Noninvasive Measurement of Left Atrial Functions
Using Transesophageal Echocardiography

Takeshi NAKAO, MD, Masami SHIMIZU, MD,
Yoshihito KITA, MD, Hiroyuki YOSHIO, MD,
Yoshiyuki ARAI, MD, Hidekazu INO, MD
and Ryoyu TAKEDA, MD

SUMMARY

The use of transesophageal pulsed Doppler echocardiography provides an ideal approach for determining both pulmonary venous flow and transmitral flow. This approach thus provides information about the flow of blood into and out of the left atrium. We designed a new method for separately evaluating left atrial functions on the basis of the time-velocity integrals of pulmonary venous flow and transmitral flow using transesophageal pulsed Doppler echocardiography, assuming that the cross-sectional areas of the mitral ring during the left ventricular diastolic phase and of the four pulmonary venous orifices throughout a cardiac cycle were constant and that the blood flows of the four pulmonary veins exhibited identical velocity profiles. Good correlation was observed between the indices of left atrial function (i.e. left atrial reservoir, conduit and forward contractile volume) using this new method of analysis of Doppler echocardiographic data and those of a conventional method using contrast angiography. In conclusion, transesophageal pulsed Doppler echocardiography provided satisfactory information about left atrial function, and our new method may be one of the most practical techniques for estimating individual left atrial functions. (Jpn Heart J 1996; 37: 227–238)

Key words: Pulsed Doppler echocardiography Pulmonary venous flow Transmitral flow

UNTIL recently, left atrial functions such as reservoir, conduit and booster pump function have been evaluated based on the changes in left atrial volume and left ventricular volume obtained by contrast angiography or radio-nuclide angiography. The left atrium can be easily observed using transesophageal echocardiography because of the favorable anatomical location of the esophagus. Transesophageal pulsed Doppler echocardiography provides information about blood flow velocities across the mitral valve and pulmonary...
venous orifice simultaneously throughout a cardiac cycle. Therefore, these measurements of left atrial inflow and outflow may allow evaluation of left atrial volume changes and left atrial functions. The purpose of this study was to validate the clinical usefulness of our new method by analyzing transesophageal Doppler data to estimate left atrial functions.

**METHODS**

**Subjects:** We performed transesophageal Doppler echocardiography, left atrial angiography and left ventricular angiography in 42 consecutive patients without significant valvular diseases or regional dyskinesis in the left ventricular wall. Twenty-one patients were excluded from the study — 19 because left atrial angiograms could not be satisfactorily traced and 2 because adequate Doppler measurements could not be obtained. Therefore, 21 patients (8 with angina pectoris, 5 with mild hypertensive heart, 3 with chest pain syndrome, 2 with myocarditis, and 1 each with dilated cardiomyopathy, diabetic cardiomyopathy,

| No. | E (cm) | F (cm) | A (cm) | (R-R)_m | s (cm) | f (cm) | a (cm) | (R-R)_p | x (ml) | y (ml) | z (ml) | (R-R)_LA | Z (ml) | Y (ml) | (R-R)_LV (ms) | E, F and A = transmitral time-velocity integrals of early diastolic, slow filling and atrial contraction phases; (R-R)_m, (R-R)_p, (R-R)_LA, and (R-R)_LV = R-R intervals during transmitral flow recordings, pulmonary venous flow recordings, left atrial angiography and left ventricular angiography; s, e, f and a = pulmonary venous time-velocity integrals of systolic, early diastolic, slow filling and atrial contraction phases; x, y and z = left atrial maximal and minimal volumes and just before the left atrial contraction; Z, X and Y = left ventricular maximal and minimal volumes and just before the left atrial contraction. |
and non-Q wave infarction) were included in this study (Table). All subjects had a normal sinus rhythm with a rate of less than 90 beats/min at the time of performing the Doppler study and cardiac catheterization. This study was approved by the Institutional Committee on Human Research of our hospital. Written informed consent was obtained from each patient.

**Transesophageal Doppler echocardiographic examination:** All cardioactive medications were withheld for at least 12 hours before the examination, and all patients were studied in the fasting state. Echocardiograms were obtained with an Aloka SSD-870 ultrasound imager. After local anesthesia of the pharyngeal region with 2% viscous xylocaine, a 5 MHz transesophageal echocardiographic probe (Aloka Co., Tokyo) was inserted into the esophagus in the lateral decubitus. After the patient assumed a supine position, transmitral flow velocities were measured by positioning the sample volume at the center of the mitral ring. Pulmonary venous flow velocities were then measured by positioning the sample volume at the center of the left upper pulmonary venous orifice. Finally, transmitral flow velocities were measured again to obtain recordings of an R-R interval similar to that of pulmonary venous flow. If necessary, additional Doppler recordings were conducted. For each recording, an attempt was made to maintain the angle between the ultrasound beam and mitral inflow or pulmonary venous flow within 20 degrees using color flow imaging. Hard-copy tracings of the Doppler signals, a simultaneous single-lead electrocardiogram and a phonocardiogram were recorded at paper speeds of 100 mm/s. Doppler recordings of pulmonary venous flow and transmitral flow were selected in order to obtain similar R-R intervals. Doppler signals from five consecutive cardiac cycles were measured and the mean value used in subsequent analyses.

The following variables were derived from Doppler tracings of pulmonary venous flow and transmitral flow (Figure 1). The time-velocity integrals were measured as areas under the Doppler waveforms using a light pen and microprocessor system (Sigma 5/E, Medical Systems Research Company, Tokyo). From the transmitral flow velocity tracings we measured the time-velocity integrals of the early diastolic (E), slow filling (F), and atrial contraction (A) phases, while the pulmonary venous flow velocity tracings were used to measure the time velocity integrals of the systolic (s), early diastolic (e), slow filling (f), and atrial contraction (a) phases. “Systolic phase” indicates the left ventricular systolic period and isovolumic relaxation period. The slow filling phase was defined as the interval from the inflection point on the deceleration limb of the early diastolic flow velocity curve to the onset of atrial contraction on both Doppler tracings. If this inflection point was unclear, the time-velocity integral of the slow filling phase was regarded as zero and the early diastolic phase was taken as the interval from the onset of left ventricular filling to the onset of atrial contraction.
Figure 1. Measurement of Doppler indices. Left panel shows Doppler recordings of pulmonary venous flow (PVF) and transmitral flow (TMF). Right upper panel shows cumulative time-velocity integral curves of pulmonary venous flow (1) and transmitral flow (3). The y-axis represents the cumulative time-velocity integral and the x-axis the time from the start of the systolic wave of pulmonary venous flow. The 2 bold lines in the right middle panel indicate the time-velocity integral changes of pulmonary venous flow corrected by k (2) and of the equivalent of left atrial volume change (4), derived by subtracting the time-velocity integral change of pulmonary venous flow corrected by k from the time-velocity integral change of transmitral flow. Right lower panel shows left atrial volume measurements and individual left atrial functions separate from the cumulative time-velocity integral curves. dBO = equivalent of left atrial forward contractile volume; dCO = equivalent of left atrial conduit volume; dLAV1 = equivalent of maximal left atrial volume change; dLAV2 = equivalent of left atrial volume change during the atrial contraction; dRE = equivalent of left atrial reservoir volume; k = s2/s1; s1 = cross-sectional area of mitral ring; s2 = cross-sectional area of four pulmonary venous orifices; PVF = pulmonary venous flow; TMF = transmitral flow. Other abbreviations are the same as in Table. (Reproduced with slight modification from Nakao et al by permission of the Japan Society of Ultrasonics in Medicine.)
Changes in the cumulative time-velocity integral of left atrial inflow and outflow were obtained (Figure 1). We assumed that the cross-sectional areas of the mitral ring during the left ventricular diastolic phase and of the four pulmonary venous orifices throughout a cardiac cycle were constant, and that the blood flows of the four pulmonary veins exhibited identical velocity profiles. Stroke volume was calculated as

\[ \int_0^T (\text{cross-sectional area}) \times (\text{blood flow velocity}) \, dt, \]  

where \( T \) is cardiac cycle length. Left atrial outflow volume to the left ventricle during the left ventricular diastolic phase and left atrial inflow volume from pulmonary veins during a cardiac cycle are derived from the transmitral and pulmonary venous flow velocity tracing as

\[ \int_0^T s_1 \cdot v_1(t) \, dt \quad \text{and} \quad \int_0^T s_2 \cdot v_2(t) \, dt, \]  

where \( s_1 \) and \( s_2 \) are cross-sectional areas of the mitral ring and of the four pulmonary venous orifices, and \( v_1(t) \) and \( v_2(t) \) are the volumetric flow rates of left ventricular inflow and pulmonary venous flow, respectively, as a function of time. Assuming that \( s_1 \) and \( s_2 \) were constant during a cardiac cycle, formula (ii) can be rewritten as:

\[ \int_0^T s_1 \cdot v_1(t) \, dt = s_1 \cdot (E + F + A) \quad \text{and} \quad \int_0^T s_2 \cdot v_2(t) \, dt = s_2 \cdot (s + e + f - a), \]  

where \( E, F, \) and \( A \) are the transmitral flow time-velocity integrals at the early diastolic, slow filling and atrial contraction phases, respectively, and \( s, e, f, \) and \( a \) are the pulmonary venous flow time-velocity integrals at the systolic, early diastolic, slow filling and atrial contraction phases. The total time-velocity integral of left atrial outflow through the mitral ring to the left ventricle during the left ventricular diastolic phase is equal to that of left atrial inflow from the pulmonary veins in a cardiac cycle; that is,

\[ s_1 \cdot (E + F + A) = s_2 \cdot (s + e + f - a) \]  

Thus,

\[ E + F + A = s_2/s_1 \cdot (s + e + f - a) \]  

Since \( s_1 \) and \( s_2 \) were assumed to be constant,

\[ k = s_2/s_1 \]  

was also a constant, where \( k \) is a correction factor. Substituting for \( k \) in equation (v),

\[ E + F + A = k \cdot (s + e + f - a). \]
When we used this correction factor, it was possible to obtain time-velocity integrals of left atrial inflow that were directly comparable with those of left atrial outflow. Therefore, the time-velocity integral changes equivalent to left atrial volume changes could be calculated by subtracting the changes in the cumulative time-velocity integral of left atrial outflow from the changes in the cumulative time-velocity integral of left atrial inflow corrected by k.

The following indices were obtained from these integrals: equivalent of maximal left atrial volume change ($dLAV_1 = k_s$), equivalent of left atrial volume change during the atrial contraction ($dLAV_2 = k(s + e + f) - (E + F)$), equivalent of left atrial reservoir volume defined as the blood volume which was reserved for left ventricular filling from the pulmonary veins during left ventricular systole, determined by subtracting the left atrial volume before atrial contraction from the maximal left atrial volume ($dRE = dLAV_1 - dLAV_2$), equivalent of left atrial conduit volume defined as the blood volume which passed through the left atrium from the pulmonary veins to the left ventricle during left ventricular diastole ($dCO = k(e + f)$), and the equivalent of left atrial forward contractile volume ($dBO = A$). These indices were normalized by the equivalent of the stroke volume ($E + F + A$) and were defined as $\%dLAV_1$, $\%dLAV_2$, $\%dRE$, $\%dCO$, and $\%dBO$, respectively.

**Cardiac catheterization:** Diagnostic cardiac catheterization was performed within five days after the echocardiographic study. All patients were studied in the fasting state and did not receive any cardioactive medications for at least 12 hours before. Routine left ventriculography was performed at 60 frames/sec. Left atrial biplane cineangiography in the anteroposterior and left lateral projections.

![Figure 2](image-url)  
**Figure 2.** Measurement of angiographical indices. Left ventricular volume curve ($LVV$) and left atrial volume curve ($LAV$) were obtained using the methods reported by Sauter et al (5) and Kasser et al. ($gBO =$ left atrial forward contractile volume ($=Z-Y$); $gCO =$ left atrial conduit volume ($=(Y-X)-(x-y)$); $gRE =$ left atrial reservoir volume ($=x-y$); $gLAV_1 =$ maximal left atrial volume change ($=x-z$); $gLAV_2 =$ left atrial volume change during the left atrial contraction ($=y-z$); Other abbreviations are the same as in Table.)
was performed at 60 frames/sec with contrast material injected into the main pulmonary artery.

Left atrial and left ventricular volumes were calculated as described by Sauter et al.\textsuperscript{5} and Kasser et al.\textsuperscript{6} The angiographical silhouettes were outlined frame by frame with a light pen on a video screen. Left atrial and left ventricular volume curves were fitted using fifth-order harmonics in the Fourier's series. From these reconstructed volume curves, the $d^2V/dt^2$ was calculated and the $d^2V/dt^2$ curve constructed. The onset of the atrial contraction phase was defined as the inflection point where $d^2V/dt^2$ reached a peak during late diastole. The points of maximal and minimal volumes and volume just before left atrial contraction were determined from the volume curves and defined as $x$, $z$, and $y$ in the left atrial volume curve, and $Z$, $X$, and $Y$ in the left ventricular volume curve, respectively (Figure 2). The following indices were calculated: maximal left atrial volume change ($gLAV1 = x-z$), left atrial volume change during the atrial contraction ($gLAV2 = y-z$), left atrial reservoir volume ($gRE = x-y$), left atrial conduit volume ($gCO = (Y-X)-(x-y)$), and left atrial forward contractile volume ($gBO = Z-Y$).\textsuperscript{1,2} These indices were normalized by the stroke volume and defined as % $gLAV1$, % $gLAV2$, % $gRE$, % $gCO$, and % $gBO$, respectively.

**Statistical Analysis:** The results are presented as the mean ± 1 standard deviation. Linear regression analysis performed by means of the least-squares method was used to compare transesophageal Doppler indices with those derived from left atrial and left ventricular angiograms.

![Figure 3](image_url)

**Figure 3.** Relationship between left atrial volume changes determined using the Doppler and angiographical methods. % $dLAV1$ and % $dLAV2$ were calculated by dividing $dLAV1$ and $dLAV2$ by $(E + F + A)$ (%). % $gLAV1$ and % $gLAV2$ were calculated by dividing $gLAV1$ and $gLAV2$ by the stroke volume (%). Other abbreviations are the same as in Figures 1 and 2.
Figure 4. Relationship between left atrial functions determined by the Doppler and angiographical methods. \( \%dRE, \%dCO \) and \( \%dBO \) were calculated by dividing \( dRE, dCO \) and \( dBO \), respectively, by \( E+F+A(\%) \). \( \%gRE, \%gCO \) and \( \%gBO \) were calculated by dividing \( gRE, gCO \) and \( gBO \) by the stroke volume (\%). Other abbreviations are the same as in Figures 1 and 2.

Results

The results of the Doppler and angiographical measurements are summarized in the Table.

The difference in R-R intervals was only 2.6 ± 1.5% between the pulmonary venous flow and transmitral flow recordings and 7.8 ± 5.9% between the left atrial and ventricular angiograms.

Normalized maximal left atrial volume change obtained by the Doppler method (\( \%dLAV1 \)) showed a linear correlation with the index by the angiographical method (\( \%gLAV1 \)) \((r = 0.83, p < 0.001)\), and likewise there was a correlation between normalized left atrial volume change during atrial contraction by the Doppler method (\( \%dLAV2 \)) and the index using the angiographical
method (gLAV2) \( r = 0.74, p < 0.001 \); Figure 3). Moreover, concerning left atrial reservoir volume, left atrial conduit volume, and left atrial forward contractile volume, the indices obtained using the Doppler method were found to correlate with that using the angiographical method (%dRE and %gRE: \( r = 0.78, p < 0.001 \); %dCO and %gCO: \( r = 0.84, p < 0.001 \); %dBO and %gBO: \( r = 0.76, p < 0.001 \), respectively; Figure 4).

**Discussion**

Noninvasive methods used to evaluate left atrial functions include radionuclide ventriculography\(^2,7\), M-mode\(^8,9\), two-dimensional\(^10\) and pulsed Doppler echocardiography\(^11-17\). Although the radionuclide method provides the left atrial functions derived from volume curves of the left ventricle and left atrium separately, it is impossible to repeat the measurement in short intervals and errors can result from background correction and overlap between the left atrium and left ventricle. There are limits to the M-mode and two-dimensional echocardiography methods because both yield only fragmentary information about left atrial volume, such as one diameter or area. On the other hand, Doppler flow signals reflect the whole volume change, regardless of whether the shape of the left atrium is ellipsoid or not, or whether the motion of the whole left atrial wall is equal or not. Although most Doppler studies have been limited to evaluating transmitial flow by transthoracic echocardiography\(^14-16\), the widespread use of transesophageal echocardiography makes it very easy to examine not only transmitial flow\(^17\) but also pulmonary venous flow\(^12,13\).

Transesophageal echocardiography provides an ideal approach for obtaining both pulmonary venous flow and transmitial flow using a pulsed Doppler technique. This approach thus provides information about left atrial blood inflow and outflow, and makes possible the evaluation of changes in left atrial volume. Until now, the Doppler velocity of the pulmonary venous flow has not been directly compared with that of the transmitial flow because of the different sizes of the orifices through which the flow passes. Despite this problem, however, if the ratio of the two areas is constant throughout the cardiac cycle, the two velocities should be comparable. Moreover, because we can obtain volume changes in left atrial inflow and outflow separately using the transesophageal Doppler technique, left atrial functions such as reservoir, conduit, and booster pump function can also be estimated separately\(^1,2\).

In this study, we assumed that the cross-sectional areas for the mitral ring during the left ventricular diastolic phase and for the four pulmonary venous orifices throughout the cardiac cycle were constant and that the blood flows of the four pulmonary veins exhibited identical velocity profiles. We also examined
whether or not the left atrial volume changes and left atrial functions estimated by our transesophageal Doppler technique were clinically satisfactory. The results showed that the left atrial volumes and functions measured by our new transesophageal Doppler method correlated with those using conventional left ventricular and left atrial cineangiography, indicating that our method can be used for semiquantitative estimations of left atrial functions.

Several limitations of this study must be considered. First, the pulmonary venous flow time-velocity integral and transmitral flow time-velocity integral were used as indicators of pulmonary venous flow and transmirtal flow, assuming that the cross-sectional flow areas are relatively constant throughout the cardiac cycle. It has been reported that the cross-sectional area of the left upper lobe pulmonary vein varies by 17.5% during the cardiac cycle in dogs. Since we measured the velocity at the pulmonary venous orifice, the cross-sectional area may change even less than the area of the pulmonary veins. Moreover, Hoit et al showed that there is an excellent correlation between the pulmonary venous systolic to diastolic flow time-velocity integral measured by pulsed Doppler echocardiography and flow measured using a flow probe, indicating that changes in the pulmonary vein cross-sectional area during the cardiac cycle can be ignored. On the other hand, the cross-sectional area of the mitral ring also changes during the cardiac cycle. Ormiston et al reported that the mitral valve area varied by 12% in size during the cardiac cycle. However, the present study focused only on the left ventricular diastolic phase in evaluating the flow from the left atrium to left ventricle. Thus, the change in mitral annular area most likely has only a slight effect on the calculation of flow volume. Moreover, recent investigations have shown good correlations between invasive determinations of cardiac output and those made by Doppler techniques with a single diastolic estimation of mitral annular area. Therefore, the above assumption is acceptable. Second, there is another assumption, that the velocity curves of all four pulmonary veins are similar. It is known that in patients with mitral regurgitation the velocity curve in one pulmonary vein may not be the same as the other. Although the position of the patient may influence the velocity curves, the time-velocity integrals of left and right pulmonary venous flow are similar when the subject is in the supine position. No patients with mitral regurgitation were enrolled in this study and all Doppler recordings of pulmonary venous flow were conducted with the subject in the supine position. Therefore, we do not believe that this assumption detracted from the overall results. Third, our method requires that the R-R interval of the pulmonary venous Doppler tracing be the same as that of the transmital flow Doppler tracing. We repeated the Doppler recordings until this condition was nearly fulfilled, and the difference between the two R-R intervals was only 2.6%.
The left atrial forward contractile volumes were overestimated in a few patients when measured using the Doppler method. This overestimation may be due partly to the difference in R-R intervals between the left atrial and ventricular angiograms. Further combination studies with gated radionuclide angiography or magnetic resonance imaging should help elucidate this problem.

Despite these limitations, examination of pulmonary venous flow velocity and transmitral flow velocity by transesophageal pulsed Doppler echocardiography provided satisfactory information about left atrial functions. We used only the time-velocity integral as a substitute for volumetric flow after conventional cineangiography to evaluate left atrial functions. The Doppler tracing provides other information concerning left atrial functions, such as the acceleration of flow and pressure gradient. Recently, Manning et al attempted to assess noninvasively left atrial function using the acceleration of transmitral Doppler signal during atrial systole. Therefore, combining separate left atrial functions using our method and other Doppler-derived indices may enable us to assess left atrial performance in more detail. Furthermore, echocardiography can be used at bedside, and is easily repeatable. Since transesophageal echocardiography is convenient and allows rapid evaluation of pulmonary venous flow and transmitral flow, our method may be the most practical clinical technique for estimating left atrial performance.

REFERENCES


