The Role of Right Ventricular Systolic Dysfunction and Elevated Intrapericardial Pressure in the Genesis of Low Output in Experimental Right Ventricular Infarction

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SUMMARY To elucidate the pathophysiology of severe right ventricular infarction (RVI), isolated RVI was produced in 15 dogs with the pericardium intact or open. After RVI in dogs with the pericardium intact, RV systolic pressure decreased by 27%, aortic pressure by 29% and cardiac output by 34%. RV transmural pressure, RV end-diastolic size and intrapericardial pressure increased, left ventricular transmural pressure and end-diastolic size decreased and the diastolic pressures equalized. Pericardiectomy after RVI resulted in increased ventricular transmural pressures and diastolic size, improved cardiac output and resolution of equalized diastolic pressures. RVI in dogs with the pericardium open resulted in similar changes, but of lesser magnitude and without equalization of diastolic pressures. These results indicate that reduced left ventricular preload due to impaired RV systolic function contributes to low cardiac output in RVI. Elevated intrapericardial pressure further reduces left ventricular preload and produces equal diastolic pressures.

RIGHT VENTRICULAR infarction (RVI) can precipitate low-output syndrome in some patients with acute myocardial infarction. RVI occurs primarily in the setting of acute inferoposterior infarction of the left ventricle. Noninvasive techniques detect involvement of the right ventricle in 30-40% of patients with transmural inferoposterior infarcts, but low-output syndrome occurs in only a small percentage of these patients. Clinically, severe RVI is characterized by a low-output state and signs of predominant right-heart failure, with little or no evidence of left-heart failure. Hemodynamic evaluation usually demonstrates low cardiac output and disproportionate elevation of RV filling pressure. In some patients, the ventricular diastolic pressures equalize, which suggests pericardial constriction or tamponade.

Marked RV systolic dysfunction is a probable mechanism underlying the low-output syndrome. Alternatively, increased intrapericardial pressure, consequent upon marked dilatation of the right-heart chambers due to RVI, may compromise left ventricular (LV) filling and thereby precipitate a low-output state. The significance of these mechanisms in the genesis of the low-output state associated with severe RVI needs to be delineated. Therefore, we undertook this study to determine whether RV systolic dysfunction can produce a low-output state in the absence of concomitant primary LV dysfunction, and to determine whether increased intrapericardial pressure is an important mechanism in the hemodynamic abnormalities of RVI.

Methods

To produce isolated RVI by selective intra-coronary injection of mercury, 15 mongrel dogs that weighed 20-30 kg were anesthetized with i.v. sodium pentothal, 20 mg/kg. The dogs were intubated and ventilated by a volume respirator with room air and supplemental oxygen. Anesthesia was maintained with i.v. alpha chloralose, 60 mg/kg. The dogs were prepared as follows for hemodynamic measurements. A triple-lumen thermodilution catheter (Edwards Laboratories) was inserted into the pulmonary artery through the femoral vein. Solid-state catheter-tipped pressure transducers (model PC480, Millar Instruments) were inserted into the right ventricle and left ventricle through the right internal jugular vein and left carotid artery, respectively. We measured aortic pressure with a cardiac catheter and an external pressure transducer (Statham P23Db). A median sternotomy was performed and the pericardium partially opened with a lateral incision originating at the pericardial reflection on the aorta and continuing 3–4 cm toward the right atrial appendage. An electromagnetic flow probe (model 501, Carolina Medical Electronics) was placed around the ascending aorta. To secure an access line for injecting intracoronary mercury, the right coronary artery was dissected from its origin for approximately 2 cm along its course adjacent to the right atrial appendage. To prevent reflux of mercury, a hydraulic occluder constructed of polyethylene tubing was placed around the right coronary artery at its most proximal point.

A nonobstructive, free-floating Silastic catheter (0.012-inch i.d.; 0.025-inch o.d.) was inserted into the proximal right coronary artery using a technique...
modified from Herd and Barger. Atrial pacing wires for bipolar pacing were sutured onto the right atrial appendage. A pericardial balloon catheter, modified from Holt et al., was constructed of a soft polyethylene bag attached to a fluid-filled catheter and inserted into the pericardium on the anterior surface of the heart at the level of the interventricular sulcus. The pericardium was closed edge to edge and a small gap was left near the pericardial reflection on the aorta where the pericardial catheter and pacing wires exited. The hearts were paced at an average of 130 beats/min to maintain a constant rate throughout the experiment. Prophylactic antiarrhythmic therapy was initiated with i.v. procainamide (loading dose 10 mg/kg) slowly administered approximately 20 minutes before control recordings. To assess changes in RV and LV size, two-dimensional echocardiography was performed using a wide-angle (80°), phased-array scanner and a 3-MHz transducer (model V-3000, Varian). The heart was imaged from a subdiaphragmatic approach. A hand-held transducer was placed intraabdominally through a small midline epigastric incision, and directed at the apex of the heart using the diaphragm as a window. A long-axis two-chamber view of both ventricles, oriented according to the interventricular septum and atioventricular valve planes, was obtained. The transducer was then angled to maximize first RV and then LV diastolic size and to obtain a clear endocardial outline of the respective cavities. The images were recorded on ½-inch videotape. Ventricular diastolic size was analyzed using a light-pen microcomputer system (Varian).

Data Collection
Arterial blood gases and pH were monitored frequently. The ventilator was adjusted and bicarbonate administered to maintain PO₂ and pH in the normal range. Core body temperature monitored by rectal probe averaged 36°C. Hematocrit was monitored and averaged 41%. The reference lumens of the RV and LV transducer-tipped catheters were connected with a manifold to the pressure transducer used to measure pericardial pressure. This transducer had been balanced to atmospheric pressure at the midplane of the left ventricle. Before and after each recording, the RV and LV diastolic pressures measured with the solid-state transducers were compared with pressures measured through the lumen and corrected if necessary. These pressures and the ECG were recorded on a direct-writing strip-chart recorder (model M-28, MFE Corp.), a tape recorder (model 5600C, Electronics for Medicine) and a photographic recorder (model 1856, Electronics for Medicine). The electromagnetic flow probe was calibrated in vitro by passing blood through the probe at a known rate. The flowmeter gain was preset to match the individual probes during the experiment and was corrected for the hematocrit value.

Experimental Protocol
To study the synergistic and separate effects of isolated RV dysfunction and pericardial-ventricular interactions, two groups of dogs were studied. In the 10 dogs in group 1, RVI was produced and the pericardium was left intact. Control measurements were recorded after 25–30 minutes. The hydraulic occluder was then inflated and 0.15 ml of elemental mercury was injected into the right coronary artery through the indwelling catheter over 5–10 seconds. Hemodynamic values stabilized 5–7 minutes after infarction and the hemodynamic and echocardiographic measurements were repeated. The pericardium was then opened laterally from the aorta toward the lateral RV free wall and measurements were again repeated after the hemodynamics had stabilized.

In the five dogs in group 2, a similar protocol was followed, except that after control recordings, the pericardium was opened along its lateral axis and measurements were made after the hemodynamics had stabilized but before injection of mercury. Mercury was then injected as in group 1 and measurements were recorded at the new level of stabilization.

Analysis of Data
Aortic, ventricular and pericardial pressures, and left ventricular positive maximal dP/dt were analyzed from the photographic recordings. Cardiac output data were obtained from the thermodilution cardiac output computer, except in three experiments in which stroke volume was derived from the aortic flow probe signal, which was displayed in the photographic recordings on a beat-to-beat basis. Because pulmonary artery pressure was not measured, an index of RV stroke work was calculated as: (RV peak systolic pressure - pericardial systolic mean pressure) - (RV diastolic mean pressure - pericardial mean diastolic pressure) \times stroke volume \times 0.0136. LV stroke work was calculated as: (LV systolic mean pressure - pericardial systolic mean pressure) - (LV mean diastolic pressure - pericardial mean diastolic pressure) \times stroke volume \times 0.0136.

Ventricular transmural pressures were calculated by subtracting pericardial end-diastolic pressure from ventricular end-diastolic pressure. An index of pulmonary vascular resistance was calculated as: (RV peak systolic pressure - LV diastolic mean pressure/cardiac output) \times 80. Systemic vascular resistance was calculated as: (mean arterial pressure - RV diastolic mean pressure/cardiac output) \times 80.

Two-dimensional echocardiographic ventricular diastolic size was analyzed using a light-pen microcomputer system calibrated vertically and horizontally with an ultrasonic calibrating standard, which allows the operator the choice of three algorithms for calculating volumes from traced outlines. End-diastole was considered as the peak of the R wave of the QRS complex and end-diastolic frames were selected for optimal endocardial visualization. Ventricular outlines were traced by applying the light pen to the inner border of the chamber wall. The long axis for the area-length method was defined as the longest line running from the atioventricular plane to the apex. Three separate frames at each measured period (control,
postinfarction and postpericardiotomy) were analyzed. The traced area outlines and lengths were stored in the computer memory and recalled individually to calculate an analog of LV volume by a single-plane area-length method. These measurements were used to estimate ventricular diastolic size and were expressed as relative percent sequential changes after interventions. Mercury distribution in the hearts was confirmed by postmortem radiography. Films of the intact heart from anteroposterior and right lateral views were obtained. The hearts were then dissected into RV free wall, LV free wall and septal sections, which were then individually filmed.

Statistical Analysis

Ten dogs in group 1 survived infarction. However, because five dogs died from arrhythmias immediately after pericardiotomy, only five dogs were available for postpericardiotomy analysis. Therefore, postinfarction data from group 1 were compared with control data in all 10 dogs by paired t test; postpericardiotomy data were compared with control and postinfarction data by a two-way analysis of variance. All data from group 2 experiments were analyzed by two-way analysis of variance. Significance was defined at the 95% level.

Results

Postmortem Radiographic Analysis of Intracardiac Mercury Distribution

The arterial circulation of the RV free wall was diffusely and uniformly filled with mercury in each experiment. The mercury was selectively distributed to the right ventricle; little or no mercury was present in the left ventricle or septum (fig. 1).

Group 1

The hemodynamic abnormalities after RVI with the pericardium intact are summarized in table 1. Within 15–20 seconds after injection of mercury into the right coronary artery, RV peak systolic pressure (RVS), LV systolic mean pressure (LVSM), and aortic mean pressure (AoP) decreased. These pressures stabilized within 5–7 minutes after RVI (fig. 2). RVS decreased by an average of 27%, while LVSM and AoP decreased by 29%. RV stroke work decreased by 60% from control levels and LV stroke work decreased 54%. Cardiac output decreased 34%, and because the heart rate was constant, stroke volume decreased proportionately. There was no significant change in LV dP/dt.

RV end-diastolic pressure (EDP) increased by 3.1 ± 1.8 mm Hg (p < 0.0005) and intrapericardial pressure increased by 2.9 ± 2.2 mm Hg (p < 0.025). LVEDP did not change significantly. Despite an increase in intrapericardial pressure, RV transmural pressure, the true filling pressure of the right ventricle, increased by 0.7 ± 1.1 mm Hg (p < 0.05). The LV transmural pressure, however, decreased by 2.6 ± 1.5 mm Hg (p < 0.0005). Echocardiographic evaluation of ventricular volume revealed that RV end-diastolic size increased 110% while that of the left ventricle decreased 31% (fig. 3). RV, LV and intrapericardial diastolic pressures equalized, simulating pericardial tamponade in seven of the 10 experiments (fig. 4).

Alterations in RV performance after RVI were evident. Visual inspection revealed gross dilatation and impaired contraction of the right ventricle. The decreased RV stroke work and the increase in RV transmural pressure indicate depressed RV systolic function. The decrement in LV stroke work, however, was accompanied by a decrease in LV transmural pressure, which indicates no obvious depression of LV function (fig. 5).

Group 1: Response to Pericardiotomy

The hemodynamic effects of pericardiotomy after RVI are summarized in table 2. Pericardiotomy resulted in rapid and dramatic improvement in hemodynamic variables and pump function. Within 2 minutes after pericardiotomy, AoP increased by 35% and LVSM improved by 34%. The increment in RVS was insignificant (fig. 2). LVSW increased by 108%, but the small increase in RV stroke work was not significant.

Because pressure outside the ventricle became zero after pericardiotomy, LVEDP decreased slightly and
LV transmural pressure increased significantly. Similarly, RV transmural pressure increased and RVEDP decreased. The increment in LV transmural pressure was associated with an 80% increase in echocardiographic LV end-diastolic size. RV diastolic size also increased after pericardiotomy (fig. 3). After pericardiotomy, diastolic pressures were no longer equal in the dogs that had this phenomenon with the pericardium intact (fig. 4). Changes in RV and LV function after pericardiotomy are illustrated in figure 6. RV and LV stroke work and RV and LV transmural pressures increased, indicating a right and upward shift of the respective ventricular function curves.

**Group 2: Response to Pericardiotomy Before Infarction**  
The hemodynamic changes after pericardiotomy before production of RVI are summarized in table 3. Within 2 minutes after pericardiotomy, hemodynamic values stabilized. There were small but significant increments in AoP and LVSM pressure, though RVS did not change significantly. Cardiac output and stroke volume increased, as did LV and RV stroke work. Transmural pressure increased in both ventricles after pericardiotomy. RV and LV diastolic size increased slightly, but not significantly.

**Effect of RVI with Open Pericardium**  
The hemodynamic changes after RVI produced with the pericardium open are summarized in table 3. RVI resulted in decreases in AoP (16%), LVSM (19%) and RVS (23%). RV and LV stroke work decreased by 45% and 35%, respectively. LV dP/dt did not change significantly. The decline in LV stroke work was associated with a decrease in LV transmural pressure (NS). However, there was a significant decrease in LV end-diastolic size determined by echocardiography. The RV transmural pressure increased significantly, accompanied by an increase of the RV diastolic size.

**Discussion**  
We produced selective RVI to evaluate the role of RV dysfunction in the genesis of low-output syndrome. Though clinical RVI occurs in the setting of LV infarction, we believed that isolating the insult to the right ventricle might allow more precise evaluation of its role in the pathophysiologic mechanisms underlying the low-output state that may accompany RVI. Further, by performing two series of experiments, one in which the infarction was produced with the pericardium intact and another with the pericardium open, we hoped to assess the role of the pericar-
Figure 2. Pressure recording during control, after ventricular infarction, and after pericardiotomy in an experiment from group 1. Pressures are expressed in mm Hg. After infarction, right ventricular (RV) systolic, aortic and left ventricular (LV) systolic pressures decreased. RV diastolic pressure and intrapericardial pressure increased, but LV diastolic pressure decreased.

Figure 3. Hemodynamic and echocardiographic data in group 1 after right ventricular infarction (RVI) and pericardiotomy (PCX). Echocardiographic chamber size is expressed as percent change from the control value defined as 100%. Each bar shows mean and SEM.
dium in the hemodynamic abnormalities of RVI. Postmortem radiographic analysis revealed that mercury was lodged in the arterial branches of the right coronary artery almost exclusively within the distribution of the RV free wall. The embolization of mercury into the coronary circulation has been shown to produce myocardial necrosis with a histologic pattern similar to that of human and experimental infarcts.24 Our findings indicate that the injection of mercury into the right coronary artery caused isolated infarction of the right ventricle and little or no obvious damage to the left ventricle or septum.

Two-dimensional echocardiography has potential limitations in the precise quantitative analysis of ventricular volumes and function.20 However, our primary purpose was to assess relative changes in RV and LV diastolic size after infarction and pericardiotomy. Two-dimensional echocardiography has been shown to be useful in the assessment of clinical RV volume overload.29 The changes in RV chamber size in this study were grossly visible and correlated with the changes in echocardiographic chamber size (average increase of 110% after infarction); thus, the qualitative directional change in RV size was obvious. Echocardiographic analysis of LV volume should be quantitatively more accurate and is better established.20, 21, 23 The decrease (average 31%) in LV diastolic size after infarction was clear and statistically significant. Thus, echocardiography enabled us to assess qualitative directional changes in ventricular preload and to obtain a semiquantitative estimate of these alterations. Because of potential limitations in the accuracy of precise quantitation of ventricular volume, we expressed the echocardiographic measure-
ments as relative sequential changes in chamber size.

Another potential methodologic error in our study involves the measurement of intrapericardial pressure. For technical reasons, we found it necessary to use a balloon catheter rather than a catheter with an open side hole. While there may be a small overestimation of intrapericardial pressure measured in this manner, the directional changes in intrapericardial pressure in our study were consistent, and because each dog served as its own control, small measurement artifacts that might have been present would not significantly influence our findings.

In the present study, RVI profoundly depressed RV function. RV stroke work decreased markedly despite increases in RV transmural pressure and diastolic size. LV preload decreased concomitantly, as shown by decreased LV transmural pressure and reduced diastolic size. LV stroke volume and LV stroke work also decreased. Therefore, it appears that the reduced systemic output that accompanies RVI results, at least in part, from reduced LV preload.

One mechanism of reduced LV preload in the presence of RVI appears to be marked RV dysfunction. Within a few minutes after RVI was produced, RV

Table 2. Group 1: Response to Pericardiotomy

<table>
<thead>
<tr>
<th></th>
<th>Post-infarction</th>
<th>Post-pericardiomy</th>
<th>p*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systemic arterial systolic pressure (mm Hg)</td>
<td>92 ± 21</td>
<td>122 ± 13</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Systemic arterial diastolic pressure (mm Hg)</td>
<td>72 ± 20</td>
<td>101 ± 12</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>Systemic mean arterial pressure (mm Hg)</td>
<td>83 ± 20</td>
<td>112 ± 14</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>RV systolic pressure (mm Hg)</td>
<td>21 ± 4.6</td>
<td>22 ± 2.6</td>
<td>NS</td>
</tr>
<tr>
<td>RV mean diastolic pressure (mm Hg)</td>
<td>8.0 ± 0.7</td>
<td>5.4 ± 1.7</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>RV end-diastolic pressure (mm Hg)</td>
<td>9.2 ± 1.1</td>
<td>6.2 ± 1.6</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>RV transmural pressure (mm Hg)</td>
<td>1.8 ± 2.5</td>
<td>6.2 ± 1.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RV end-diastolic size (% of control)</td>
<td>210%</td>
<td>298%</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>RV stroke work (g-m/m²)</td>
<td>1.8 ± 1.0</td>
<td>3.3 ± 1.1</td>
<td>NS</td>
</tr>
<tr>
<td>Pericardial mean diastolic pressure (mm Hg)</td>
<td>6.6 ± 1.7</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Pericardial end-diastolic pressure (mm Hg)</td>
<td>7.6 ± 2.0</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LV peak systolic pressure (mm Hg)</td>
<td>89 ± 21</td>
<td>117 ± 13</td>
<td>&lt;0.025</td>
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<tr>
<td>LV mean systolic pressure (mm Hg)</td>
<td>82 ± 20</td>
<td>110 ± 14</td>
<td>&lt;0.025</td>
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<tr>
<td>LV mean diastolic pressure (mm Hg)</td>
<td>8.8 ± 1.6</td>
<td>8.4 ± 2.7</td>
<td>NS</td>
</tr>
<tr>
<td>LV end-diastolic pressure (mm Hg)</td>
<td>9.6 ± 2.0</td>
<td>9.2 ± 2.8</td>
<td>NS</td>
</tr>
<tr>
<td>LV transmural pressure (mm Hg)</td>
<td>2.0 ± 1.6</td>
<td>9.2 ± 2.8</td>
<td>&lt;0.001</td>
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<td>LV end-diastolic size (% of control)</td>
<td>69%</td>
<td>120%</td>
<td>&lt;0.005</td>
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<td>LV stroke work (g-m/m²)</td>
<td>10.2 ± 4.8</td>
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<td>&lt;0.005</td>
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<td>LV positive maximal dP/dt (mm Hg/sec)</td>
<td>1363 ± 497</td>
<td>1544 ± 495</td>
<td>NS</td>
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<tr>
<td>Stroke volume (ml)</td>
<td>10.7 ± 4.7</td>
<td>15.3 ± 4.7</td>
<td>&lt;0.01</td>
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<td>Cardiac output (l/min)</td>
<td>1.22 ± 0.49</td>
<td>1.75 ± 0.48</td>
<td>&lt;0.025</td>
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<tr>
<td>Pulmonary vascular resistance (dyn-sec-cm⁻⁵)</td>
<td>724 ± 191</td>
<td>691 ± 203</td>
<td>NS</td>
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<tr>
<td>Systemic vascular resistance (dyn-sec-cm⁻⁵)</td>
<td>4885 ± 2046</td>
<td>5791 ± 1264</td>
<td>NS</td>
</tr>
</tbody>
</table>

Values are mean ± SEM.
*Statistical analysis by paired t test.
Abbreviations: RV = right ventricular; LV = left ventricular.

In the present study, RVI profoundly depressed RV function. RV stroke work decreased markedly despite increases in RV transmural pressure and diastolic size. LV preload decreased concomitantly, as shown by decreased LV transmural pressure and reduced diastolic size. LV stroke volume and LV stroke work also decreased. Therefore, it appears that the reduced systemic output that accompanies RVI results, at least in part, from reduced LV preload.

One mechanism of reduced LV preload in the presence of RVI appears to be marked RV dysfunction. Within a few minutes after RVI was produced, RV

Figure 6. Left and right ventricular function evaluated by plotting stroke work vs diastolic transmural pressure from postinfarction (closed squares) to postpericardiomy (arrows) in group 1 experiments.
dilatation and impaired contraction were obvious by gross inspection. Further, RV peak systolic pressure and RV stroke work decreased markedly despite increased RV transmural pressure and diastolic size, indicating marked depression of RV pump performance. Pulmonary vascular resistance decreased, which shows that depressed RV pump performance was not related to increased RV afterload. Thus, impaired RV systolic function was associated with decreased RV stroke volume, which contributed to reduced LV preload.

The increased intrapericardial pressure that occurred after acute RVI compromised LV filling and further reduced LV preload. In the experiments in which RVI was produced with the pericardium intact, intrapericardial pressure increased significantly and was associated with a marked reduction in LV diastolic size and LV transmural pressure. The decrements in LV stroke work, systemic pressure and cardiac output were more profound compared with the experiments where RVI was produced with the pericardium open. After pericardiotomy, there was a prompt increase in LV diastolic size and transmural pressure; RV transmural pressure also increased, and both RV and LV function improved. These findings indicate that the increased intrapericardial pressure imposed a significant restriction on diastolic filling of the ventricles. This was also evident because diastolic pressures equalized in the majority of the experiments in which RVI was produced with the pericardium intact, and because this hemodynamic abnormality disappeared after pericardiotomy. When RVI was produced with an open pericardium, the diastolic pressures did not equalize.

The pericardium is a stiff constraining shell characterized by a relatively steep pressure-volume relation. The massive RV dilatation accompanying RVI probably encroached significantly on intrapericardial volume and caused elevation of intrapericardial pressure. Although the increment in intrapericardial pressure caused a concomitant increase in LV diastolic pressure, there was a decrease in transmural pressure, the true filling pressure of the LV. As RV diastolic size increased, LV diastolic size decreased after RVI with intact pericardium. An acute increase in intrapericardial volume is likely to cause a disproportionate elevation of intrapericardial pressure and consequently compromise ventricular filling.

### Table 3. Group 2: Right Ventricular Infarction with the Pericardium Open

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Post-pericardiotomy</th>
<th>Post-infarction</th>
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</thead>
<tbody>
<tr>
<td>Systemic arterial systolic pressure (mm Hg)</td>
<td>112±17</td>
<td>131±25§</td>
<td>107±29§</td>
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<tr>
<td>Systemic arterial diastolic pressure (mm Hg)</td>
<td>88±11</td>
<td>103±15†</td>
<td>85±23†</td>
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<td>Systemic mean arterial pressure (mm Hg)</td>
<td>101±13</td>
<td>116±19†</td>
<td>97±27‡</td>
</tr>
<tr>
<td>RV systolic pressure (mm Hg)</td>
<td>22.2±3.5</td>
<td>22.4±2.6</td>
<td>17.2±1.9†</td>
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<tr>
<td>RV mean diastolic pressure (mm Hg)</td>
<td>3.8±1.5</td>
<td>3.0±1.2*</td>
<td>4.2±1.3‡</td>
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<tr>
<td>RV end-diastolic pressure (mm Hg)</td>
<td>4.6±2.1</td>
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<td>4.8±1.6</td>
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<tr>
<td>RV transmural pressure (mm Hg)</td>
<td>0.4±0.9</td>
<td>3.2±1.8*</td>
<td>4.8±1.6</td>
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<td>RV end-diastolic size (% of control)</td>
<td>100</td>
<td>133%</td>
<td>246%§</td>
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<tr>
<td>RV stroke work (g-m/m²)</td>
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<tr>
<td>Pericardial mean diastolic pressure (mm Hg)</td>
<td>3.4±1.8</td>
<td>0±0†</td>
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<tr>
<td>Pericardial end-diastolic pressure (mm Hg)</td>
<td>4.4±1.7</td>
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<td>0±0</td>
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<td>LV peak systolic pressure (mm Hg)</td>
<td>106±15</td>
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<td>100±25§</td>
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<td>LV mean systolic pressure (mm Hg)</td>
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<td>114±21†</td>
<td>92±24§</td>
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<td>LV mean diastolic pressure (mm Hg)</td>
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<tr>
<td>LV end-diastolic pressure (mm Hg)</td>
<td>8.2±4.3</td>
<td>8.2±4.8</td>
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<tr>
<td>LV transmural pressure (mm Hg)</td>
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<td>LV end-diastolic size (% of control)</td>
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<td>110%</td>
<td>84%†</td>
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<tr>
<td>LV stroke work (g-m/m²)</td>
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<td>23.5±2.2†</td>
<td>15.3±2.9</td>
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<td>LV positive maximal dP/dt</td>
<td>1087±105</td>
<td>1143±136</td>
<td>1006±158</td>
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<td>Stroke volume (ml)</td>
<td>14.6±3.4</td>
<td>16.5±3.3†</td>
<td>13.4±2.2$</td>
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<td>Cardiac output (l/min)</td>
<td>1.68±0.36</td>
<td>1.91±0.35‡</td>
<td>1.55±0.26§</td>
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<td>Pulmonary vascular resistance (dyn-sec-cm⁻²)</td>
<td>741±108</td>
<td>628±107</td>
<td>621±106</td>
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<tr>
<td>Systemic vascular resistance (dyn-sec-cm⁻²)</td>
<td>4907±1810</td>
<td>5038±1904</td>
<td>5026±2182</td>
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</table>

Statistical analysis was by two-way analysis of variance. Values are mean ± SEM.

* $p < 0.05$.
† $p < 0.01$.
‡ $p < 0.025$.
§ $p < 0.005$.
Experimental studies of RVI, using cauterization of the RV free wall with an open pericardium, have shown no significant alteration in RV systolic pressure generation despite gross RV dilatation and loss of visible RV contraction. Though RV filling pressure increased, overall systemic output was not affected. These studies concluded that isolated RV destruction would not adversely affect systemic output. However, the failure to produce impairment of RV systolic pressure generation and the lack of an intact pericardium are major limitations of these studies. In the experimental animal, simple occlusion of the right coronary artery will not produce RVI unless there is pre-existing right ventricular hypertrophy. Brooks et al. combined right coronary artery occlusion with pulmonary outflow tract obstruction and produced rapid failure of RV pressure generation and subsequent decreases in LV transmural pressure and systemic output. Though this model combined acute cor pulmonale with RV ischemia, the findings of impaired RV systolic pressure development, RV dilatation, decreased LV filling and low output are complementary to ours. Berglund et al. produced LV dilatation and elevated intrapericardial pressure by obstructing the aortic outflow tract. They also found a limitation to RV filling and decreased RV output. The notion that alterations in systolic and diastolic function of the RV can adversely affect the filling and output of the LV has been well substantiated. Pressure or volume overload of the RV results in progressive RV dilatation and elevated RV EDP, increased LVEDP despite reduced LV filling and distorted LV geometry. Though mechanical coupling of the ventricles occurs with the pericardium open, this interaction is enhanced with an intact pericardium. When intrapericardial pressure is elevated to levels that produce cardiac tamponade, there is significant impairment of ventricular filling with reduced ventricular volume, decreased LV transmural pressure despite increased end-diastolic pressure, equalization of ventricular diastolic pressures, decreased systemic output and impaired coronary blood flow. These studies further support the concept that primary RV systolic dysfunction can lead to secondary changes in the systolic and diastolic function of the left ventricle, in part through ventricular interactions augmented in the presence of an intact pericardium and exacerbated by elevation of intrapericardial pressure.

The results of this experimental study must be extrapolated to clinical RVI with caution. The extent of damage to the right ventricle was severe; in clinical RVI, extensive damage is not frequently seen, which explains the relatively low incidence of severe low-output state in these patients. Further, clinical RVI is seen almost exclusively in patients with LV infarction. Thus, the contribution of LV dysfunction in the genesis of a low-output state in these patients must be considered. Nevertheless, the results in the present study may provide some insight regarding the pathophysiologic mechanisms underlying the hemodynamic changes with clinical RVI. The demonstration of primary RV systolic dysfunction, with resultant reduction in LV preload and systemic output, is analogous to the clinical presentation of hypotension and right-heart failure without signs of pulmonary venous congestion. Our experimental observation that the pericardium must be intact for diastolic ventricular pressures to equalize suggests that the pericardium is at least partly responsible for this hemodynamic phenomenon. The more profound hemodynamic compromise accompanying RVI produced with intact pericardium and resolution of the diastolic equalization pattern and significant hemodynamic improvement after pericardiomy suggest that increased intrapericardial pressure may be an important mechanism in the pathophysiology of low cardiac output in clinical RVI.

In the present study, the hemodynamic changes resulted from isolated RV systolic dysfunction and elevated intrapericardial pressure. The comprehensive effects of these pathophysiologic mechanisms may be further exacerbated in the presence of abnormal LV function, where delivery of inadequate preload to the left ventricle that may critically depend on increased end-diastolic volume might further compromise cardiac output. Thus, a degree of RV systolic dysfunction that might have trivial effects on a left ventricle with well preserved function could have significant impact on cardiac performance in the presence of marked LV dysfunction.

In conclusion, the evidence from the present study emphasizes the importance of a functional right ventricle in the maintenance of cardiac output. Low cardiac output in experimental RVI is due primarily to reduced LV preload, which results in part from depressed RV function. Elevated intrapericardial pressure secondary to RV dilatation further reduces LV preload and produces diastolic pressure equalization. Pericardiomy after RVI improves LV filling and results in increased cardiac output.

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