The relationship between pericardial pressure and right atrial pressure: an intraoperative study

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ABSTRACT The objective of this study was to determine the constraining effect of the normal human pericardium. Accordingly, immediately after thoracotomy in nine patients undergoing elective cardiac surgery, we measured mean pericardial surface pressure over the lateral free wall of the left ventricle with a flat balloon as well as mean right atrial pressure while incrementally infusing up to 2.1 liters of Ringer’s solution to increase right atrial pressure. In each case, the slope of the relationship between right atrial (range -4 to 20 mm Hg, overall) and pericardial pressures was near unity (1.16 ± 0.20 mean ± SD) and the intercept was approximately zero (0.71 ± 2.48 mm Hg). Correlation coefficients ranged from .86 to .97. These observations suggest that right atrial pressure can be used as an estimate of pericardial surface pressure. If this is the case, true left ventricular preload (i.e., effective distending pressure or transmural diastolic pressure) might be estimated from the difference between left ventricular filling pressure and right atrial pressure, both conveniently measurable clinically by means of a triple-lumen, flow-directed catheter.


ALTHOUGH it is well recognized that the diseased pericardium may cause a significant impairment to ventricular filling, the effect of the normal pericardium on the diastolic properties of the ventricles remains controversial. Based on measurements obtained with fluid-filled catheters, there has been a general consensus that pericardial pressure is equal to intrathoracic pressure and is thus of little hemodynamic significance. However, Holt et al. using a flat liquid-containing balloon, demonstrated that the magnitude of pericardial pressure was substantial and similar to right atrial pressure.

To resolve these conflicting findings, we recently used an animal preparation to compare the two means of measuring pericardial pressure (an open catheter and a flat liquid-containing balloon) with a calculated value of pericardial pressure (assumed to be equal to the difference between left ventricular intracavitary pressure and directly measured transmural pressure at the same left ventricular diameter). (Transmural pressure can be measured directly in that it is equal to intracavitary pressure when the pericardium is removed and the lungs retracted.) We found that the balloon accurately measured pericardial pressure over a wide range of pressures regardless of the volume of fluid within the pericardium. In contrast, the open catheter seriously underestimated pericardial pressure unless there was more than 30 ml of fluid present. Moreover, using the balloon technique in dogs, we confirmed the results of Holt et al., finding that pericardial pressure was directly proportional and virtually equal to right ventricular filling pressure. Accordingly, the goal of the present study was to determine whether these findings applied in patients. We sought to answer two questions: (1) What is the magnitude of pericardial pressure in man and (2) does pericardial pressure have any useful relationship to right atrial pressure that might provide a feasible estimate of pericardial pressure in a variety of clinical circumstances?

Patients and methods

Nine patients (mean age 54 years) scheduled for elective cardiac surgery gave informed consent to participate in this investigation; the protocol was previously reviewed and approved by the institutional ethics committee on human research. Patient data are given in Table 1.
TABLE 1

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex</th>
<th>Age (yr)</th>
<th>Surgery</th>
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<tr>
<td>1</td>
<td>M</td>
<td>44</td>
<td>CABG</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
<td>6</td>
<td>M</td>
<td>47</td>
<td>Aortic V</td>
</tr>
<tr>
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</tr>
<tr>
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<td>M</td>
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<td>CABG</td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>72</td>
<td>CABG</td>
</tr>
</tbody>
</table>

CABG = coronary artery bypass graft; Aortic V = aortic valve replacement.

Until the time of surgery, all patients were maintained on their cardiac drugs. General anesthesia was induced with an intravenous combination of 5 to 15 mg of morphine sulfate, 2 to 4 mg of lorazepam, and 0.3 to 0.4 mg of scopolamine hydrobromide. Anesthesia was maintained with fentanyl (30 mg/kg iv) and isoflurane, or halothane as required. A median sternotomy from the xiphoid process to the suprasternal notch exposed the pericardial sac. At a point above the apex of the heart, a 1 to 2 cm horizontal incision was made in the pericardium; through this aperture a 3 × 3 cm Silastic balloon was inserted and positioned to lie on the left lateral surface of the heart. A detailed description of this Silastic balloon for measuring pericardial pressures has been presented elsewhere.4 Into this balloon was injected a volume of saline previously determined to be appropriate. Right atrial pressure was recorded from either a thermodilution (Model 93-113-7F; Edwards Laboratories, Santa Ana, CA) or a venous catheter (Model PMS-5; Intracath Bard Canada, Mississauga, Ontario). Mean pericardial balloon and mean right atrial pressures were obtained (Model P231; Statham-Gould, Inc., Oxnard, CA) and continuously recorded (Model VR-6, Electronics for Medicine/Honeywell, White Plains, NY) at a paper speed of 10 mm/sec. Pressure measurements were referenced (zeroed) to a mid left ventricular level.

Vascular volume loading was induced by the addition of lactated Ringer’s solution (0.5 to 2.1 liters) infused through the basilic vein over 5 to 15 min until the mean right atrial pressure rose to a maximum of 20 mm Hg. After the infusion, the pericardial balloon was removed and its pressure measuring characteristics were evaluated in vitro. A large air-filled plastic bag was placed over the Silastic balloon.4 Manual compression yielded a pressure correction factor (range 1.09 to 1.67, mean 1.30) that was applied to the pericardial pressure measurements.

Results

Figure 1 shows the data collected from each of the nine patients. It is apparent from comparison with the line of identity and from table 2 that in each individual case the change in mean pericardial pressure induced by volume loading was similar to the change in mean right atrial pressure (the mean value of the slope was

\[ P_{\text{pericardium}} \] vs \[ P_{\text{right atrium}} \]

FIGURE 1. Mean right atrial pressure vs mean pericardial surface pressure over anterolateral surface of the left ventricle (compare data with line of identity).
1.16 ± 0.21 [1 SD]). With the exception of patient 5, the intercept was near zero (0.71 ± 2.8 overall, −0.04 ± 1.10 excluding patient 5). These combined data (excluding those of patient 5) are shown in figure 2. Correlation coefficients always exceeded .87 and averaged .94 ± .03.

To determine how reliably the change in mean right atrial pressure reflected the change in pericardial pressure, the differences between data points were analyzed. Furthermore, since the initial observation was not fundamentally unique and since one might expect pericardial pressure to fall as well as to rise in other common clinical situations, we took the differences between every pair of observations and plotted the results (from all the patients) in figure 3. Ninety-five percent confidence intervals of the points suggest that the change in mean right atrial pressure accurately predicts the change in mean pericardial pressure.

### Table 2

Results of linear regression

<table>
<thead>
<tr>
<th>Patient</th>
<th>Slope</th>
<th>Intercept</th>
<th>r</th>
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<tbody>
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<td>1.00</td>
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<td>.97</td>
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<tr>
<td>2</td>
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<td>0.02</td>
<td>.94</td>
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<td>.94</td>
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<td>−0.29</td>
<td>.96</td>
</tr>
<tr>
<td>Mean</td>
<td>1.16</td>
<td>0.71</td>
<td>.94</td>
</tr>
<tr>
<td>SD</td>
<td>0.20</td>
<td>2.48</td>
<td>.03</td>
</tr>
</tbody>
</table>

### Figure 2

Combined data from eight patients. (Data for patient 5 were excluded because of possible baseline error.) $P_{ra} = .98 P_{peri} + .90; r = .89, p < .0005.$

### Figure 3

To determine whether the change in pericardial pressure was equal to the change in right atrial pressure, the difference between each pair of observations from all nine patients was plotted. Regression line $(\Delta P_{ra} = .99 \Delta P_{peri} + .69) \pm 95\%$ confidence limits for the individual points $(r = .84, p < .0005)$.

### Discussion

In complete agreement with our previous experimental results, these findings in patients show that pericardial pressure is directly proportional and very similar in magnitude to mean right atrial pressure and, as such, represents a significant fraction of left ventricular intracavitary pressure. Because of this close relationship, mean right atrial pressure should prove useful as an estimate of pericardial pressure in human beings, thus providing a reliable estimate of true left ventricular preload (i.e., left ventricular transmural end-diastolic pressure) from measurements commonly made in a variety of clinical circumstances with a triple-lumen catheter.

Until approximately 10 years ago, it was generally assumed that the relationship between diastolic pressure and volume of a given left ventricle was constant except for the effects of gradual processes such as dilatation or hypertrophy. This was shown not to be the case in two sets of circumstances. The first, Barry et al. and Grossman and his collaborators showed that pacing-induced tachycardia in the presence of ischemia produced a transient upward shift in the pressure-volume relationship during the first several beats after resumption of the normal heart rate. Later, Serizawa et al. showed that this phenomenon was definitely not caused by the pericardium, since it was present in dogs after pericardectomy. The other set of circumstances in which the left ventricular diastolic pressure-volume relationship shifts acutely is characterized by alterations in ventricular loading. Nitroglycerin, sodium nitroprusside, and captopril have been shown to
shift the curve downward (i.e., increased apparent left ventricular diastolic “compliance”\textsuperscript{13}). Conversely, angiotensin\textsuperscript{11} and isometric handgrip exercise\textsuperscript{14} have been shown to decrease diastolic compliance. We proposed that the shift in the left ventricular diastolic pressure-volume relationship induced by these loading alterations were in reality caused by unappreciated changes in pericardial pressure related to changes in cardiac volume.\textsuperscript{15}

The credibility of this hypothesis of course depends on the true magnitude of pericardial pressure. If pericardial pressure is approximately equal to intrathoracic pressure, changes in this pressure can scarcely account for 20 mm Hg displacements in the pressure-volume curve.\textsuperscript{16} However, if pericardial pressure is similar in magnitude to right atrial pressure, it is possible that the changes in right atrial pressure could be comparable to the magnitude of observed shifts in the pressure-volume curve. This is supported by preliminary data from our laboratory with nitroglycerin.\textsuperscript{16}

The remarkable difference between pericardial pressure as measured with an open catheter and that measured with a balloon\textsuperscript{4} demand further explanation. Agostoni and Mead,\textsuperscript{17, 18} in their studies of pleural surface mechanics, differentiated between “liquid pressure” and “surface pressure.” Liquid pressure is measured with an open catheter and is “true” pressure in that it is transmitted equally in all directions, thereby obeying Pascal’s law. Surface pressure is equal to liquid pressure plus “deformational forces” (i.e., in the case of the pericardium, compressive contact stress). The contrast between the two phenomena may be most obvious when considering the knee joint. Surface pressure is equal to the weight of the body and thigh distributed over a small articular surface (approximately 3 cm\textsuperscript{2} for each knee\textsuperscript{19}). Normal liquid pressure as measured with a needle inserted into the joint capsule is slightly less than atmospheric pressure\textsuperscript{20} and thus obviously not fundamentally related to the mechanics of the knee joint. Similarly, pericardial liquid pressure as measured by an open catheter or a catheter-tip transducer in a protected space communicating with the pericardial cavity is not necessarily related to the effective constraint of the pericardium. It becomes virtually equal to surface pressure if the pericardium contains a modest effusion but it is significantly less if the pericardium is empty or is not sealed.\textsuperscript{4}

The virtual identity between pericardial and right atrial mean pressure implies that right atrial and right ventricular diastolic transmural pressure is minimal (note figures 5 and 8 in Refsum et al.\textsuperscript{21}). This might not be true in chronic heart failure when the pericardium might be enlarged. Similarly, there might be a difference between mean right atrial pressure and pericardial pressure in the presence of right ventricular hypertrophy, although this remains to be demonstrated. Indeed, in the case of right ventricular hypertrophy, one might expect that the relationship between right atrial and pericardial pressure would deviate systematically, being virtually identical at low pressures but with right atrial pressure exceeding that in the pericardium to an increasing degree as the right ventricle became progressively dilated. That right ventricular filling pressure normally equals pericardial pressure also suggests that the ventricular septum is mechanically similar to the lateral left ventricular free wall. If pericardial surface pressure over the right ventricle is equal to that over the lateral left ventricular free wall, negligible force is required to minimally displace the heart leftward or rightward.

Mangano’s work stands as an apparent contradiction to this interpretation of the role of the pericardium.\textsuperscript{22, 23} He showed in patients studied intraoperatively that opening the pericardium did not result in more stroke work for a given left ventricular diastolic pressure.\textsuperscript{22} In a very recent study Mangano et al.\textsuperscript{23} also measured end-diastolic volume with first-pass radionuclide angiography and confirmed and extended their previous conclusion: pericardiotomy does not change apparent compliance or the relationship between left ventricular stroke work and end-diastolic volume. If pericardial constraint had limited left ventricular transmural filling pressure, end-diastolic volume should have been greater after the pericardium was removed and stroke work should have been greater, according to the Frank-Starling relationship. Although we can only speculate, it seems possible that their results might be explained, at least in part, by any of three mechanisms: (1) Although some data were collected at high left ventricular end-diastolic pressures, most of the data were gathered at lower pressures at which the effect of the pericardium may not have been discernible. (2) In a scarred and stiffened ventricle an intracavitary pressure of 20 mm Hg might be due entirely to transmural pressure (i.e., pericardial pressure could be negligible). In the first study,\textsuperscript{22} of the eight patients in whom left ventricular filling pressure exceeded 15 mm Hg, only one (No. 8) did not have a healed myocardial infarction (personal communication). In the second study,\textsuperscript{23} 13 of 15 patients had a previous myocardial infarction. (3) Finally and probably most importantly, although the pericardium was incised, it is not at all obvious that effective extraventricular constraint was eliminated, since a netlike pericardium with several

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incisions or the lungs themselves can raise pericardial surface pressure. The structure of the human mediastinum might easily restrict ventricular filling even if the anterior aspect of the pericardium is incised.

Perhaps the greatest practical significance of our studies relates to the understanding of the Frank-Starling mechanism. It has long been observed that although vasodilators may reduce left ventricular filling pressure remarkably, stroke volume tends to be maintained or even increased. Although this is undoubtedly due in part to reduced afterload, an important part of the explanation may be that preload (i.e., left ventricular end-diastolic transmural pressure) is essentially maintained, despite a large reduction in left ventricular filling pressure. This would be the case if the reduction in left ventricular filling pressure were paralleled by a similar reduction in right atrial and pericardial pressures. Under these circumstances, end-diastolic volume will tend to be maintained and, on the basis of the Frank-Starling mechanism, one would predict that ventricular performance should be unimpaired.

In summary, two conclusions may be drawn from this study. First pericardial pressure in patients without evident pericardial disease represents a significant fraction of left ventricular intracavitary pressure. Second, pericardial pressure is proportional and similar in magnitude to mean right atrial pressure over a wide range. The importance of the second observation is the implication that pericardial pressure and therefore left ventricular preload can be reliably estimated in patients with the aid of triple-lumen catheters. Our observations imply that left ventricular transmural pressure may be only approximately one-half the value of left ventricular intracavitary pressure and that changes in preload might be greatly overestimated by changes in intracavitary pressure.

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