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The Deceleration Time of Pulmonary Venous Diastolic Flow Is More Accurate Than the Pulmonary Artery Occlusion Pressure in Predicting Left Atrial Pressure

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OBJECTIVES This study compared a prediction of mean left atrial pressure (P_{LA}) ascertained by Doppler echocardiography of pulmonary venous flow (PVF), with predicted P_{LA} using the pulmonary artery occlusion pressure (P_{PAO}).

BACKGROUND In select patient groups, PVF variables correlate with P_{PAO}, an indirect measure of P_{LA}.

METHODS In 93 patients undergoing cardiac surgery, we recorded with transesophageal echocardiography mitral valve early (E) and late (A) wave velocities, deceleration time (DT) of E (DT_E), and pulmonary vein systolic (S) and diastolic (D) wave velocities, DT of D (DT_D) and systolic fraction. The P_{PAO} was measured using a pulmonary artery catheter zeroed to midaxillary level. A further catheter was held at midatrial level to zero a transducer and was then inserted into the left atrium. A prediction rule for P_{LA} from DT_D was developed in 50 patients and applied prospectively to estimate P_{LA} in 43 patients.

RESULTS A close correlation ($r = -0.92$) was found between P_{LA} and DT_D. Systolic fraction ($r = -0.63$), DT_E ($r = -0.61$), D wave ($r = 0.57$), E wave ($r = 0.52$), and E/A ratio ($r = 0.13$) correlated less closely with P_{LA}. The mean difference between predicted and measured P_{LA} was 0.58 mm Hg for DT_D method and 1.72 mm Hg for P_{PAO}, with limits of agreement (mean ± 2 SE) of −2.94 to 4.10 mm Hg and −2.48 to 5.92 mm Hg, respectively. A DT_D of <175 ms had 100% sensitivity and 94% specificity for a P_{LA} of >17 mm Hg.

CONCLUSIONS Deceleration time of pulmonary vein diastolic wave is more accurate than P_{PAO} in estimating left atrial pressure in cardiac surgical patients. (J Am Coll Cardiol 2001;37:2025–30) © 2001 by the American College of Cardiology

Pulmonary artery occlusion pressure (P_{PAO}) is considered the clinical gold standard for estimation of mean left atrial pressure (P_{LA}), an indirect indicator of left ventricular intracavity filling pressures (1,2). However, insertion of a pulmonary artery catheter is not a risk-free procedure, and a reliable, less-invasive alternative has been sought (3). Both pulsed-wave Doppler echocardiography of mitral inflow and, subsequently, pulmonary vein flow (PVF) have been extensively studied, and a clear relationship between selected variables and P_{PAO} was found (4–12). However, mitral inflow and PVF patterns are influenced by multiple factors including left atrial pressure, left ventricular relaxation (4,13), compliance and afterload (14,15), ventricular interaction (16,17), heart rate (18,19), cardiac output (20) and age (21). These confounding factors preclude routine clinical use of mitral inflow or PVF patterns to predict P_{LA}.

Two recent studies have found a close relationship between the deceleration time of the diastolic wave (DT_D) of PVF and P_{PAO} in selected patient groups (22,23). Therefore, this study set out to investigate the relationship between the DT_D and directly measured P_{LA} in a more general group of cardiac surgical patients. We then attempted to predict P_{LA} in a test group using a regression equation developed from the correlation between DT_D and P_{LA} in the study group. Finally, we compared the accuracy of this method of estimating P_{LA} with P_{PAO} estimation of P_{LA}.

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METHODS

Patients. Ninety-three patients scheduled for coronary artery bypass surgery and/or aortic valve replacement were studied in the operating room. Patients were divided into two groups: Patients in group 1 (50 patients)—the derivation group—were used to develop the prediction rule for P_{LA}, and group 2 patients (43 patients)—the test group—were used to test the prediction rule. All patients had undergone cardiac catheterization ± transthoracic echocardiography prior to surgery. Patients with any degree of mitral stenosis, moderate or severe mitral regurgitation (24,25), or a history of prior cardiac surgery were excluded. The study protocol was approved by the St. Paul's Hospital Research Ethics Board. All patients gave written, informed consent in a preadmission clinic or on the cardiac ward after full explanation of the study protocol.

Echocardiographic data. Following induction of anesthesia, endotracheal intubation and placement of a pulmonary artery catheter (Model 131 F7, Baxter, Deerfield, Illinois), a multiplane 5-MHz transesophageal probe (Hewlett-Packard, Palo Alto, California) was placed in the esophagus.

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Abbreviations and Acronyms

- A = late mitral inflow
- CI = confidence interval
- D = diastolic pulmonary vein flow
- DT_D = deceleration time of diastolic pulmonary vein flow
- DT_E = deceleration time of early mitral inflow
- E = early mitral inflow
- P_{LA} = mean left atrial pressure
- P_{PAO} = pulmonary artery occlusion pressure
- PVF = pulmonary venous flow
- S = systolic pulmonary vein flow
- SE = standard error

Data were obtained using a Hewlett-Packard Sonos 1500 ultrasound unit and recorded on videotape for later analysis. All measurements were obtained after pericardotomy, with the patient in a stable hemodynamic state, and ventilation briefly suspended at end expiration. Pulmonary venous flow was obtained by placing the pulsed-wave Doppler sample volume approximately 1 cm beyond the orifice of a superior pulmonary vein. Color flow Doppler was used when necessary to assist with optimal sample volume placement. Mitral flow was obtained in a four-chamber view with the pulsed-wave Doppler sample volume placed at the tips of the mitral leaflets. All Doppler tracings were recorded at 100 mm/s sweep speed.

Hemodynamic data. After induction of anesthesia, a transducer for the pulmonary artery catheter was zeroed visually at the midaxillary level by the anesthesiologist and then fixed in relation to the chest. The P_{PAO} measurements were taken by the anesthesiologist immediately after the echocardiographic data were acquired.

Following P_{PAO} measurement, a fluid-filled catheter attached to a 21-gauge needle was held by the surgeon adjacent to the mid-right atrial wall to rezero the pressure transducer. The left atrium was then cannulated to directly record P_{LA}. All measurements were obtained in a steady hemodynamic state with ventilation briefly suspended at end expiration. The maximum time to acquire all echocardiographic and hemodynamic data was 10 min.

Echocardiographic analysis. Analysis of the echocardiographic data was performed offline by an interpreter (T.K.) blinded to the hemodynamic data. For all measurements, five consecutive beats were traced and the results averaged.

Pulmonary venous flow was analyzed for peak systolic (S) and diastolic (D) wave velocities, their ratio, and velocity time integrals. The DT_D, and the peak velocity and duration of the atrial reversal wave were also measured. In the presence of a bimodal D wave deceleration slope, the initial, steeper part was extrapolated to zero to obtain the deceleration time (Fig. 1) (22). The systolic fraction of PVF was calculated as the ratio of the velocity-time integral of the S

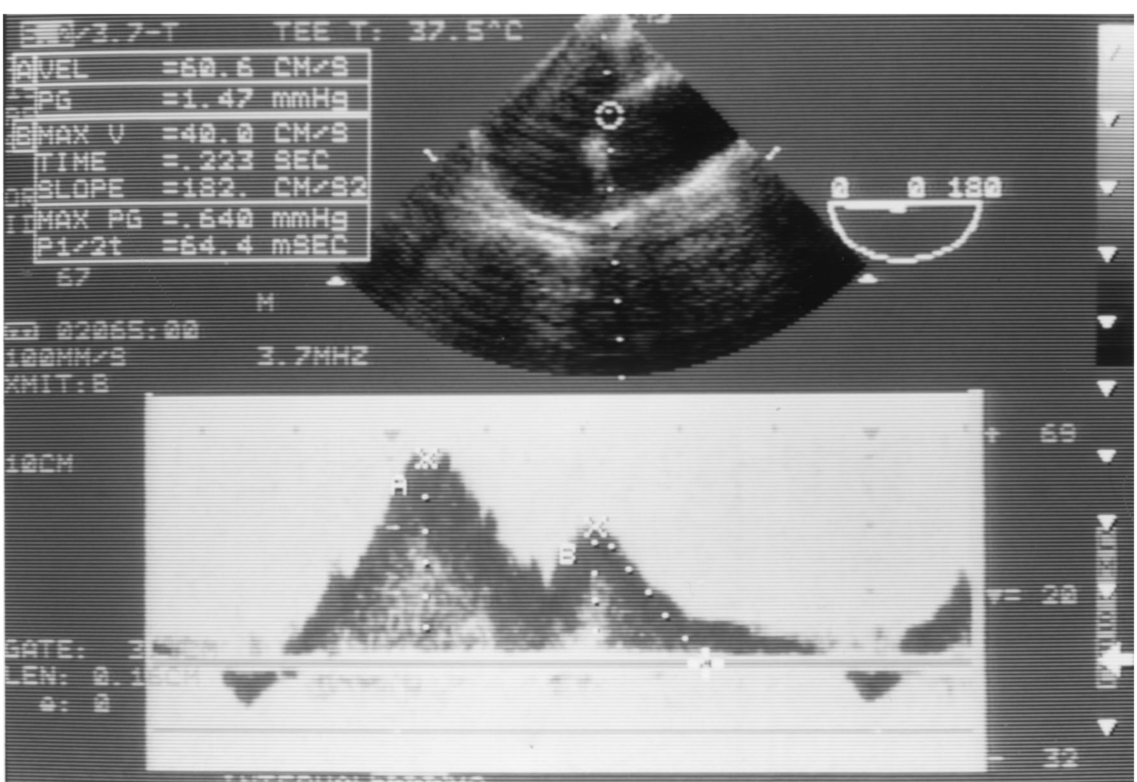

Figure 1. Transesophageal pulsed-wave Doppler showing a biphasic slope of deceleration of the diastolic wave (D) of pulmonary venous flow. The deceleration time of the D wave is measured as the time interval between peak velocity and the upper deceleration slope extrapolated to zero. The deceleration time in this case is 223 ms.

Table 1. Clinical and Hemodynamic Characteristics of the Study Population

	Group 1 (n = 50)	Group 2 (n = 43)
Age (yr)	65 (57, 71)	70 (61, 74)
Gender (M/F)	42/8	36/7
Coronary artery disease	47	36
Aortic stenosis	6	8
Rhythm (Sinus/AF)	48/2	42/1
LV ejection fraction (%)	62 (48, 70)	63 (53, 70)
Systolic pressure (mm Hg)	110 (101, 124)	104 (95, 123)
Cardiac index (liter/min/m^2)	2.3 (2.1, 2.8)	2.3 (2.0, 2.6)
Heart rate (beats/min)	63 (58, 69)	62 (55, 72)

Data presented as median (quartile 1, quartile 3) or absolute numbers.
AF = atrial fibrillation; LV = left ventricle.

wave to that of the combined velocity-time integral of the S and D waves.

From mitral flow recordings, the velocities of peak early (E) and late (A) waves and their ratio, E wave deceleration time (DT_E) and A wave duration were measured. The initial and steeper part of the E deceleration slope was also extrapolated to baseline where necessary to measure DT_E. The difference between the duration of the A wave and the duration of the atrial reversal wave was also calculated.

Statistical analysis. Using Statistical Analysis Software (SAS Institute, Cary, North Carolina), quadratic regression analysis was performed to examine the correlation between Doppler variables and P_{LA} and the correlation between P_{PAO} and P_{LA}. A P_{LA} prediction rule was developed based on the correlation between DT_D and P_{LA} in the first 50 patients (group 1) and then applied prospectively to the subsequent 43 patients (group 2). To evaluate the agreement between predicted and actual P_{LA}, and between P_{PAO} and P_{LA} (in the same 43 patients), the data were processed by the Bland-Altman method, and the 95% confidence intervals (CI) expressed (26). Sensitivity and specificity were calculated with standard formulae.

RESULTS

The baseline clinical and hemodynamic characteristics of the study group are described in Table 1. Group 2 patients were slightly older and had a higher incidence of aortic stenosis than patients in group 1. Ejection fraction was measured during cardiac catheterization.

Correlation of mitral and PVF variables with P_{LA}. A close correlation (r = −0.92) was found between DT_D and P_{LA} for the entire patient group (Fig. 2), whereas correlation of the other echocardiographic parameters was less close (Table 2). Among the PVF variables, DT_D, systolic fraction and D wave peak velocity correlated most closely with P_{LA}. Of the mitral inflow variables, DT_E and E wave peak velocity correlated most closely with P_{LA}. A DT_D of <175 ms had 100% sensitivity and 94% specificity for a P_{LA} of ≥17 mm Hg in the entire group, and 100% sensitivity and 90% specificity for a P_{LA} of > 17 mm Hg in the test group. A DT_D >275 ms predicted a P_{LA} of ≤6 mm Hg , with 88% sensitivity and 95% specificity. There was no correlation between ejection fraction and DT_D.

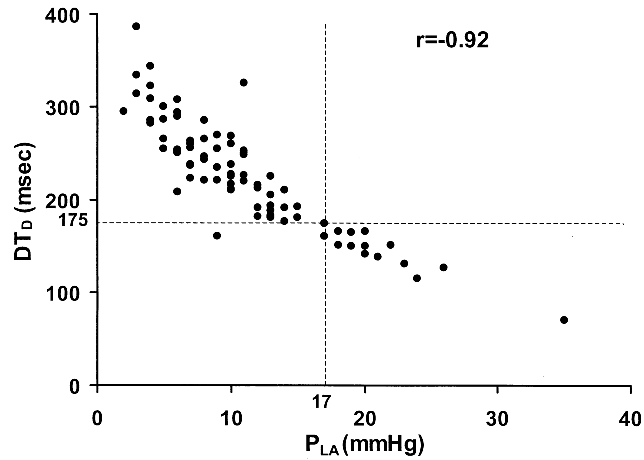

Figure 2. Scatterplot of the correlation between deceleration time of the diastolic wave of pulmonary venous flow (DT_D) and mean left atrial pressure (P_{LA}). Data are plotted for group 1 combined with group 2. The **horizontal dashed line** indicates a DT_D of 175 ms, which predicted a P_{LA} of >17 mm Hg, with 100% sensitivity and 98% specificity.

Estimation of P_{LA} from DT_D in the test group. Using the DT_D and P_{LA} plot from group 1, the following regression equation was developed:

$$P_{LA} = 53.236 - [0.302 - DT_D] + [0.000484\,(DT_D^{2})]$$

This formula was then applied prospectively to group 2 to predict P_{LA}. The correlation between the estimated P_{LA} using DT_D and actual P_{LA} is shown in Figure 3. Figure 4 displays a Bland-Altman plot of the difference between estimated and actual P_{LA} versus actual P_{LA}. The mean difference between predicted and measured P_{LA} was 0.58 mm Hg, with 95% CI (mean ± 2 SE) of −2.94 to 4.10 mm Hg.

Table 2. Correlations Between Echocardiographic Variables and Mean Left Atrial Pressure

Echocardiographic Variable	r Value
Mitral inflow	
E wave	0.52
E/A ratio	0.13
DT_E	−0.61
Pulmonary venous flow	
S wave	−0.06
D wave	0.57
S/D ratio	−0.36
Systolic fraction	−0.63
AR wave	0.44
VTI_S	−0.40
VTI_D	0.21
D_A–D_{AR}	−0.43
DT_D	−0.92

AR wave = peak velocity PVF atrial reversal; D = peak velocity diastolic PVF flow; D_A–D_{AR} = difference between duration of late mitral inflow and duration of AR; DT_D = deceleration time of D wave; DT_E = deceleration time of E wave; E = peak velocity early mitral flow; PVF = pulmonary venous flow; S = peak velocity systolic PVF flow; VTI_D = velocity-time integral D wave; VTI_S = velocity-time integral S wave.

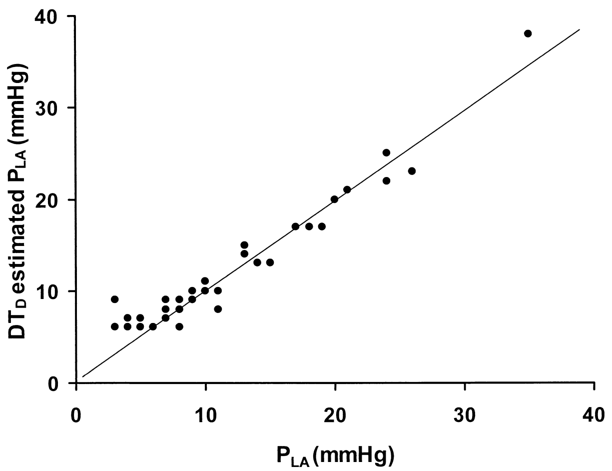

Figure 3. Scatterplot of the correlation between estimated mean left atrial pressure (P_{LA}) (calculated from the deceleration time of diastolic pulmonary venous flow [DT_D] using the derived quadratic regression equation) and the directly measured P_{LA} in group 2.

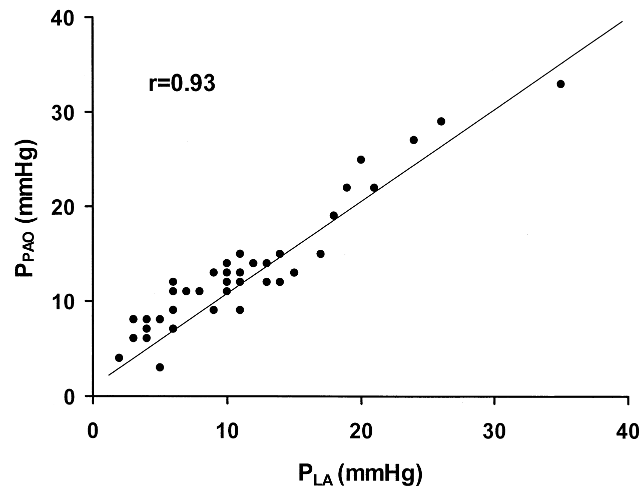

Figure 5. Scatterplot of the correlation between pulmonary artery occlusion pressure (P_{PAO}) and mean left atrial pressure (P_{LA}). The tendency for the P_{PAO} to overestimate the P_{LA} is apparent from this plot.

Estimation of P_{LA} from P_{PAO} in the test group. There was also a close relationship between P_{PAO} and P_{LA} (r = 0.93, Fig. 5) although a systematic error was introduced, in part, by the visual estimation of the midaxillary line. When the zero point from this level was referenced to the surgeon's visual zero at midatrial level, the midaxillary estimation was, in general, consistently lower than midatrial level. Thus, the mean difference between predicted P_{LA} from P_{PAO} and measured P_{LA} was 1.72 mm Hg, with 95% CI (mean ± 2 standard error) of −2.48 to 5.92 mm Hg.

Thus, although both P_{PAO} and DT_D predict the P_{LA} with a similar SE, the DT_D method is not influenced by the systematic error introduced by visual estimation of the midaxillary line.

Intraobserver and interobserver variability. This was assessed from 20 random Doppler recordings. In measuring the DT_D, the mean percentage of variation between observers was 6% and for repeated measurement was 4%.

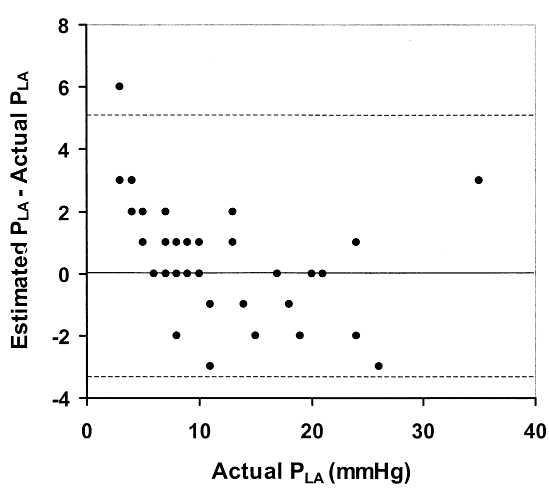

Figure 4. Bland-Altman plot of the differences between estimated mean left atrial pressure (P_{LA}) using the deceleration time of diastolic wave and actual P_{LA} versus the actual P_{LA}. The 95% confidence intervals for P_{LA} estimation are −2.94 to 4.10 mm Hg and are shown by **dashed lines.**

DISCUSSION

We have shown that the DT_D correlates strongly with the P_{LA} in a group of general cardiac surgical patients. The other mitral inflow and PVF variables measured correlate less well with P_{LA}.

Comparison with previous studies. Two previous studies have directly examined the DT_D and P_{LA} relationship. Chirillo et al. (22) studied the correlation between the two variables in patients with atrial fibrillation in whom more traditional measures of diastolic function such as the E/A ratio or systolic fraction cannot be used. They found a very close correlation between DT_D and P_{PAO}, (r = −0.91), and they concluded that in patients with atrial fibrillation, DT_D could be used to estimate P_{PAO}. More recently, Yamamuro et al. (23) studied the relationship in patients within one week of an acute myocardial infraction and also found a close relationship between P_{PAO} and DT_D (r = −0.89). The correlation between DT_D and P_{PAO} or P_{LA} is remarkably similar in all three studies, as are the regression lines. To our knowledge, our study is the first to show the strong correlation between mean P_{LA} and DT_D in a more general group of cardiac patients and to compare directly the prediction of P_{LA} from P_{PAO} and DT_D.

Mechanism of relationship between DT_D and P_{LA}. Controversy exists as to whether the left atrium is a passive structure through early diastole and ventricular systole. Little et al. (14), in an experimental model, found that DT_E depended strictly on left ventricular chamber stiffness and assumed that, in early diastole, the left atrium and left ventricle act as a common conduit. However, Henein et al. (27) believe that the left atrium is active throughout most of the cardiac cycle. The discrepancy between DT_D and DT_E found in the Henein et al. (27) study, and by other investigators, suggests that the left atrium in the patient group studied behaves as a receiving chamber in its own right (22,23). Differing left ventricular and left atrial compliances may have an important role in modulating both PVF and mitral inflow patterns. If this is the case, then the driving pressure between the pulmonary veins and the left atrium and the compliance of the left atrium itself might be the most important determinants of the deceleration time of the DT_D. This would explain the much closer correlation between DT_D and P_{LA} than between DT_E and P_{LA} found in the present study.

Thus, in early diastole, blood flowing into the left ventricle will cause a rapid pressure drop in a poorly compliant left atrium (with volume loss), resulting in blood accelerating in from the pulmonary veins (28). Rapid pulmonary vein inflow associated with low left atrial compliance will result in a rapid rise in left atrial pressure, an early abolition of the driving pressure gradient and a short deceleration time of early diastolic pulmonary flow. We did not examine the relationship between DT_D and left atrial volumes in this study because of the inherent difficulties in accurate measurement of left atrial diameters from the transesophageal route, and because of time constraints. Future studies investigating left atrial compliance and PVF are needed.

Comparison between echocardiography and P_{PAO} estimation of P_{LA}. To our knowledge, this is the first study in which left atrial pressure was measured directly rather than estimated using P_{PAO}. Kuecherer et al. (9) used direct left atrial pressure measurement in a third of the periods studied in his series and measured P_{PAO} in the remainder. Cannulation of the left atrium enables a comparison between echocardiographic estimation and P_{PAO} estimation of P_{LA} to be made.

We validated the regression equation developed from the initial patient data in the test group and were able to predict P_{LA} within limits that would make it clinically useful. The 95% CIs for the estimate are narrower than in a previous study, which may reflect comparison with direct measurement, rather than estimation of P_{LA} (22). The SE of the estimate of P_{LA} using DT_D was similar to the SE of the estimate using P_{PAO}. However, there was a tendency for the P_{PAO} to consistently overestimate the P_{LA} as reflected by a mean difference of 1.72 mm Hg. The explanations for this consistent error are threefold: 1) the tendency for the estimate of midatrial level (as referenced to the midaxillary level) to be too low; 2) as found in the original study relating P_{PAO} to left atrial pressure, the P_{PAO} does overestimate the P_{LA} because of the contribution of pulmonary venous resistance (29); and (3) the contribution of the right ventricular systolic pressure wave to P_{PAO} (30). Our findings suggest that the prediction of P_{LA} from DT_D is more accurate than the prediction from P_{PAO}—the current clinical practice.

Risks of pulmonary artery catheters. Recent controversy has centered on whether pulmonary artery catheters improve or worsen survival in critically ill patients (31). Irrespective of this controversy, there are well-recognized risks of pulmonary artery catheter placement including pneumothorax, pulmonary artery rupture and sepsis (3,32). Alternative and less invasive techniques to obtain hemodynamic data such as esophageal Doppler echocardiography and thoracic bioimpedance are emerging technologies (33,34).

Study limitations. Patients were studied after pericardotomy to allow left atrial cannulation to take place immediately after echocardiography and P_{PAO} measurements. It is possible that the relationship found between DT_D and P_{LA} would be different with a closed pericardium. However, in nine patients we measured DT_D immediately before and after pericardotomy and found no significant difference in the predicted P_{LA}.

A further study limitation is that only three patients were in atrial fibrillation and, therefore, it is not possible to conclude from this study alone that the DT_D can be used to estimate P_{LA} in patients in atrial fibrillation. However, in a previous study examining only patients in atrial fibrillation (22), there was a similar correlation between DT_D and P_{PAO} as found in the present study. Therefore, the combined evidence suggests that the DT_D can be routinely applied to predict P_{LA} in patients with atrial fibrillation as well as to patients in sinus rhythm. The present study considered only the relationship between DT_D and P_{LA} in a steady hemodynamic state. If echocardiography is to replace the pulmonary artery catheter in certain situations, further work is needed to investigate whether changes in hemodynamic parameters and P_{LA} are reflected by appropriate changes in the DT_D.

Measurements of PVF were made using transesophageal ultrasound because the study was conducted during cardiac surgery. Routine clinical application would be facilitated if transthoracic measurements were feasible. Pulmonary vein flow can be recorded in over 80% of patients from the transthoracic approach, and measurements taken correlate closely with simultaneous transesophageal recordings (35,36). Previous studies (22,23) showing a similar correlation between P_{PAO} and DT_D as found in our study were conducted using transthoracic ultrasound. Therefore, the use of the transesophageal rather than the transthoracic approach should not prevent extrapolation of the study results to wider clinical practice.

Conclusions. Finally, we conclude that, in cardiac surgical patients, measurement of the DT_D using echocardiography can reliably estimate P_{LA}, and it may obviate the need for invasive hemodynamic measurement with its attendant risks.

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