The relative merits of pulsus paradoxus and right ventricular diastolic collapse in the early detection of cardiac tamponade: an experimental echocardiographic study

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ABSTRACT An inspiratory decline in systolic arterial blood pressure exceeding 10 mm Hg has been used clinically to identify hemodynamically significant pericardial effusions. Recently, the echocardiographic sign of right ventricular diastolic collapse (RVDC) has been shown to occur early in the course of cardiac tamponade in association with a hemodynamically important decline in cardiac output. This study was undertaken to compare the relative merits of pulsus paradoxus and the onset of RVDC in the early detection of cardiac tamponade in an unanesthetized canine preparation. We studied six chronically instrumented, conscious dogs with two-dimensional echocardiography during cardiac tamponade induced by continuous infusion of saline into the pericardial space. We recorded intrapericardial pressure, cardiac output (electromagnetic flowmeter), aortic (catheter-tip transducer) and right atrial blood pressures, heart rate, and respiration. None of the dogs had RVDC when the pericardial space was empty, but all dogs showed RVDC during cardiac tamponade. We found that RVDC was strongly related to all of the cardiac parameters evaluated (intrapericardial pressure, cardiac output, aortic blood pressure, heart rate, and stroke volume) and provided information on each that was independent of that provided by pulsus paradoxus. Furthermore, RVDC appeared to be more strongly related to most cardiac parameters than was pulsus paradoxus and to be more sensitive and specific than pulsus paradoxus in detecting changes in intrapericardial pressure early in cardiac tamponade.


ECHOCARDIOGRAPHY is a sensitive and accurate method for the detection of pericardial effusion. The use of echocardiography to assess the hemodynamic effects of progressive pericardial effusion has been described recently.2–8 Right ventricular diastolic collapse (RVDC) appears to be one of the most useful echocardiographic signs of cardiac tamponade. Clinical studies have shown that RVDC is both a sensitive and specific marker for cardiac tamponade in patients with pericardial effusion.9, 10 Moreover, we have demonstrated in a chronic animal preparation that RVDC begins early in the course of cardiac tamponade before a fall in systemic arterial blood pressure and is associated with a hemodynamically important decrease in cardiac output.11 The presence of an inspiratory reduction in arterial blood pressure exceeding 10 mm Hg (pulsus paradoxus) is often used clinically as an indication of a hemodynamically significant pericardial effusion.12, 13 However, the relationship between RVDC and the traditional clinical sign of pulsus paradoxus, both indicators of impaired cardiac function caused by pericardial effusion, has not been established. Therefore, the purpose of our study was to compare RVDC detected by two-dimensional echocardiography with pulsus paradoxus in a chronically instrumented, unanesthetized animal preparation of cardiac tamponade.

Materials and methods
Six mongrel dogs weighing 23.4 to 32.2 kg were studied. A chronically instrumented model of inducible pericardial effusion was surgically prepared in each dog by methods previously described.11 With this preparation, measurements of intrapericardial pressure, cardiac output, aortic and right atrial blood
pressures, heart rate, and respiratory rate can be made in an awake, unanesthetized animal during infusion of fluid into the pericardial space and the development of cardiac tamponade.

After recovery from surgery, the conscious dog was allowed to stand comfortably in a sling. The right atrial and one of the two pericardial catheters were attached directly to Statham P23Db pressure transducers (Statham Instrument Co.) with the zero-pressure reference point one-third of the vertical distance between the sternum and spine. Respiration was measured by recording the change in electrical resistance in a small mercury-filled, silicone rubber tube (Whitney gauge) placed around the thorax. The pericardium and pleural space were drained and control data were recorded when the animal was comfortable and measured values had achieved a steady state. When necessary, normal saline at room temperature was infused intravenously so that mean right atrial blood pressure was between 0 and 4 mm Hg during the control period. Cardiac tamponade was produced by continuous infusion of 0.9% saline at 37°C into the pericardial space through the second pericardial catheter at a rate of 10 ml/min with a Masterflex infusion pump (Cole Parmer Instrument Co.). During the infusion, hemodynamic data were continuously recorded with an FM tape recorder (A. R. Vetter Co.) and every 2 min on a Gould strip-chart recorder (Model 2800; Gould, Inc.). The data were then digitized onto computer disk for 30 sec periods during the following times of the experiment: (1) control phase, (2) at 2 mm Hg increments of intrapericardial pressure above the control level, and (3) at the onset of RVDC. Short-axis two-dimensional echocardiograms were obtained with a hand-held transducer (2.5 M Hz) in the right fourth or fifth intercostal space and an Irex System III phased-array echocardiograph (Irex Medical Systems). The echocardiographic data were recorded on videotape with a Sony Betamax video cassette recorder (Model SLO-232; Sony Corp.) and were reviewed with a Microsonics Image Analyzer (Microsonics, Inc.). Short-axis two-dimensional echocardiograms were studied in real time and slow motion. The onset of diastole was defined on the echocardiogram as the point of aortic valve closure or mitral valve opening. A typical example of RVDC is shown in figure 1. RVDC was considered to be present only if the right ventricular free wall was indented or concave during diastole as indicated by the arrow in figure 1. All echocardiograms were reviewed independently by two observers and a consensus was reached regarding the presence or absence of RVDC. In no case was there appreciable disagreement between the observers concerning the timing of the onset of RVDC. No more than a 2 min or 20 ml pericardial fluid difference was present between the point at which each observer identified the earliest onset of RVDC. The appearance of RVDC was so striking and its onset frequently so abrupt that the volume of pericardial fluid causing it to occur could often be determined within 5 ml.

A decrease in the mean aortic blood pressure of 20 mm Hg below the control level was used as the end point for each episode of cardiac tamponade. Stroke volume was calculated from cardiac output and heart rate and all hemodynamic data were measured by averaging the results obtained during each 30 second period of data collection. For the determination of pulsus paradoxus, the largest respiratory difference in systolic aortic blood pressure that occurred during each respiratory cycle of the 30 sec period of data collection was measured. “Mean” pulsus paradoxus was defined as the average of all of these pulsus paradoxus values. Animals with a respiratory rate of greater than 25 respirations/min during the control period were excluded from the study because pulsus paradoxus could not be determined accurately.

Each dog underwent between one and seven experiments (average 4.0), with a total of 24 episodes of cardiac tamponade created. A maximum of three experiments were performed in 1 day on a single animal with sufficient time for recovery between experiments. The first experiment was performed between 4 and 7 days (mean 5.0 days) and the last between 5 and 8 days (mean 6.3 days) after surgery. Correct positions of all catheters were confirmed at autopsy.

For testing the significance of the relationship between each cardiac parameter and RVDC, we used multiple regression analysis to adjust for each episode of infusion and other specified covariables. Depending on the analysis, these covariables included pulsus paradoxus or the degree of cardiac tamponade. To determine whether the adjustment for intrapericardial pressure was adequate, we divided the observations into three groupings on the basis of intrapericardial pressure and performed a multiple regression in each grouping, including intrapericardial pressure as one of the covariables. We then pooled the results of the three regressions using standard statistical techniques. Multiple regression analysis was also used to test the association of pulsus paradoxus and each cardiac parameter after adjusting for infusion episode and any other specified covariables. We used the technique of Sweeney and Ulveling to obtain the mean of each cardiac parameter for the observations with RVDC and for observations without RVDC after adjusting for infusion episode and other covariables. The partial correlation of pulsus paradoxus with each cardiac parameter after adjusting for infusion episode and other covariables was calculated with standard methods. A second regression analysis was used to test the difference in the strength of the association.
of RVDC and pulsus paradoxus with each cardiac parameter. For this analysis we considered pulsus paradoxus a binary rather than a continuous variable as it was in the first analysis. Pulsus paradoxus greater than 8 mm Hg was used to indicate cardiac tamponade. This degree of pulsus paradoxus was chosen for this analysis since a level of 10 mm Hg had a very low sensitivity for the detection of cardiac tamponade (a high percentage of false negatives) and a level of 6 mm Hg had a very low specificity (a high percentage of false positives). Both pulsus paradoxus greater than 8 mm Hg and RVDC were then entered into the analysis as covariables and the difference in the regression coefficients was tested.

A stepwise maximum likelihood logistic analysis adjusted for infusion episode was used to estimate the sensitivity of RVDC or pulsus paradoxus in detecting a given change in intrapericardial pressure. The constant used when graphing the logistic function was chosen so that the mean of the expected percentage of observations with a positive diagnostic test was equal to the observed percentage of all observations with a positive test.

Results

Table 1 presents the adjusted mean values of each cardiac parameter before RVDC, the adjusted mean values obtained when RVDC was present, and the associated t and p values for each comparison. The analysis was based on 153 measurements during 24 episodes of cardiac tamponade. In the first group in table 1, the observed values have been statistically adjusted to eliminate the variability in the cardiac parameters between dogs and between infusions for each dog. In addition, the second group has been statistically adjusted to eliminate the influence of pulsus paradoxus. In group 3, the results shown in group 1 have been adjusted to remove the changes caused by intrapericardial pressure.

Table 2 presents the correlation of pulsus paradoxus with the same measured cardiac parameters. In each case, the correlation and associated t and p values are indicated. In group 1, adjustment has been made for infusion episode (as it was in the corresponding column of table 1), group 2 is adjusted to eliminate the influence of RVDC, and in the last group adjustments have been made to eliminate the changes caused by intrapericardial pressure (as was done in the last group of table 1).

Figure 2 illustrates the relative sensitivity and specificity of RVDC and pulsus paradoxus in detecting increases in intrapericardial pressure.

Discussion

The results shown in tables 1 and 2 suggest several related generalizations:

RVDC is closely related to all of the cardiac parameters evaluated. In each case, the statistical significance of these pre-RVDC vs RVDC differences is p < .001 (table 1, group 1).

RVDC provides information on each cardiac parameter evaluated that is independent of that provided by pulsus paradoxus. This follows from consideration of the data summarized in table 1, groups 1 and 2. There is very little difference in the corresponding changes from pre-RVDC to RVDC mean data between these two groups, and all changes in group 2 (where the influence of pulsus paradoxus has been statistically removed but that of RVDC is still present) remain very significant. For example, mean cardiac output decreased from 2.02 to 1.69 liters/min (a difference of 0.33) in group 1 and from 2.01 to 1.71 liters/min (a difference of 0.30) in group 2. In both cases, the changes are significant at the p < .001 level.

RVDC may be more strongly related to most cardiac parameters than is pulsus paradoxus. When the strength of the association of each cardiac parameter with the presence of RVDC was compared with its association with the presence of pulsus paradoxus greater than 8 mm Hg, RVDC was found to be significantly and more strongly associated with intrapericardial pressure, cardiac output, heart rate, and stroke volume.

**TABLE 1**

<table>
<thead>
<tr>
<th>Cardiac parameters</th>
<th>Group 1: Adjusted for run only</th>
<th>Group 2: Adjusted for pulsus paradoxus</th>
<th>Group 3: Adjusted for IPP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No RVDC</td>
<td>RVDC</td>
<td>t value</td>
</tr>
<tr>
<td>Pulsus paradoxus (mm Hg)</td>
<td>7.91</td>
<td>12.04</td>
<td>4.76c</td>
</tr>
<tr>
<td>IPP (mm Hg)</td>
<td>1.85</td>
<td>6.62</td>
<td>11.79c</td>
</tr>
<tr>
<td>Cardiac output (l/min)</td>
<td>2.02</td>
<td>1.69</td>
<td>9.19c</td>
</tr>
<tr>
<td>Aortic BP (mm Hg)</td>
<td>91.83</td>
<td>88.42</td>
<td>4.13c</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>15.10</td>
<td>11.09</td>
<td>9.40c</td>
</tr>
</tbody>
</table>

BP = blood pressure; IPP = intrapericardial pressure.
Analysis was based on 153 measurements during 24 episodes of cardiac tamponade in six dogs.
Statistical comparisons: *p < .05; **p < .01; ***p < .001.
volume (p < .001 for each parameter). There was no difference in the association of blood pressure with the two diagnostic tests. This conclusion is also supported by the greater t values for the association of each cardiac parameter with RVDC than for the association of the cardiac parameter with the degree of pulsus paradoxus. Mean aortic blood pressure is the only exception. The difference in t values is especially large for cardiac output and stroke volume. For example, the t value reflecting the correlation between RVDC and cardiac output exclusive of the influence of pulsus paradoxus is 7.77 (table 1, group 2) and that reflecting the correlation between pulsus paradoxus and cardiac output exclusive of the influence of RVDC is 2.10 (table 2, group 2).

For predicting the degree of compromise in cardiac function as indicated by decreased cardiac output or stroke volume, pulsus paradoxus provides little additional information to that provided by RVDC. This follows from the results presented in table 2, group 2. After adjusting for RVDC, pulsus paradoxus is only weakly associated with cardiac output and not significantly associated with stroke volume. Pulsus paradoxus did provide significant additional information in predicting intrapericardial pressure, aortic blood pressure, and heart rate.

RVDC and pulsus paradoxus together provide more information on all cardiac parameters (except stroke volume) than does either alone. This follows from the results presented in table 1, group 2, and table 2, group 2. Each of these two indicators of the severity of cardiac tamponade is still significantly related to the cardiac parameters tested when those associations are adjusted to eliminate the influences of the other. The sole exception is stroke volume, which has no significant independent relationship with pulsus paradoxus.

We also found statistical evidence that RVDC was associated with decrements in cardiac output even after careful adjustment for the influence of intrapericardial pressure. Of course, this statistical association cannot be used to prove that RVDC directly contributes to the decreased cardiac output.

After adjustment for intrapericardial pressure, RVDC had a weaker relationship with heart rate than with the other variables and no significant relationship with mean aortic blood pressure. There was also a significant relationship between RVDC and pulsus paradoxus after adjusting for intrapericardial pressure. This relationship is weak, however, and the adjusted RVDC is associated with a decrease in pulsus paradoxus. Because the relationship is of borderline statistical significance and is difficult to explain, it may have occurred by chance alone. There was no strong association between pulsus paradoxus and any cardiac parameter after adjustment was made for intrapericardial pressure (table 2, group 3). The correlation between pulsus paradoxus and increased stroke volume is

<table>
<thead>
<tr>
<th>Cardiac parameter</th>
<th>Group 1:</th>
<th>Group 2:</th>
<th>Group 3:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correlation adjusted for run only</td>
<td>Correlation adjusted for RVDC</td>
<td>Correlation adjusted for IPP</td>
</tr>
<tr>
<td>IPP (mm Hg)</td>
<td>.68</td>
<td>.63</td>
<td></td>
</tr>
<tr>
<td>Cardiac output (l/min)</td>
<td>-0.38</td>
<td>-0.18</td>
<td>0.13</td>
</tr>
<tr>
<td>Aortic BP (mm Hg)</td>
<td>-0.47</td>
<td>-0.39</td>
<td>-0.15</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>0.42</td>
<td>0.27</td>
<td>0.02</td>
</tr>
<tr>
<td>Stroke volume (ml)</td>
<td>-0.34</td>
<td>-0.12</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Analysis based on 153 measurements during 24 episodes of cardiac tamponade in six dogs. Abbreviations as in table 1. Statistical comparisons: *p < .05; **p < .001.

FIGURE 2. The relative sensitivity and specificity of RVDC and pulsus paradoxus of 8 and 10 mm Hg in detecting increases in intrapericardial pressure above the control levels. All data were pooled after adjustment for dog and run, and a best fit curve was derived for each diagnostic test. Specificity estimated from graphic analysis is shown in each case and remains constant for each curve regardless of intrapericardial pressure.
weak and in an unexpected direction and therefore may not be meaningful.

The most desirable test should accurately detect cardiac tamponade early in its course so that the appropriate therapy may be administered with less risk than if it were to be delayed. Sensitivity and specificity should be high in the region of interest. As shown in figure 2, RVDC was far superior to pulsus paradoxus in both sensitivity and specificity (which remains constant for each test) early in cardiac tamponade in these otherwise normal dogs. The specificities derived from graphic analysis were 100% for RVDC, 93% for pulsus paradoxus greater than 8 mm Hg, and 96% for pulsus paradoxus greater than 10 mm Hg.

The diagnosis and early detection of hemodynamically important pericardial effusion remains a challenge to the clinician. Cardiac tamponade should be viewed as a continuous spectrum ranging from pericardial effusion with minimal hemodynamic impairment, which may be asymptomatic, to an effusion with severe cardiac compression and circulatory collapse. Our goal in this study was to compare the relative value of pulsus paradoxus and the onset of RVDC as early indicators of hemodynamically important pericardial effusion in our chronically instrumented, unanesthetized animal preparation.

Earlier observations are consistent with the hypothesis that RVDC is a pressure-related phenomenon and suggest that it may occur later in the course of cardiac tamponade (or not at all) in the presence of decreased right ventricular compliance or increased resistance to right ventricular outflow. Since none of the animals in this study had evidence of such abnormalities, our results are not applicable to those situations.

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