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 of mitral inflow 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}.

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.
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 DTD, 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 wave to the total velocity-time integral of PVF.

**Abbreviations and Acronyms**

- $A =$ late mitral inflow
- $Cl =$ 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

**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.
Correlation of mitral and PVF variables with PLA. A close correlation ($r = -0.92$) was found between DT$_E$ 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 $\geq 17$ 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$_E > 275$ ms predicted a P LA of $\leq 6$ mm Hg with 88% sensitivity and 95% specificity. There was no correlation between ejection fraction and DT$_E$.

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:

$$P_{LA} = 53.236 - [0.302(\text{DT}_D) + 0.000484 (\text{DT}_D^2)]$$

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

<table>
<thead>
<tr>
<th>Echocardiographic Variable</th>
<th>$r$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitral inflow</td>
<td></td>
</tr>
<tr>
<td>E wave</td>
<td>0.52</td>
</tr>
<tr>
<td>E/A ratio</td>
<td>0.13</td>
</tr>
<tr>
<td>DT$_E$</td>
<td>-0.61</td>
</tr>
<tr>
<td>Pulmonary venous flow</td>
<td></td>
</tr>
<tr>
<td>S wave</td>
<td>-0.06</td>
</tr>
<tr>
<td>D wave</td>
<td>0.57</td>
</tr>
<tr>
<td>S/D ratio</td>
<td>-0.36</td>
</tr>
<tr>
<td>Systolic fraction</td>
<td>-0.63</td>
</tr>
<tr>
<td>AR wave</td>
<td>0.44</td>
</tr>
<tr>
<td>VTIs</td>
<td>-0.40</td>
</tr>
<tr>
<td>VTIs</td>
<td>0.21</td>
</tr>
<tr>
<td>DA–DAR</td>
<td>-0.43</td>
</tr>
<tr>
<td>DT$_D$</td>
<td>-0.92</td>
</tr>
</tbody>
</table>

AR wave = peak velocity PVF atrial reversal; D = peak velocity diastolic PVF flow; DA–DAR = 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; VTIs = velocity-time integral D wave; VTIs = velocity-time integral S wave.
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 \pm 2 standard error) of \(-2.48 \) to 5.92 mm Hg.

Thus, although both \( P_{PAO} \) and \( DTD \) predict the \( P_{LA} \) with a similar SE, the \( DTD \) 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 \( DTD \), the mean percentage of variation between observers was 6% and for repeated measurement was 4%.

**DISCUSSION**

We have shown that the \( DTD \) 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 \( DTD \) 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 \( DTD \) and \( P_{PAO} \) (\( r = 0.91 \)), and they concluded that in patients with atrial fibrillation, \( DTD \) could be used to estimate \( P_{PAO} \). More recently, Yamamura et al. (23) studied the relationship in patients within one week of an acute myocardial infarction and also found a close relationship between \( DTD \) and \( P_{PAO} \) (\( r = -0.89 \)). The correlation between \( DTD \) 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 \( DTD \) in a more general group of cardiac patients and to compare directly the prediction of \( P_{LA} \) from \( P_{PAO} \) and \( DTD \).

**Mechanism of relationship between \( DTD \) 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 \( DTE \) 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 \( DTD \) and \( DTE \) 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 DTD and PLA than between DTE and PLA 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 PPAO estimation of P_LA.** To our knowledge, this is the first study in which left atrial pressure was measured directly rather than estimated using PPAO. Kuecherer et al. (9) used direct left atrial pressure measurement in a third of the periods studied in his series and measured PPAO in the remainder. Cannulation of the left atrium enables a comparison between echocardiographic estimation and PPAO 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 PPAO. However, there was a tendency for the PPAO 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 PPAO to left atrial pressure, the PPAO 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 PPAO (30). Our findings suggest that the prediction of P_LA from DT_D is more accurate than the prediction from PPAO—the current clinical practice.

**Risks of pulmonary artery catheters.** Recent controversy has centered on whether pulmonary artery catheters im-

**Study limitations.** Patients were studied after pericardotomy to allow left atrial cannulation to take place immediately after echocardiography and PPAO 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 PPAO 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 PPAO 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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