0±4.1</td>
</tr>
<tr>
<td>Fractional area shortening (%)</td>
<td>53.0±13.4</td>
<td>50.9±11.0</td>
</tr>
</tbody>
</table>

Values are given as mean±SD.

n, Number of study periods; LAP, left atrial pressure; SBP, systolic arterial blood pressure; DBP, diastolic arterial blood pressure; PA, pulmonary artery; VTI, velocity-time integral.

*p<0.001 vs. normal mean LAP; †p<0.05 vs. normal mean LAP.

by transesophageal Doppler echocardiography can be used to estimate mean LAP but that mitral inflow is less accurate. Specifically, we found that the systolic fraction of pulmonary venous flow correlated more closely with mean LAP than did Doppler variables of mitral inflow. Similarly, changes in the systolic fraction correlated more strongly with changes in mean LAP in individual patients than did changes in mitral inflow variables. The stronger correlation of pulmonary venous flow with mean LAP may be explained in part by our finding that in this study population, heart rate and systolic arterial blood pressure significantly influenced mitral inflow but not pulmonary venous flow. Additional evidence for the correlation between pulmonary venous flow and mean LAP shows that as mean LAP rises above normal, the normal pattern of predominant systolic pulmonary venous flow shifts to one of predominant early diastolic flow. For these reasons, and also because the shift from normal to abnormal flow patterns is easily recognized by direct inspection, pulmonary venous flow patterns may serve as an "eyeball index" of mean LAP.

Our findings agree with previous results. Pulmonary venous flow patterns demonstrating predominance of higher velocities during systole parallel the results of previous studies using transthoracic Doppler echocardiography in normal subjects. The shift in mitral inflow velocities, described as pseudonormalization of the mitral inflow pattern, corresponds to the results of previous studies describing a diminished atrial contribution to left ventricular filling in patients with significantly elevated left ventricular filling pressures.

Possible mechanisms that explain shifts in the timing of pulmonary venous flow velocities are worth consideration. It is well recognized that the biphasic profile of pulmonary venous forward flow is inversely related to the levels of the LAP tracing profile. Thus, surges of systolic and diastolic flow occur...
FIGURE 4. Effect of increased mean left atrial pressure (mean LAP) on pulmonary venous flow patterns. Left: Predominant systolic pulmonary venous flow velocities (X) in patient with normal LAP (a, 12 mm Hg; v, 10 mm Hg; mean LAP, 9 mm Hg). Right: Pulmonary venous flow velocities shifted toward early diastole (Y) in same patient in response to increase in LAP (a, 14 mm Hg; v, 22 mm Hg; mean LAP, 15 mm Hg). For purposes of illustration, LAP is displayed simultaneously with pulmonary venous flow tracings. Note incisure (double arrow heads) on upward deflection of systolic wave, which we believe results from temporal dissociation of atrial relaxation and mitral annulus motion (descent of base).

FIGURE 5. Effect of increased mean left atrial pressure (mean LAP) estimated by pulmonary capillary wedge pressure (PCWP) on mitral inflow patterns. Left: Predominant late diastolic filling (A) of mitral inflow in patient with PCWP of 5 mm Hg. Right: Decreased late diastolic filling (A) and increased early diastolic filling (E) in same patient in response to increase in mean PCWP to 20 mm Hg.
during the X and Y descents, respectively (Figure 4). Pulmonary venous flow is minimal after the peaks of the a and v waves. Therefore, the systolic fraction of pulmonary venous flow determined in this study may depend on the relative sizes of the X and Y descents, that is, on the magnitude of the v wave relative to the a wave. Early diastolic forward flow in the pulmonary veins may be higher than systolic flow when the v wave is higher than the a wave.

The degree of systolic forward flow in the extraparenchymal pulmonary veins is determined mainly by atrial relaxation, left ventricular systolic function (suction effect), mitral regurgitation, and left atrial compliance and pressure. Three of these factors (impaired left ventricular systolic function, mitral regurgitation, and decreased left atrial compliance) could explain the shift in pulmonary venous flow. Of these three, we believe that decreased left atrial compliance is the most likely. Impaired systolic function may not primarily account for the shifts in pulmonary venous flow since fractional area shortening as an index of left ventricular systolic function was no different in patients with normal and elevated LAP. However, because fractional shortening of the left ventricular short-axis area does not take into account the behavior of the left ventricular long axis (i.e., descent of the base), we cannot rule out the possibility that left ventricular systolic dysfunction, primarily affecting the descent of the mitral annulus, contributes to the shift in pulmonary venous flow. We can rule out mitral regurgitation as a factor that may decrease systolic pulmonary venous flow since patients with mitral regurgitation of greater-than-mild severity were excluded from this study. Thus, we speculate that a decrease in left atrial compliance due to an increase in LAP, left atrial volume, or both might best explain the shifts in pulmonary venous flow. Increased LAP and left atrial volume may have resulted from increased atrial afterload due to an increase in left ventricular filling pressure, increased atrial contractility, or both. An increase in residual volume could cause the atrial chamber to operate on the steeper portion of its curvilinear pressure-volume relation, thereby increasing the v wave, which increases mean LAP that subsequently decreases systolic pulmonary venous flow.

Regardless of the precise interplay of these factors, we believe that phasic pulmonary venous flow can be used as semiquantitative estimates of mean LAP and pressure changes.

Before our conclusions can be accepted, several limitations of this study must be considered. First, we recorded pulmonary venous flow velocities rather than its volume, assuming that the cross-sectional flow area in the pulmonary veins is relatively constant throughout the cardiac cycle. If this assumption is incorrect, pulmonary venous flow velocities may not have a linear relation to flow volume in the pulmonary veins. To date, experimental studies have shown that the cross-sectional area in extraparenchymal pulmonary veins decreases during ventricular systole by approximately 20%. Under these circumstances, decreases in flow velocities would tend to underestimate true decreases in systolic pulmonary venous flow, thus supporting rather than weakening the validity of our observations. Second, Doppler recordings were compared with mean LAP derived from PCWP tracings in the majority of the study periods (64 of 87). Although PCWP is widely used as the clinical benchmark to evaluate mean LAP, it may not be as precise a measure of LAP as was assumed in this study.

Third, mechanical ventilation may have influenced pulmonary venous flow patterns. Since the respiratory cycle was not separately monitored or superimposed on the Doppler tracings, the timing of inspiration and expiration relative to Doppler flow patterns could not be standardized from one patient to the next. However, to avoid a significant influence of respiration on the Doppler tracings, end expiration was visually identified by observing the ventilator; care was taken to acquire Doppler tracings at end expiration and to mark these frames for later analysis. Since experimental studies suggest that ventilation does not influence flow distribution in the pulmonary veins, we believe that LAP changes, not respiratory variations, account for the marked shifts in pulmonary venous flow in this study. Anesthesia is a fourth factor that could have influenced our results because of a possible myocardial depressant effect. However, it is unlikely that anesthetic agents accounted for the linear relation between systolic forward flow and LAP.

We must also consider that the relation between systolic forward flow and LAP described in this study may not necessarily apply in those situations where intrinsic myocardial contractility is normal and an increase in left ventricular filling pressure occurs because of an increase in left ventricular preload alone (Frank-Starling mechanism), thus increasing left ventricular stroke volume. In this situation, atrial preload will increase, and the absolute amount of systolic forward flow in the pulmonary veins is also likely to increase. Whether the systolic fraction of total forward flow will increase, decrease, or remain the same will depend on where the ventricle and atrium lie on their Starling curves.

Another potential limitation is that acute and chronic LAP elevations may have different effects on pulmonary venous flow patterns. However, we did not observe a significant difference in pulmonary venous flow patterns in acute as compared with chronic pressure elevations in this study population. Still, it is possible that in patients with chronic LAP elevation but preserved left atrial function, the left atrium may be less sensitive to afterload and thus may allow greater systolic atrial filling than we observed.

In addition, when estimating LAP using the calculated regression equation (Figure 2), the potential variability of predicting values of LAP should be emphasized. When comparing the means of measured and predicted pressure values with their
differences, predicted values closely agree with measured values (Figure 6), with a mean difference of \(-0.26\) mm Hg (95% confidence interval, \(-1.07\) to \(+0.55\) mm Hg). However, the 95% confidence intervals for upper and lower limits of agreement are 4.71 to 7.68 mm Hg and \(-8.15\) to \(-5.29\) mm Hg, respectively. Therefore, these limits of agreement may not be sufficiently small to reliably recognize borderline normal LAP. To overcome this limitation, systolic fraction may be used to predict whether LAP exceeds a certain cutoff value. Our results in this group of intraoperative patients suggest that a systolic fraction of less than 55% is both a sensitive (91%) and specific (87%) marker of predicting a mean LAP (PCWP) of less than or equal to 15 mm Hg.

Despite these limitations, this study provides evidence that pulmonary venous flow measured by intraoperative transesophageal pulsed Doppler echocardiography estimates mean LAP sufficiently well to be used as a possible index of left ventricular diastolic performance in anesthetized patients undergoing cardiovascular surgery. Furthermore, in contrast to the insertion of a pulmonary artery flotation catheter for the measurement of PCWP, which carries a risk of complications in critically ill patients, the Doppler measurement of pulmonary venous flow is safe, relatively noninvasive, and simple. Since this technique is widely available and allows rapid, beat-by-beat visual evaluation of the systolic fraction of pulmonary venous velocities, it may be the most practical of the noninvasive techniques for estimating mean LAP. Although this technique has not been validated outside the operating theater or in patients with rhythm disorders, it may be useful for estimating mean LAP as a clinically practical indicator of left ventricular filling pressure in patients undergoing cardiovascular surgery. Its role in the outpatient and intensive care unit settings has yet to be investigated.

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**References**


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