Effects of intravascular volume state on the value of pulsus paradoxus and right ventricular diastolic collapse in predicting cardiac tamponade

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ABSTRACT Both pulsus paradoxus and right ventricular diastolic collapse detected by two-dimensional echocardiography are noninvasive markers of impaired cardiac function in cardiac tamponade, yet the reliability of each may vary with the patient's state of hydration. To examine the relative value of these noninvasive markers at various states of hydration, we studied five chronically prepared, conscious mongrel dogs during 37 episodes of cardiac tamponade at three different intravascular volumes. We continuously measured cardiac output (electromagnetic flowmeter), aortic blood pressure, right atrial blood pressure, intrapericardial pressure, and respirations. Intravascular volume was varied by adjusting the mean right atrial blood pressure to hypovolemic (-2 to -6 mm Hg), euclidean (0 to 4 mm Hg), or hypervolemic (6 to 10 mm Hg) levels. The sensitivity and specificity of right ventricular diastolic collapse in predicting increases in intrapericardial pressure remained high at all levels of hydration. Pulsus paradoxus showed good sensitivity and specificity at low intravascular volumes, but both sensitivity and specificity declined at higher intravascular volumes. Thus right ventricular diastolic collapse was more sensitive and more specific than pulsus paradoxus in detecting increases in intrapericardial pressure during euvoemia and hypervolemia whereas the two tests were equally valuable in hypovolemic states.


CARDIAC TAMPOONADE should be viewed as a continuous spectrum ranging from pericardial effusion with minimal hemodynamic impairment, which may be asymptomatic, to effusion with severe cardiac compression and circulatory collapse.1–3 The use of a 10 mm Hg inspiratory decline in systemic arterial blood pressure (i.e., pulsus paradoxus) has been suggested to identify hemodynamically significant cardiac tamponade.4–6 In clinical studies of cardiac tamponade, Guberman et al.4 have suggested the following criteria for diagnosis: pericardial effusion, an elevated systemic venous pressure, usually a paradoxical arterial pulse (10 mm Hg), and loss of the high venous pressure and paradoxical pulse with the removal of the effusion. The sign of right ventricular diastolic collapse seen on two-dimensional echocardiography provides an additional means of detecting cardiac tamponade.

The most desirable noninvasive test should reliably detect impaired cardiac function during cardiac tamponade early in its hemodynamic progression before arterial blood pressure falls. Right ventricular diastolic collapse has proved to be a very sensitive and specific marker of cardiac tamponade in patients with pericardial effusion.7–9 We have shown in a euvoicmic animal preparation that right ventricular diastolic collapse has a higher sensitivity and specificity than pulsus paradoxus in detecting changes in intrapericardial pressure early in cardiac tamponade.10 Furthermore, right ventricular diastolic collapse was more strongly related to cardiac output, stroke volume, and heart rate than was pulsus paradoxus.

Changes in intravascular volume may alter our abili-
ty to detect these markers in cardiac tamponade. Pulsus paradoxus, for example, may be absent in cardiac tampan-
dode in the circumstance of extreme hypovolemia or hypotension\(^1\) \(^2\) and the time of onset of right ventricular
adiastolic collapse in cardiac tamponade may be affected by the state of hydration.\(^3\) The purpose of this
study was to examine the influence that alterations in intravascular volume have on the relative ability of
pulsus paradoxus and right ventricular diastolic collapse to detect changes in intrapericardial pressure early
in cardiac tamponade.

**Methods**

Five adult mongrel dogs weighing from 24 to 29 kg were selected for study, screened for parasites, and brought to the
laboratory after an overnight fast. By techniques previously
described,\(^2\) \(^3\) a left thoracotomy in the fifth intercostal space
was performed and the animals were instrumented to measure cardiac output, aortic blood pressure, right atrial blood
pressure, intrapericardial pressure, and heart rate. A chronically instrumented, conscious canine preparation of inducible cardiac
tamponade was thus created.

Five days after surgery, the conscious animal was brought to
the laboratory and allowed to stand comfortably in a sling. One
pericardial, the aortic, and the right atrial catheters were attached
directly to pressure transducers as described earlier.\(^2\) \(^3\) Respi-
rations were measured by recording the change in electrical
resistance in a small mercury-filled Silastic tube (Whitney
gauge) placed around the thorax. Three separate intravascular
volume states were investigated with mean right atrial blood
pressure used as an index: hypovolemic (−2 to −6 mm Hg),
euvolemic (0 to 4 mm Hg), and hypervolemic (6 to 10 mm Hg).
Sterile normal saline and dextran 40 (Rheomacrodex 10%,
Pharmacia Laboratories) were used to increase intravascular
volume, and hemorrhaging was used to lower the mean right
atrial blood pressure to the prescribed limits. Animals received
10,000 U of heparin intravenously before hemorrhage and all
shed blood was replaced at the conclusion of the experimental
period. Baseline data at each intravascular volume state were
recorded after the pleural and pericardial cavities had been
drained, 5 to 10 ml of normal saline replaced in the pericardial
space, and a hemodynamic steady state achieved. Cardiac tam-
ponade was produced by continuous infusion of warmed normal
saline into the pericardial space and hemodynamic data were
continuously recorded as described previously.\(^4\) Short-axis
two-dimensional echocardiograms were obtained with a hand-
held transducer in the right fourth or fifth intercostal space
by means of an Irex HSP-1 phased-array ultrasonoscope (Johnson
and Johnson). The echocardiograms were reviewed by two
independent observers in real time and right ventricular diastolic
collapse was considered to be present if there was indentation or
abnormal inward motion of the right ventricular free wall or
right ventricular outflow tract during diastole.

The state of intravascular volume was varied so that each
animal was randomly exposed to any state only once in a given
day. Once a steady-state baseline at any volume level was estab-
lished, decompensated cardiac tamponade was produced. A
maximum of three episodes of cardiac tamponade were pro-
duced per day per animal, allowing adequate time for recovery
between episodes. Decompensated cardiac tamponade was de-


**Results**

In chronically prepared, conscious dogs, a total of
37 episodes of cardiac tamponade were analyzed: 11
hypovolemic, 14 euvoilemic, and 12 hypervolemic.
For our analysis of pulsus paradoxus, an inspiratory
decline in mean arterial blood pressure both greater
than 8 mm Hg and greater than 10 mm Hg was exam-
ined. In our previous study, a degree of pulsus paradoxus
greater than 8 mm Hg was associated with a
higher sensitivity in detecting increases in intrapericar-
dial pressure than was pulsus paradoxus greater than
10 mm Hg.\(^5\) The values for mean pulsus paradoxus at
baseline (empty pericardium), the onset of right ventri-
cular diastolic collapse, and decompensated cardiac
tamponade are shown in table 1. Pulsus paradoxus
equals or exceeds 10 mm Hg at the time of onset of
right ventricular diastolic collapse only for the hyper-
voilemic group. Although present at all intravascular
volumes during decompensated cardiac tamponade,
this marker clearly occurs later in the progression of

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TABLE 1
Mean values for pulsus paradoxus during cardiac tamponade

<table>
<thead>
<tr>
<th></th>
<th>Hypovolemia</th>
<th>Euvolemia</th>
<th>Hypervolemia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>4.44 ± 1.24</td>
<td>8.71 ± 0.99</td>
<td>8.45 ± 1.12</td>
</tr>
<tr>
<td>Onset of RVDC</td>
<td>5.46 ± 0.97</td>
<td>9.76 ± 0.81</td>
<td>13.62 ± 0.96</td>
</tr>
<tr>
<td>Decompensation</td>
<td>14.80 ± 0.60</td>
<td>12.80 ± 1.40</td>
<td>13.57 ± 1.35</td>
</tr>
<tr>
<td>Observations A</td>
<td>11</td>
<td>14</td>
<td>12</td>
</tr>
</tbody>
</table>

RVDC = right ventricular diastolic collapse.

Mean values of pulsus paradoxus (mm Hg ± SEM) at baseline (empty pericardium), right ventricular diastolic collapse, and decompensated cardiac tamponade are given for all episodes of cardiac tamponade at each level of intravascular volume.

*Observations = the number of episodes of cardiac tamponade analyzed in each volume state. The levels of significance comparing values of mean pulsus paradoxus between volume states at analogous points in time are shown.

cardiac tamponade than does the onset of right ventricular diastolic collapse. When pulsus paradoxus greater than 8 mm Hg is chosen, the specificity of the marker decreases because the euvolemic and hypervolemic populations exhibit this level of paradoxical pulse when the pericardium is empty. When the pericardium is empty, increasing intravascular volume causes an increase in pulsus paradoxus only between the hypovolemic and euvolemic states, whereas early in cardiac tamponade (at the time of onset of right ventricular diastolic collapse) pulsus paradoxus increases continuously as intravascular volume is increased.

In figure 1, A, the sensitivity and specificity of pulsus paradoxus greater than 8 mm Hg in detecting a change in intrapericardial pressure from baseline is shown. All three curves differ significantly from each other (p < .05 to p < .001). The rate of rise in sensitivity for this degree of pulsus paradoxus is low in both the euvolemic and hypervolemic populations. Furthermore, the specificity of pulsus paradoxus greater than 8 mm Hg in detecting changes in intrapericardial pressure declines abruptly as the magnitude of intravascular volume increases.

Figure 1, B, illustrates the sensitivity of the more classic 10 mm Hg inspiratory decline in systolic arterial blood pressure in predicting an increase in intrapericardial pressure during cardiac tamponade. All curves differ from one another significantly (p < .01). As with pulsus paradoxus of greater than 8 mm Hg, this level of pulsus paradoxus shows a slow rate of rise in sensitivity for the euvolemic and hypervolemic groups and the specificity of the test declines at higher levels of intravascular volume.

By contrast, the ability of right ventricular diastolic collapse to detect an increase in intrapericardial pressure is shown in figure 1, C. Hypovolemic and hypervolemic curves differ (p < .01), but neither is significantly different from the euvolemic situation. For each level of intravascular volume, the onset of right ventricular diastolic collapse exhibits excellent specificity with a rapid rate of rise in sensitivity over the range of intrapericardial pressures of interest. There is a signifi-
cant trend toward decreased sensitivity of this test as intravascular volume is increased (p < .02).

Figure 2, A to C, illustrates the relative value of the three indicators of increasing intrapericardial pressure for each intravascular volume studied. The curves for pulsus paradoxus greater than 8 mm Hg and pulsus paradoxus greater than 10 mm Hg do not differ significantly within any volume state. There were no significant differences among any of the curves in the hypovolemic animals (panel A). During euvoemia and hypervolemia (panels B and C), the onset of right ventricular diastolic collapse was more sensitive and specific than either degree of pulsus paradoxus in detecting an increase in intrapericardial pressure from baseline during cardiac tamponade (p < .001).

Discussion

We recently examined the relative merits of right ventricular diastolic collapse and pulsus paradoxus in detecting increases in intrapericardial pressure from baseline during cardiac tamponade in a chronically instrumented, euvoelemic animal preparation. In that study, we found right ventricular diastolic collapse to be more strongly related to changes in cardiac output, stroke volume, and intrapericardial pressure during cardiac tamponade than pulsus paradoxus of greater than 8 mm Hg or pulsus paradoxus greater than 10 mm Hg. Indeed, pulsus paradoxus provided little additional information concerning hemodynamic parameters to that provided by right ventricular diastolic collapse.

Both tests together were better predictors of increased intrapericardial pressure than was either alone.

Although right ventricular diastolic collapse is a better independent marker for hemodynamically significant cardiac tamponade than pulsus paradoxus in an euvoelemic animal population, alterations in intravascular volume are known to affect the appearance and reliability of both of these tests. Because it is difficult at times to know the status of intravascular volume in a patient with impending cardiac tamponade, a marker of increasing intrapericardial pressure that is reliable, regardless of volume status, would be most advantageous. Hence, in this study we have examined the relative sensitivity and specificity of these two markers in detecting changes in intrapericardial pressure during cardiac tamponade as the intravascular volume was varied.

The ideal marker for significant cardiac tamponade should detect increasing intrapericardial pressure early in the hemodynamic progression of events and long before the point of circulatory collapse. Its usefulness to the clinician would improve if both the sensitivity and specificity of the test remained high regardless of the influence of such factors as the state of hydration of the patient being evaluated.

The results of this study clearly show the limitations of pulsus paradoxus greater than 8 mm Hg or pulsus paradoxus greater than 10 mm Hg as noninvasive markers for an increase in intrapericardial pressure during cardiac tamponade. Both the sensitivity and

![Graph](http://circ.ahajournals.org/)
specificity of each degree of pulsus paradoxus decreases as the intravascular volume increases (figure 1, A and B). Although the sensitivity of pulsus paradoxus exceeds that of right ventricular diastolic collapse in detecting small changes in intrapericardial pressure at low intrapericardial pressures in euvoletic and hypervolemic populations (figure 2, B and C), it does so with very low specificity. In these two populations, the onset of right ventricular diastolic collapse is a far better indicator of increasing intrapericardial pressure because it is both sensitive and specific.

Despite the relative positions of the curves in the hypovolemic population (figure 2, A), right ventricular diastolic collapse has no clear statistical advantage over pulsus paradoxus in predicting an increase in intrapericardial pressure during cardiac tamponade. All three indicators have excellent specificities for this state of hydration. Although there is a trend toward a higher sensitivity for right ventricular diastolic collapse in detecting small elevations in intrapericardial pressure compared with either degree of pulsus paradoxus in this group, this relationship does not reach statistical significance.

It is interesting that pulsus paradoxus showed a lower percentage of false negatives (better sensitivity) in the hypovolemic group than in the euvoletic or hypervolemic groups (figure 1, A and B). One might reasonably expect a higher percentage of false negatives in this population. Although we were able to effect a significant reduction in resting cardiac output and aortic blood pressure from the euvoletic situation with the degree of hypovolemia we studied, perhaps further volume contraction in our animal preparation would have resulted in the lower sensitivity others have observed.

It is important to note that both the sensitivity and specificity of right ventricular diastolic collapse in detecting increases in intrapericardial pressure from baseline during cardiac tamponade remain high at low intravascular volumes. It has been suggested that right ventricular diastolic collapse may be too sensitive in volume-contracted states with the potential for false-positive identification of significant cardiac tamponade. The specificity of right ventricular diastolic collapse we observed in our hypovolemic population (98.9%) suggests few false-positive identifications in this animal preparation.

In conclusion, in this chronically instrumented, conscious animal preparation of cardiac tamponade, we have shown that the state of hydration does affect the ability of pulsus paradoxus to detect changes in intrapericardial pressure with worsened sensitivity and specificity at higher intravascular volumes, whereas there appears to be no major affect of the state of hydration on the ability of right ventricular diastolic collapse to detect increases in intrapericardial pressure. Right ventricular diastolic collapse is both more sensitive and more specific than pulsus paradoxus in detecting increases in intrapericardial pressure during cardiac tamponade in euvoletic or hypervolemic states, whereas right ventricular diastolic collapse and pulsus paradoxus are equally valuable in detecting elevations in intrapericardial pressure during hypovolemia.

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