Comparison of the myocardial performance index derived by use of pulsed Doppler echocardiography and tissue Doppler imaging in dogs with volume overload

Yasutomo Hori, DVM; Shoh-ichi Kunihiro, DVM; Fumio Hoshi, DVM, PhD; Sei-ichi Higuchi, DVM, PhD

Objective—To investigate the relationship between the myocardial performance index (MPI) determined by use of pulsed Doppler (PD) echocardiography and tissue Doppler imaging (TDI) in the response to volume overload–related changes in left ventricle (LV) performance.

Animals—7 male Beagles.

Procedures—Dogs were anesthetized and intubated. A 6-F fluid-filled catheter was placed in the LV to measure LV peak systolic (LVPs) and LV end-diastolic (LVED) pressures. Preload was increased by IV infusion of lactated Ringer’s solution (rate of 200 mL/kg/h for 60 minutes) into a cephalic vein. Transmitral flow velocities and aortic outflow were measured, and TDI velocities were obtained from the 4-chamber view.

Results—Acute volume overload induced a significant increase in heart rate, LVPs pressure, and LVED pressure, compared with baseline values. A significant decrease in the PD-MPI and TDI-MPI values and a significant correlation (r = 0.70) between PD-MPI and TDI-MPI were detected. The PD-derived A-wave velocity, ejection time, and isovolumic relaxation time (IRT) and the TDI-derived IRT, MPI, and ratio of the velocity of the E wave to the velocity of the ventricular portion of the E wave during early diastole had equal ability to predict LVED pressure (r² = 0.63).

Conclusions and Clinical Relevance—The TDI-MPI was closely correlated with LV filling pressure and may be helpful in evaluating global cardiac function in dogs. (Am J Vet Res 2007;68:1177–1182)

Pulsed Doppler echocardiography is used to noninvasively assess ventricular diastolic dysfunction. However, PD-derived variables including TMF velocity, deceleration time, and IRT can be affected by several factors, such as heart rate and loading conditions.1–3 In animals with an increase in LV and left atrial filling pressures, a pseudonormal pattern of the TMF velocity may lead to an incorrect assessment of diastolic function.4 The MPI has been described5–7 as a PD measurement that is related to ventricular systolic and diastolic functions. The PD-MPI provides information on the severity of heart disease and prognosis for patients.8–10 Similarly, the MPI is significantly higher in dogs with dilated cardiomyopathy than in clinically normal dogs, although there is intraobserver variability.11 In addition, the PD-MPI has a major limitation (ie, the TMF and ET cannot be measured in the same cardiac cycle). Therefore, additional techniques are required to interpret the MPI in a clinical assessment of ventricular diastolic function.

Tissue Doppler imaging has been used to study velocity of the mitral annulus during systole and diastole.12–16 The TDI-derived myocardial velocities are useful for distinguishing between patients with diastolic dysfunction and patients with a pseudonormal pattern of the TMF velocity.17–19 In addition, the modified MPI derived from the TDI has been used in clinical studies to evaluate cardiac function.20–22 However, the difference between the abilities of the PD-MPI and TDI-MPI to determine LV performance with filling abnormalities has not been studied in dogs. Therefore, the study reported here was conducted to investigate the relationship between the

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PD-MPI and TDI-MPI in response to volume overload–related changes in LV performance in dogs.

Materials and Methods

Animals—Seven male Beagles that weighed between 8 and 12 kg and were 1 to 2 years old were used in the study. Dogs were housed separately in cages. Dogs were fed commercial dry food and had ad libitum access to water. The study was conducted in accordance with the Guidelines for Institutional Laboratory Animal Care and Use at the School of Veterinary Medicine, Kitasato University, Japan.

Procedures—Dogs were given atropine sulfate (0.025 mg/kg, SC) and sedated by administration of butorphanol tartrate (0.2 mg/kg, IV). Dogs were then anesthetized by administration of propofol (6.0 mg/kg, IV) and intubated. Anesthesia was maintained with 2% isoflurane in oxygen. Dogs were positioned in left lateral recumbency.

Respiratory rate was maintained with an artificial ventilator. End-tidal $\text{Paco}_2$ was maintained between 35 and 45 mm Hg, and heart rate was monitored by use of an ECG. The LVPs and LVED pressures were measured with a 6-F fluid-filled catheter placed in the LV through the right carotid artery by use of fluoroscopic guidance. The catheter in the LV was connected to strain-gauge manometers to measure LV pressure. After completing these procedures, a 20- to 30-minute stabilization period was allowed to establish a stable baseline condition for echocardiographic and left ventricular pressure measurements. All baseline measurements were recorded before echocardiographic examinations were performed.

Preload was increased by infusing lactated Ringer's solution (rate of 200 mL/kg/h for 60 minutes) into a cephalic vein. This was a modification of the dose reported by other investigators. During the IV infusion, the influence of volume overload on hemodynamic variables was monitored and the LVED pressure was approximately 20 mm Hg higher than the baseline value.

Echocardiographic examinations were performed every 10 minutes. After the final echocardiographic examination, furosemide (2 mg/kg, IV) was administered to each dog, and dogs were allowed to recover from anesthesia.

Table 1—Mean ± SD values for hemodynamic measurements obtained before (baseline) and during infusion of lactated Ringer's solution (200 mL/kg/h for 60 minutes) to create volume overloading in 7 Beagles.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline</th>
<th>Volume overloading (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>101±13</td>
<td>104±10</td>
</tr>
<tr>
<td>LVPS pressure (mm Hg)</td>
<td>71±10</td>
<td>82±11</td>
</tr>
<tr>
<td>LVED pressure (mm Hg)</td>
<td>3±7</td>
<td>5±10</td>
</tr>
</tbody>
</table>

*Within a row, value differs significantly ($*P < 0.05; **P < 0.001; ***P = 0.01$) from the baseline value.

Echocardiography—The TMF velocity was measured from the 4-chamber view with the sample volume positioned at the tip of the mitral valve leaflets. Then, the diastolic peak early (ie, early portion of the E wave, which is the Doppler-derived positive wave during early diastole) and late (ie, late portion of the A wave, which is the Doppler-derived positive wave during late diastole) transmitral inflow velocities and ratio of the E-wave velocity to A-wave velocity were measured. Doppler measurements of aortic outflow were made with the sample volume placed immediately below the aortic valve in the apical long-axis view. Ejection time was measured as the interval from the onset to the end of aortic outflow. Time interval measurements were performed by the internal analysis package supplied with the ultrasonographic unit. Intervals were measured by use of 2 carefully placed vertical cursors that were moved with a track ball. From the PD recordings, the MPI was calculated in a standard manner (ie, total isovolumic [contraction and relaxation] time divided by ET). The interval from cessation of the mitral valve A wave to onset of the mitral valve E wave of the next cardiac cycle equals the total isovolumic time plus the ET (Figure 1). The MPI was calculated by use of the following equation: (total isovolumic time – ET)/ET. The IRT was calculated by subtracting the interval between the peak of the R wave and end of the ET from the interval between the peak of the R wave and onset of the E wave. The ICT was calculated by subtracting

![Figure 1](image.png)
the sum of the ET and IRT from the interval between cessation of the A wave and the onset of the E wave of the next cardiac cycle.

The TDI program was set to pulse-wave Doppler mode. Filters were used to exclude high-frequency signals. Gain was minimized to provide a clear tissue signal with minimal background noise. The TDI velocities were obtained from the 4-chamber view. A 2-mm sample volume was placed at the lateral corner of the mitral valve annulus. Peak myocardial velocity for \( S' \), \( E' \), and \( A' \) was measured (Figure 1). The ratios of the velocity of \( E' \) to the velocity of \( A' \) and the velocity of the E wave to the velocity of \( E' \) were calculated. From the TDI recordings, the duration of \( S' \) was the interval from the onset to the end of \( S' \). The ICT was the interval from the end of \( A' \) to the onset of \( S' \). The IRT was the interval from the end of \( S' \) to the onset of \( E' \) of the next cardiac cycle. The modified MPI obtained by use of TDI was calculated as the total isovolumic time (ie, ICT + IRT) divided by the duration of \( S' \).

Transathoracic echocardiography was performed by use of an ultrasonographic unit and 12-MHz probe. Echocardiographic measurements were obtained during the expiratory phase. Echocardiograms were analyzed by use of the commercial analysis software package supplied with the system. The mean of 3 cardiac cycles was calculated. Data were stored digitally and analyzed off-line by a single investigator.

**Statistical analysis—**Data were reported as mean ± SD. Values for preload conditions were compared with baseline values by use of a 1-factor repeated-measures ANOVA. Significant differences between the mean values at baseline and at each condition were tested by use of the Tukey multiple comparison test. The regression equation and \( r \) were calculated between PD-MPI and TDI-MPI. Values of \( P < 0.05 \) were considered significant. Bland-Altman analysis was performed to determine mean differences between each MPI and the SD of the differences and 95% confidence intervals. Stepwise regression analysis was used to determine the LVPs and LVED pressures that correlated best with specific Doppler variables. Values of \( F > 2.0 \) were considered significant.

**Results**

Compared with values obtained at baseline, acute volume overloading induced a significant increase in heart rate \( (P < 0.001) \), LVPs pressure \( (P = 0.011) \), and LVED pressure \( (P < 0.001; \text{Table 1}) \). Representative recordings of the PD and TDI were obtained and the PD measurements reported (Figure 2; Table 2). The TDI variables were significantly \( (P < 0.001) \) increased from baseline values, whereas the ratios for the E-wave variables to the A-wave variables were unchanged. Acute volume overloading significantly \( (P < 0.001) \) decreased the ICT and decreased (but not significantly) the IRT. The ET was significantly \( (P < 0.001) \) prolonged from baseline values. As a result, there was a significant \( (P < 0.001) \) decrease in the PD-MPI.

The TDI measurements obtained during volume overloading were summarized (Table 3). The TDI patterns were recorded as 1 positive wave (ventricular systole) and 2 negative diastolic waves (early diastole and late diastole). Compared with values obtained at baseline, acute volume overloading induced a significant increase in heart rate \( (P < 0.001), \text{LVPs pressure } (P = 0.001), \) and LVED pressure \( (P < 0.001; \text{Table 1}) \). Representative recordings of the PD and TDI were obtained and the PD measurements reported (Figure 2; Table 2). The TDI variables were significantly \( (P < 0.001) \) increased from baseline values, whereas the ratios for the E-wave variables to the A-wave variables were unchanged. Acute volume overloading significantly \( (P < 0.001) \) decreased the ICT and decreased (but not significantly) the IRT. The ET was significantly \( (P < 0.001) \) prolonged from baseline values. As a result, there was a significant \( (P < 0.001) \) decrease in the PD-MPI.

![Figure 2](image.png)

**Table 2—**Mean ± SD values for PD measurements obtained during volume overloading in 7 Beagles.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity of E wave (cm/s)</td>
<td>49 ± 9</td>
<td>60 ± 9</td>
<td>67 ± 8*</td>
<td>66 ± 14*</td>
<td>74 ± 8</td>
<td>79 ± 9</td>
<td>73 ± 6</td>
</tr>
<tr>
<td>Velocity of A wave (cm/s)</td>
<td>26 ± 6</td>
<td>36 ± 8</td>
<td>39 ± 7</td>
<td>42 ± 8</td>
<td>40 ± 6</td>
<td>45 ± 6</td>
<td>43 ± 5</td>
</tr>
<tr>
<td>E wave:A wave</td>
<td>2.0 ± 0.6</td>
<td>1.7 ± 0.3</td>
<td>1.8 ± 0.3</td>
<td>1.6 ± 0.4</td>
<td>1.8 ± 0.1</td>
<td>1.8 ± 0.2</td>
<td>1.7 ± 0.1</td>
</tr>
<tr>
<td>ICT (ms)</td>
<td>56 ± 16</td>
<td>41 ± 12</td>
<td>32 ± 20†</td>
<td>29 ± 13†</td>
<td>19 ± 13†</td>
<td>16 ± 10†</td>
<td>16 ± 13†</td>
</tr>
<tr>
<td>IRT (ms)</td>
<td>40 ± 17</td>
<td>35 ± 15</td>
<td>25 ± 21</td>
<td>24 ± 12</td>
<td>29 ± 15</td>
<td>21 ± 11</td>
<td>30 ± 9</td>
</tr>
<tr>
<td>ET (ms)</td>
<td>182 ± 20</td>
<td>206 ± 24</td>
<td>230 ± 19</td>
<td>233 ± 15</td>
<td>238 ± 12</td>
<td>250 ± 13</td>
<td>251 ± 19</td>
</tr>
<tr>
<td>MPI</td>
<td>0.6 ± 0.2</td>
<td>0.4 ± 0.2</td>
<td>0.3 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
</tr>
</tbody>
</table>

*See Table 1 for remainder of key.
increase in velocities of the E' (P = 0.002), A' (P < 0.001), and S' (P < 0.001). The ratios of the velocity for E' to the velocity for A' and the velocity of the E wave to the velocity for E' were unchanged from baseline values. Both the ICT and IRT were significantly (P < 0.001) decreased from baseline values. The duration of the S' was significantly (P < 0.001) prolonged from the duration during baseline. As a result, there was a significant (P < 0.001) decrease in the TDI-MPI.

The PD-MPI and TDI-MPI were significantly correlated (r = 0.70; P < 0.001; Figure 3). However, MPI values derived by use of TDI were significantly higher than values derived by use of PD (mean ± SD difference, 0.24 ± 0.12; Figure 4).

Stepwise regression analysis revealed that the PD-derived E wave, A wave, ratio of the velocity of the E wave to velocity of the A wave, and ET and TDI-derived IRT, MPI, and heart rate could be used to predict the LVPs pressure (r² = 0.67; P < 0.001). Moreover, the PD-derived A-wave velocity, ET, and IRT and TDI-derived IRT, MPI, and ratio of the velocity of the E wave to velocity of the E' could be used to predict the LVED pressure (r² = 0.63; P < 0.001; Table 4).

**Discussion**

The usefulness of TDI-derived myocardial velocities for assessing LV diastolic dysfunction has been...
determined for patients with congenital and acquired heart disease.\textsuperscript{15,17,23,24} The TDI-derived myocardial velocity patterns have been especially useful for discriminating between patients with and without a pseudonormal pattern of the TMF.\textsuperscript{19,21} Similarly, decreased TDI-derived systolic and early diastolic velocities have been detected in dogs with cardiomyopathy and regurgitation through the mitral valve.\textsuperscript{15,25,26} Therefore, it is expected that the TDI-derived myocardial velocities are applied to evaluate concomitant subclinical ventricular dysfunction. In addition, several investigators have reported\textsuperscript{18,23} the validity of the ratio of the velocity of the E wave to the velocity of the E′ for determining filling pressures in various patient populations. In the study reported here, the TDI-derived myocardial velocities for the E′, A′, and S′ were increased with volume overload, whereas the ratios of the velocity of the E′ to velocity of the A′ and velocity of the E wave to velocity of the E′ were not changed significantly. In dogs with preserved cardiac function in another study,\textsuperscript{27} the pulmonary capillary wedge pressure changed with the preload, which was correlated with the PD-derived E-wave velocity and the TDI-derived velocity of the E′ but not with the ratio of the velocity of the E wave to velocity of the E′. Therefore, the physiologic basis for the discrepancy in the effect of preload on TDI-derived myocardial velocities suggests that the myocardial velocities are strongly preload-dependent with preserved diastolic function, whereas the ratio of the velocity of the E wave to velocity of the E′ was a minimally preload-dependent event.

The MPI is determined primarily by use of PD echocardiography and can be useful for assessing global myocardial performance because it is independent of heart rate and blood pressure.\textsuperscript{10,28} In addition, the MPI has potential as a sensitive indicator of global LV function and for providing prognostic information in patients with heart disease.\textsuperscript{4,6,8,10,19} The TDI-derived MPI also has potential for assessing LV function in dogs.\textsuperscript{15,20} It has been reported\textsuperscript{11,13} that the MPI is significantly correlated with cardiac function and severity in dogs with mitral valve regurgitation and dilated cardiomyopathy. One caution when interpreting the PD-MPI and TDI-MPI is that both are dependent on the loading conditions.\textsuperscript{5,28} In 1 study,\textsuperscript{2} investigators reported that a reduction in preload significantly decreased ET but significantly prolonged the total isovolumic time. Consequently, a reduction in preload increased the MPI. In contrast, in another study,\textsuperscript{28} volume loading slightly decreased the MPI with normal LV function because ET increased. In the study reported here, the MPI obtained by use of both the PD and TDI was decreased significantly with acute volume overload because of the prolonged ET or duration of the S′. This discrepancy derived from differences in the methods used. Preload was increased by administering saline (0.9% NaCl) solution at a rate of 30 to 40 mL/kg/h in another study,\textsuperscript{22} whereas in the study reported here, lactated Ringer’s solution was infused at a rate of 200 mL/kg/h. Thus, the loading condition should be considered when evaluating the MPI.

To characterize LV function with the MPI, we used 2 techniques. A major limitation of the MPI derived from PD is that the ICT, IRT, and ET cannot be measured from the same cardiac cycle.\textsuperscript{20} By contrast, the TDI-derived MPI can determine these intervals in the same cardiac cycle, which may be useful for evaluating global cardiac function.\textsuperscript{10,20,28} We determined that the PD- and TDI-derived MPI values were strongly correlated, although the values at baseline and for volume loading differed between the 2 techniques. Other investigators reported\textsuperscript{27} that mice with myocardial infarction had significant increases in PD-MPI and TDI-MPI; in addition, there was a significant correlation between the PD- and TDI-derived MPI, although the PD-MPI and TDI-MPI values differed significantly. Because TDI can provide measurements of all the variables within 1 cardiac cycle, the TDI-derived MPI may reduce accuracy related to heart rate.\textsuperscript{29} Therefore, the reference range of the MPI differs on the basis of the echocardiographic technique, which indicates that any clinical assessment of cardiac function by use of the MPI should be interpreted with caution.\textsuperscript{20,31} Furthermore, we determined that the TDI-MPI was most closely correlated with the LVED pressure, which suggests that the TDI-MPI may provide more accurate information than is provided by the PD-MPI for evaluating LV filling abnormalities in dogs.

Another limitation of the study reported here is that it was conducted to investigate the response of dogs to acute volume overload as an experimental method of replicating a filling abnormality. Therefore, we cannot exclude the possibility that anesthesia may have affected echocardiographic measurements. Complete autonomic blockade was also not used in this study, and reflex autonomic changes may have affected cardiac filling variables. In addition, it has been reported\textsuperscript{12,13} that echocardiographic measurements such as TDI, TMF, and pulmonary venous flow are affected by age, body weight, and breed.\textsuperscript{32,33} Furthermore, chronic volume overload or heart disease may lead to different responses.\textsuperscript{28} Therefore, the TDI must be validated by evaluating the entire range of responses in conscious dogs with heart disease and healthy control dogs.

In the study reported here, acute volume overload caused a significant decrease in the MPI. Although the TDI-MPI and PD-MPI were significantly correlated, the values of TDI-MPI were greater than the values of PD-MPI. This suggests that the reference ranges of the MPI derived by use of the PD and TDI differ, and the MPI derived by use of differing methods should be interpreted with caution. Furthermore, we determined that the TDI-MPI was closely correlated with filling pressure. The TDI-MPI may provide additional information regarding acute filling abnormalities in clinically normal dogs.

References


