Nonuniformity of pericardial surface pressure in dogs

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ABSTRACT Previously, we have shown that pericardial constraint cannot be measured by true (hydrostatic) pressure except when an excess of pericardial fluid is present and that a device such as a balloon (which reflects radial contact stress as well as hydrostatic pressure) must be used. Since radial contact stress is the major component of the constraint exerted by the pericardium when little pericardial liquid is present, it follows that the pressure measured by the balloon might be different over different parts of the heart. In an attempt to test this hypothesis, in 11 anesthetized dogs we placed pericardial balloons over the right and left ventricular free walls, instrumented the animals to measure ventricular dimensions (sonomicrometry) and pressure, mounted pneumatic constrictors on the aortic and pulmonary artery, reapproximated the pericardium, and closed the chests under suction. We studied the transient effects of constrictions of the ascending aorta and pulmonary artery and of angiotensin infusion before and after intravenous saline infusion. Aortic constriction and, to a lesser degree, angiotensin increased pericardial pressure over the left ventricle more than over the right ventricle. Pulmonary artery occlusion increased pericardial pressure over the right ventricle but significantly decreased pericardial pressure over the left ventricle. We conclude that there are significant local differences in pericardial pressure (recorded by balloon) over the lateral ventricular surfaces during acute changes in afterload. These observations may be explained in part by decreased venous return to the contralateral ventricle, the tendency of the heart to resist lateral displacement, and the limited mobility of the pericardium.


THE ROLE of pericardial constraint as a determinant of ventricular diastolic function is still controversial.\(^1\)\(^-\)\(^5\) However, results of recent studies in our laboratory\(^6\) suggest that these disagreements are related to failure to appreciate the distinction between “liquid pressure” and so-called surface pressure.\(^7\) Liquid pressure is exerted equally in all directions (i.e., it obeys Pascal’s law) and therefore can be measured with open-ended catheters or micromanometers. Surface pressure equals liquid pressure plus deformational forces or contact stress.\(^7\) At any point where the cardiac surface is in direct contact with the parietal layer of the pericardium there is a contact stress exerted perpendicularly by one surface against the other. Thus, at any point on the cardiac surface, pericardial surface pressure is greater than liquid pressure by the magnitude of the compressive contact stress. Recently we have found support for the validity of these theoretical concepts by demonstrating that pericardial surface pressure (recorded by a flat, liquid-containing balloon) correctly measures pericardial constraint and that surface pressure exceeds liquid pressure unless the pericardium contains more than a physiologic amount of fluid.\(^6\)

A priori considerations suggest that contact stress and therefore surface pressure are probably different at various locations on the cardiac surface. The aim of the present study was to investigate regional variations in pericardial surface pressure by comparing the surface pressures recorded over the left and right ventricles during interventions that load one ventricle more than the other, thereby presumably causing local variations in ventriculopericardial contact stress. Such asymmetrical interventions were compared with an increase in blood volume, which caused a more symmetrical expansion of the two ventricles.
Methods

Animal preparation. The experiments were done in 11 mongrel dogs (23 to 30 kg). Anesthesia was induced by 25 mg/kg iv sodium thiopental (Pentothal, Abbott Laboratories, Montreal) and was maintained by intermittent bolus injections of chloralose. The dogs were intubated and artificially ventilated with a constant-volume respirator (model 607, Harvard Apparatus Co. Inc., Millis, MA). A midline sternotomy was performed with each dog in the supine position. Left and right ventricular pressures were measured by No. 8F micromanometer-tipped catheters with reference lumens (model PC-480, Millar Instruments, Houston, TX) that were introduced via a carotid artery and a jugular vein, respectively. The ventral surface of the pericardium was incised transversely along the base of the heart. Pericardial pressure was recorded by flat, liquid-containing balloons (3 × 3 cm) placed over the anterolateral surface of the right ventricle and over the lateral surface of the left ventricle. Each balloon was placed on the mid left ventricular horizontal plane (figure 1). The accuracy of such balloons for the measurement of pericardial surface pressure has been documented previously.5,6 The balloons were calibrated at the beginning of each experiment.7,8 and the calibration of the balloons was ascertained to be unchanged at the end of the experiment. Pulmonary artery pressure was recorded through the end-hole of a flow-directed, triple-lumen catheter that was introduced via a jugular vein. Aortic pressure was measured by a catheter that was introduced via a femoral artery and was advanced into the upper abdominal aorta. Left and right ventricular dimensions were measured by sonomicrometry with the dimension crystals positioned as illustrated in figure 1. Left ventricular anteroposterior diameter was recorded with the crystals labeled A and P. One double-faced crystal that was advanced midway into the ventricular septum and a crystal on each of the left ventricular and right ventricular free walls were used to measure left ventricular and right ventricular septum-to-free wall diameters, respectively. In five dogs we measured left ventricular segment length by a pair of crystals placed equatorially in the anterior left ventricular free wall. Pneumatic constrictors were positioned around the pulmonary artery and the ascending aorta. The pericardial was then loosely reapproached with sutures. The chest was closed under 5 mm Hg suction. Catheters were placed in a jugular vein and a femoral vein for the infusion of drug and fluid, respectively. The electrocardiogram was monitored from a limb lead and body temperature was maintained by a heating pad. Arterial blood gases were checked during each experiment and maintained in the physiologic range.

Pressures, dimensions, and an electrocardiogram were recorded (model VR 16, Electronics for Medicine/Honeywell, White Plains, NY) at a paper speed of 75 mm/sec. (The ventilator was stopped at end-expiration.) Data were also recorded on analog tape (model 6500, Gould, Cleveland, OH). Before each recording interval the pressure waveforms from the Millar micromanometers were compared with those from the external manometer recorded via the respective reference lumen. Any baseline shift in the micromanometer waveform was corrected by manipulation of a manual balance control.

Experimental protocol. Regional pericardial surface pressures were compared under conditions of symmetrical loading produced by volume infusion and also under conditions of dis-similar loading of the two ventricles (produced by outflow obstruction and angiotensin infusion). Acute increments in left ventricular or right ventricular afterload were produced by suddenly inflating the occluder on the ascending aorta or the pulmonary artery, respectively. Two different increments in afterload were studied. Left ventricular peak systolic pressure was first increased by approximately 50 mm Hg; after a 2 to 3 min recovery period it was increased by approximately 100 mm Hg. Right ventricular peak systolic pressure was increased by approximately 25 mm Hg and, after a 2 to 3 min recovery period, by approximately 50 mm Hg. Each constriction was maintained for up to 30 sec. We also studied the effects of angiotensin infusion and we infused angiotensin intravenously at rates that were adjusted to increase peak left ventricular systolic pressure by 50 and then 100 mm Hg. The hemodynamic variables were allowed to stabilize for 5 to 10 min at each rate of angiotensin infusion before recording was begun. Each of these interventions were also studied after the intravenous infusion of saline. The saline infusion rate was adjusted to increase left ventricular end-diastolic pressure to 15 to 20 mm Hg. Recordings were made at different left ventricular end-diastolic pressures during the infusion of saline.

Results

Constriction of the ascending aorta and the pulmonary artery caused significant local differences in pericardial surface pressure (tables 1 and 2). These differences were accentuated after volume loading. Figure 2 shows the effect of ascending aortic constriction in a representative volume-loaded dog. As aortic constriction progressively increased left ventricular systolic pressure, pericardial pressure over the left ventricle increased considerably, while that over the right ventricle increased only slightly. It is evident from the figure 2, A, and tables 1 and 2 that pericardial pressure over the left ventricle did not increase substantially unless the ascending aorta constriction was severe (i.e., the rise in left ventricular systolic pressure exceeded 50 mm Hg). Constriction of the pulmonary artery caused
directionally opposite changes in pericardial constraint over the right and the left ventricles. This is illustrated in figure 2, B, which illustrates data from a representative volume-loaded dog. When right ventricular systolic pressure was increased by more than 20 mm Hg there was a progressive increase in pericardial pressure over the right ventricle and a concurrent decrease in that over the left ventricle.

In contrast to outflow constriction, which caused regional differences in pericardial pressure, volume loading produced similar increments in pericardial pressure over the left ventricle and that over the right

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline</th>
<th>Volume loaded</th>
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<tbody>
<tr>
<td></td>
<td>Control</td>
<td>PA constr I</td>
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<tr>
<td>HR (beats/min)</td>
<td>135 ± 11</td>
<td>139 ± 10 A</td>
</tr>
<tr>
<td>Ppa (mm Hg)</td>
<td>74 ± 10 C</td>
<td>41 ± 10</td>
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<td>Ppa (mm Hg)</td>
<td>12 ± 1</td>
<td>8 ± 1</td>
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<td>Ppysys (mm Hg)</td>
<td>95 ± 9 C</td>
<td>52 ± 11</td>
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<tr>
<td>Ppysys (mm Hg)</td>
<td>26 ± 3 C</td>
<td>51 ± 33</td>
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<td>Pved (mm Hg)</td>
<td>3.4 ± 1.5 C</td>
<td>1.3 ± 1.4</td>
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<td>Pved (mm Hg)</td>
<td>4.2 ± 1.1 C</td>
<td>7.9 ± 0.9</td>
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<td>Pved (mm Hg)</td>
<td>0.7 ± 0.9 C</td>
<td>1.2 ± 0.6 C</td>
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<td>Pved (mm Hg)</td>
<td>1.8 ± 0.7 C</td>
<td>3.0 ± 0.7</td>
</tr>
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<td>Ppv (mm Hg)</td>
<td>2.7 ± 0.7 C</td>
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<tr>
<td>Ppr (mm Hg)</td>
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<td>Alv-vr (mm Hg)</td>
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<td>4839 ± 175</td>
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</table>

Abbreviations are as in table 1.

*p < .05; **p < .025; ***p < .0125.
ventricle. This is demonstrated in figure 3, A, which compares pericardial pressure over the left and right ventricles during different interventions; the volume-loading points are clustered along the line of identity, while the points representing results of constriction of the aorta and the pulmonary artery are consistently shifted toward the ordinate and abscissa, respectively. The points representing results of angiotensin infusion are not different from those for volume loading at normal volumes, but tend to be shifted slightly toward the ordinate at elevated volumes. In figure 3, B, the mean change in pericardial pressure over the left ventricle vs the change in pressure over the right ventricle are plotted with the corresponding vectors (i.e., changes relative to the preceding control observation). The local differences in pericardial surface pressure with the infusion of angiotensin are more evident.

Figure 4 suggests that the increased pericardial pressure over the left ventricle during ascending aorta constriction can be attributed primarily to dilatation of the left ventricle. There was an increase in the left ventricular cross-sectional area index. There was no significant change in pericardial pressure over the right ventricle with ascending aortic constriction, although there was a significant decrease in right ventricular septal-to-freewall diameter. The increased pericardial...
pressure over the right ventricle during pulmonary artery constriction is probably attributable to right ventricular dilatation that caused right-sided pericardial distension (figure 5). Decreased pericardial pressure over the left ventricle during pulmonary artery constriction was associated with reduced left ventricular size and a decrease in left ventricular transmural pressure and segment length (figure 6). These outflow constrictions caused only minor changes in the index of total cardiac size (tables 1 and 2).

**Discussion**

The present study demonstrates that acute, large, unilateral increments in ventricular afterload are associated with important transient regional differences in pericardial surface pressure. The most striking differences were observed during pulmonary artery constriction, which markedly increased pericardial surface pressure over the right ventricle but significantly decreased that over the left. Ascending aorta constriction and infusion of angiotensin also caused local pericardial...
ial pressure differences; these interventions increased left ventricular more than right ventricular pericardial surface pressure. However, blood volume expansion with saline (which produced a more symmetrical loading of the two ventricles) caused equal increments in pericardial surface pressure over the right and left ventricles.

As expected, balloon-measured pericardial pressure did increase when the underlying ventricle enlarged; the increase in pericardial pressure over the right ventricle during constriction of the pulmonary artery apparently reflects regional pericardial distension over the dilated right ventricle and, similarly, increased pericardial pressure over the left ventricle during constriction of the ascending aorta was caused by left ventricular dilatation. However, this pressure was not a simple function of the dimension of the underlying ventricle. This point is evident from the observation that pericardial pressure over the right ventricle increased during constriction of the ascending aorta in spite of the reduced right ventricular diameter (figure 4). This suggests that regional contact stress is also influenced by the volume of the opposite ventricle. During constriction of the ascending aorta the left ventricle is dilated and therefore occupies a greater portion of the intrapericardial space. The heart may shift rightward and this might cause the partly collapsed right ventricle to be pressed against the pericardium, leading to an increase in pericardial pressure over the right ventricle. This mechanism is not sufficient to equalize the pericardial surface pressures over the right and left ventricles. Possibly, a similar mechanism operates during pulmonary artery constriction and prevents an even greater drop in pericardial pressure over the left ventricle. This proposed mechanism implies a rightward shift of the left ventricular longitudinal axis during constriction of the ascending aorta and a leftward shift during pulmonary artery constriction, with the heart being "hinged" from the trunks of the great vessels within the parietal pericardium, which is attached to the diaphragm. The fact that local surface pressures over the two ventricles do not become equal during the outflow obstructions suggests that there is a finite resistance to lateral motion of the heart; thus, the differences between right and left ventricular pericardial surface pressures might reflect the force required to overcome this resistance to lateral displacement. Probably, this resistance is augmented by the engorgement of one or the other of the great vessels during the constrictions.

In general, regional differences in pericardial pressure may also be related to how well the pericardium conforms to the shape of the heart. Such a mechanism may have contributed to the difference between pericardial pressure over the right ventricle and that over the left ventricle observed in the present study since the unilateral outflow obstructions produced unilateral ventricular dilatation and hence marked changes in the overall configuration of the heart. Further studies are required to elucidate the mechanisms of the regional difference in pericardial pressure.

We cannot claim that the increase in pericardial pressure over the right ventricle is caused by right ventricular distension with the same degree of certain-
ty with which we explain the corresponding phenomenon on the left side. This is because we did not measure right ventricular segment length (as we did for the left ventricle) and we recognize that right ventricular septum-to-free wall diameter is a notoriously ambiguous indicator of right ventricular distension since this variable will change due to septal displacement; we can assume that the septum moved toward the left ventricle during constriction of the pulmonary artery. Nonetheless, it seems very likely that the right ventricle was distended by pulmonary artery constriction; this was obviously true after the pericardium had been removed and we assumed that pulmonary artery constriction had a similar effect when the pericardium was intact. Further studies of diastolic septal mechanics are in progress in our laboratory, the results of which should help clarify the relationships of septal shift, chamber distension, and local pericardial surface pressure.

In contrast to the results of the present study, Kenner and Wood\(^1\) found no significant changes in pericardial pressure during acute obstruction of left or right ventricular outflow. Their results may be partially explained by our findings (i.e., the pericardial surface pressure over the contralateral ventricle does not increase remarkably and may even decrease after outflow obstruction). However, this apparent discrepancy is most likely related to the fact that Kenner and Wood recorded pericardial pressure with an open-ended catheter that does not measure pericardial surface pressure. The difference between pericardial liquid pressure and surface pressure may be more than 10 mm Hg when the heart is dilated and the pericardium is empty. In the presence of sufficient pericardial fluid (>30 ml), pericardial liquid pressure equals surface pressure and then either technique can be used to record pericardial constraint.\(^6\) Furthermore, it must be noted that Kenner and Wood did not transfuse their animals, so differences in pericardial pressure at different locations would have been smaller. Also, their animals were completely intact, the pericardial catheter having been introduced with a metal stylet via the suprasternal notch.

We have previously demonstrated in dogs under a wide range of hemodynamic conditions (including selective left- and right-sided heart failure) that changes in right atrial pressure or right ventricular end-diastolic pressure approximate changes in pericardial surface pressure over the left ventricle.\(^9, 10\) More recently we have confirmed this relationship in patients.\(^11\) (These findings should not be misconstrued to suggest that right ventricular transmural diastolic pressure is zero; our studies only indicate that it is small.) However, in the present study during acute interventions that selectively and markedly increased the afterload of one ventricle at a time, right ventricular end-diastolic pressure differed significantly from pericardial surface pressure over the left ventricle. This was most clearly seen during pulmonary artery obstruction, which caused directionally opposite changes in right ventricular end-diastolic pressure and pericardial pressure over the left ventricle. This suggests some limitation of the clinical utility of right ventricular filling pressure as an estimate of pericardial pressure over the left ventricle. How frequently such asymmetrical and dramatic afterload changes are seen in clinical practice remains to be determined.

It is important to emphasize that we only examined the transient changes in regional pericardial pressure that followed acute changes in the afterload of one ventricle and did not examine whether the regional differences in pericardial pressure persisted over a longer time period. The regional differences might become attenuated over time due to pericardial creep or other mechanisms.

One of the physiologic implications of the present study could be that the local rise in pericardial surface pressure helps to prevent "overdistension" of the ventricle during sudden flow obstructions. For example, during pulmonary artery obstruction the marked rise in pericardial pressure over the right ventricle would limit the distension of the right ventricle and this might help to prevent the development of tricuspid regurgitation. Furthermore, since venous return to the left atrium may be severely compromised during pulmonary artery obstruction, the reduction in pericardial pressure over the left ventricle might help to maintain left ventricular transmural pressure (i.e., preload) in that, if pericardial pressure over the left ventricle did not decrease, left ventricular transmural pressure would be even lower.

In conclusion, the present study demonstrates significant differences in local pericardial surface pressure over the lateral ventricular surfaces during acute afterload changes. Although the mechanism is not entirely clear, these pressure differences might reflect the combined effects of a momentary decrease in venous return to the contralateral ventricle and a resistance to lateral motion of the heart within a relatively unyielding pericardium.

We thank Gerald Groves, Cheryl Pawlak, and Yoshimi Takahashi for skillful technical assistance and Gregory Douglas for preparing the manuscript. We also thank Dr. Naomi Anderson for reviewing the manuscript.

Vol. 75, No. 6, June 1987
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Circulation. 1987;75:1229-1236
doi: 10.1161/01.CIR.75.6.1229

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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