Coronary Artery Hemodynamics in Conscious Dog During Cardiac Tamponade

H. Sidney Klopfenstein, Gregory A. Bernath, Terrence L. Cogswell, and Lawrence E. Boerboom

We tested the hypothesis that coronary artery blood flow is sufficient to meet myocardial requirements throughout cardiac tamponade in a conscious euvolemic canine model recovered from surgery. Seven mongrel dogs were chronically instrumented to measure ascending aortic blood flow (electromagnetic flowmeter); intrapericardial, right atrial, and aortic blood pressures; regional myocardial blood flow (radionuclide labelled microspheres); and myocardial consumption of lactate, pyruvate, and oxygen. Data were collected during progressive cardiac tamponade induced by intrapericardial saline infusion to the point of hemodynamic decompensation. Decompensated cardiac tamponade (DCT) was defined as a decline in mean aortic blood pressure to 70% of the level present when the pericardial space was drained of fluid (baseline) and was produced in all animals within 25 minutes. Cardiac tamponade caused a continuous decline in coronary artery blood flow from 1.26 ± 0.35 (baseline, mean ± SD) to 0.53 ± 0.15 ml/min/g (DCT, p<0.01), which was associated with a decrease in myocardial oxygen consumption from 1.26 ± 0.35 (baseline) to 0.74 ± 0.27 ml/min/g (DCT, p<0.05) and a slight increase in myocardial oxygen extraction from 71 ± 3 (baseline) to 81 ± 4% (DCT, p<0.05). This change in oxygen extraction occurred because of both an increase in arterial and a decrease in coronary venous oxygen content. At all degrees of cardiac tamponade, the lactate-pyruvate ratio did not change significantly from baseline (7.56 ± 2.31), there was no evidence of lactate production, and the normal endocardial to epicardial blood flow ratio present at baseline (1.41 ± 0.23) was preserved. Although aortic blood pressure was initially well maintained, aortic blood flow declined, and right atrial blood pressure increased continuously as intrapericardial pressure increased. A second group of 2 chronically instrumented animals was prepared to determine whether an adequate coronary vasodilatory reserve was present throughout cardiac tamponade. The reactive hyperemic response to brief coronary artery occlusion (hydraulic occluder) of a large epicardial vessel was measured (Doppler flow probe) in the conscious animal during progressive cardiac tamponade. Although a normal reactive hyperemic response was found at all stages of cardiac tamponade, the peak coronary artery blood flow obtained during reactive hyperemia decreased as intrapericardial pressure increased. Thus, in this conscious canine model of acute progressive cardiac tamponade, despite a continuous decline coronary artery blood flow was always adequate to support aerobic metabolism, and a normal coronary artery vasodilatory reserve was present, even at the time of hemodynamic decompensation. In this euvolemic animal model, myocardial ischemia did not contribute to the deterioration in cardiac function that occurred during acute cardiac tamponade. (Circulation Research 1987;60:845–849)

Cardiac tamponade is caused by the progressive accumulation of pericardial fluid under pressure. As intrapericardial pressure rises, cardiac output declines, and heart rate, left and right atrial blood pressure, and peripheral vascular resistance increase. Arterial blood pressure decreases progressively throughout cardiac tamponade in anesthetized or convalescing animals, whereas in conscious dogs who have recovered from surgery, it is generally maintained until late in tamponade when it abruptly declines. Isaacs et al used an anesthetized open-chest canine preparation to demonstrate the importance of reduced effective filling pressure in diastole as a cause of the decline in cardiac output during cardiac tamponade and stressed that the myocardium is not functionally impaired. O’Rourke et al studied the relation between cardiac performance and coronary artery blood flow during cardiac tamponade in a closed-chest anesthetized canine model. They found that despite a striking decrease in both coronary artery blood flow and external left ventricular work, myocardial oxygen consumption did not change significantly. A decline in coronary sinus oxygen content led these investigators to suggest that the observed fall in coronary artery blood flow may have been responsible for impaired cardiac performance rather than being a consequence of decreasing myocardial requirements. Since heart rate was increasing and wall tension decreasing, it was difficult to know what was happening to the metabolic requirements of the myocardium.

Frank and coworkers, using an anesthetized open-chest canine preparation, concluded that myocardial contractility remained unchanged during the hemodynamic collapse produced by cardiac tamponade. Left ventricular coronary artery blood flow and oxygen...
cardiac tamponade in their animal model. Wechsler et al. investigated early (first decline in systemic arterial blood pressure) and late (mean aortic blood pressure 35 to 40 mm Hg) cardiac tamponade in a closed-chest anesthetized canine model. They noted subendocardial ischemia and depressed contractility during severe cardiac tamponade and concluded that impaired coronary artery blood flow is a major, if not the principal, determining factor causing hemodynamic collapse during cardiac tamponade.

In the only study to date using conscious animals recovered from surgery, Jarmakani et al. found a progressive decrease in circumflex coronary artery blood flow during cardiac tamponade but an increase above control levels during recovery. They interpreted this increase to be a reactive hyperemic response and suggested that myocardial ischemia, perhaps resulting from extravascular compression of epicardial vessels, may be partially responsible for depressed cardiac function during tamponade. Taichman et al. observed a decline in the ratio of left ventricular endocardial to epicardial blood flow during cardiac tamponade in their anesthetized open-chest canine model. Furthermore, relief of tamponade was associated with an increase in coronary artery blood flow above control levels. Concluding that the decrease in myocardial blood flow could not be entirely the result of lowered diastolic blood pressure or reduced ventricular volume, they suggested that coronary arterial compression during cardiac tamponade may have played a role.

Thus, although there is agreement that coronary artery blood flow and external cardiac work decrease dramatically during cardiac tamponade, it is not clear whether coronary blood flow remains adequate to meet myocardial requirements or actually contributes to hemodynamic decompensation. Differences between the animal models studied and the various degrees of cardiac tamponade employed have undoubtedly contributed to the lack of consensus on this important question.

In this study, a conscious chronically instrumented euvolemic canine model recovered from surgery was used to test the hypothesis that coronary artery blood flow is sufficient to meet myocardial requirements throughout cardiac tamponade to the point of hemodynamic decompensation.

**Materials and Methods**

The 7 mongrel dogs in Group I weighed from 24 to 30 kg. Each animal was brought to the laboratory following an overnight fast, anesthetized (sodium pentobarbital 30 mg/kg to effect), intubated, and ventilated by a volume respirator (Harvard Apparatus Company, South Natick, Mass.) with oxygen enriched air (2 to 5 l/min). With sterile technique, a left thoracotomy in the fifth intercostal space was performed. The electrocardiogram and arterial blood gases were monitored throughout the procedure. A fluid-filled Tygon catheter (Tygon Microbore Tubing, 0.050 inch i.d., 0.090 inch o.d.) was inserted into the left internal mammary vein, advanced to the right atrium, and secured. A second Tygon catheter was then passed through the right internal mammary artery and advanced into the proximal descending aorta with its position manually confirmed. Next, a high-fidelity 6F catheter-tip pressure transducer (PC-460, Millar Instruments, Houston, Tex.) was inserted into the left internal mammary artery and advanced to the ascending aorta.

A 4 to 5 cm longitudinal incision was made in the pericardium overlying the pulmonary artery and left anterior descending coronary artery, and an electromagnetic flow probe was placed on the ascending aorta (Howell Instruments Company, Houston, Tex., used with a Narcomatic electromagnetic flow meter, model RT-500, Narco Biosystems, Inc., Houston, Tex.). Two fenestrated Tygon catheters were positioned in the pericardial space through separate incisions with their tips adjacent to the diaphragmatic surface of the left ventricle and were secured with purse-string sutures. A Tygon catheter was inserted into the left atrium through a purse-string suture, and the tip of a 20-gauge intravenous catheter (Angiocath, Deseret Medical Inc., Sandy, Utah) connected to a Tygon catheter (0.040 inch i.d., 0.070 inch o.d.) was inserted into the great cardiac vein using a technique developed in this laboratory. The pericardium was carefully closed with a continuous locking suture, and a watertight seal was verified. A chest tube was placed through the seventh intercostal space.

Finally, all catheters and wires were passed individually through the chest wall and tunneled subcutaneously to an area between the scapulae. The ribs were approximated with umbilical tape, and the wound was closed in layers to provide an airtight seal. All intravascular catheters were flushed, filled with a heparin solution, and sealed. The pleural and pericardial cavities were drained and 20 to 30 ml of sterile saline was placed in the pericardial space before sealing. When spontaneous respirations and reflexes were adequate, the animal was extubated, placed overnight in an incubator with controlled temperature and oxygen ventilation (5 l/min), and allowed to recover.

In the immediate postoperative period, meperidine, 1–3 mg/kg i.m. every 8 hours, was administered as needed for analgesia, and the animal received intramuscular injections of penicillin and streptomycin as a prophylactic measure. All catheters were aspirated and refilled with heparin solution daily. Five days after surgery, the conscious animal was brought to the laboratory and allowed to stand comfortably in a sling. One pericardial, the right atrial, and the aortic catheters were attached directly to Statham P23Db pressure transducers (Statham Instrument Company, Hato Rey, Puerto Rico) with the zero-pressure reference point one-third of the distance between the sternum and the spine. The Millar pressure transducer zero-pressure level was adjusted, using the fluid-filled aortic catheter.
as a reference. The pleural and pericardial cavities were drained of fluid and 5 to 10 ml normal saline was placed in the pericardial space (baseline). When necessary, normal saline was infused intravenously so that the mean right atrial blood pressure in all animals was between 0 and 4 mm Hg at baseline. Aortic blood flow and intrapericardial, right atrial, and aortic blood pressures were simultaneously recorded on an 8-channel FM recorder (model D, A. R. Vetter Company, Rebersburg, Penn.) and on an 8-channel Gould strip-chart recorder (model 2800, Gould Inc., Cleveland, Ohio).

When a hemodynamic steady state had been achieved, baseline data were recorded. Cardiac tamponade to hemodynamic decompensation was produced by continuous intrapericardial infusion of warmed saline solution at a rate of 20 ml/min with a Masterflex infusion pump (Cole Parmer Instrument Company, Chicago, Ill.). Decompensated cardiac tamponade was defined as a decline in mean aortic blood pressure to 70% of the level present at baseline. During cardiac tamponade, radionuclide-labelled microspheres were injected into the left atrium by previously described methods2 at baseline, at both 8 and 12 mm Hg intrapericardial pressure, and at decompensation. Timed collections of reference samples were obtained from the descending aortic catheter. Aortic and great coronary venous blood samples were drawn into heparinized syringes just prior to each microsphere injection and at 4 mm Hg intrapericardial pressure for measurement of oxygen content (Lex-\textsubscript{O}2-Con, Lexington Instruments, Waltham, Mass.) and pyruvate and lactate levels.

Following study, each animal was killed with a lethal intravenous dose of sodium pentobarbital, and the positions of all catheters were noted. Sections of the ventricular myocardium were obtained, weighed, and placed in counting vials. Tissue samples and reference blood samples were then assayed in a multichannel pulse-height analyzer. Separation of counts for individual radionuclides from the complex spectra was done by deriving the best-fit solution to a set of 24 simultaneous equations according to the algebraic matrix inversion technique of Baer et al. Calibration of the electromagnetic flow probe was performed by measuring timed collections of normal saline as it passed through the excised aorta with the flow probe in situ. All data were stored on analog magnetic tape and subsequently transferred to a digital computer (DEC LSI 11/23). Twenty-second data files were created at baseline, at 4, 8, and 12 mm Hg intrapericardial pressure, and during decompensation. By means of sequential interactive programs, individual beats in each 20-second file were defined, and mean pressures and flows for the intervals were calculated.

Data were compared by repeated measures analysis of variance and by paired \textit{t} tests with an appropriate correction by the Bonferroni procedure to control the error rate in multiple comparisons.

An additional group of 2 animals (Group II) was prepared to determine whether a reactive hyperemic response to brief coronary artery occlusion was present throughout cardiac tamponade. With the methods described above, catheters were placed for the chronic measurement of aortic and right atrial blood pressure, intrapericardial pressure, and for intrapericardial saline infusion. In addition, the tissue surrounding the proximal left anterior descending or circumflex coronary artery was carefully dissected and a 2-mm hydraulic occluder (In Vivo Metric, Inc., Healdsburg, Calif.) placed around the vessel just distal to a Doppler flow probe. In previous studies using radionuclide-labelled microspheres, we have found that the presence of this flow probe does not alter regional blood flow in animals studied within 10 days. After recovery for at least 5 days, the reactive hyperemic response to a 20-second coronary artery occlusion recorded in each animal was recorded at baseline, at 8, 12, and 16 mm Hg intrapericardial pressure, and at decompensated cardiac tamponade. Each animal in Group II was studied on 3 occasions.

Results

All findings in Group I animals are summarized in Table 1. Arterial and coronary venous lactate levels and myocardial lactate consumption did not change significantly during cardiac tamponade. The lactate-pyruvate ratio remained greater than 1.0 as intrapericardial pressure increased and showed no significant change from baseline. Myocardial blood flow decreased continuously during tamponade although there was no decline in the endocardial to epicardial blood flow ratio. While the values of myocardial blood flow shown in Table 1 are for the entire chamber, the pattern was the same for each individual region of the left ventricle. Despite a significant decline in calculated myocardial oxygen consumption during tamponade, myocardial oxygen extraction increased from 71 to 81\% because of both an increase in arterial (14.4 to 16.5 ml/dl) and a decrease in coronary venous (4.1 to 3.1 ml/dl) oxygen content. An increased arterial oxygen content would be expected if hematocrit increased. Although hematocrit increase has since been found to occur during cardiac tamponade in similar experiments, the hematocrit was not measured in the present study. As expected, aortic blood flow declined, and mean right atrial blood pressure and heart rate rose continuously as intrapericardial pressure increased. Aortic blood pressure fell later in the progression.

During cardiac tamponade in Group II animals, coronary occlusion for 20 seconds was always followed by a prompt reactive hyperemic coronary artery blood flow response which exhibited the same relative increase in amplitude when compared with the preoclusion blood flow (Figure 1).

Discussion

A progressive decrease in coronary artery blood flow during acute cardiac tamponade was consistently found in these animals. Despite this decrease in blood flow, no evidence of myocardial ischemia was detected, even at decompensation. At all degrees of tampon-
Table 1. Hemodynamic and Myocardial Metabolic Data From 7 Dogs During Progressive Cardiac Tamponade

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>4 mm Hg IPP</th>
<th>8 mm Hg IPP</th>
<th>12 mm Hg IPP</th>
<th>DCT (17.6 mm Hg IPP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactate (µmol/ml)</td>
<td>0.751 ± 0.11</td>
<td>0.783 ± 0.17</td>
<td>0.765 ± 0.15</td>
<td>0.889 ± 0.24</td>
<td>1.13 ± 0.36</td>
</tr>
<tr>
<td>Venous Lactate</td>
<td>0.54 ± 0.14</td>
<td>0.468 ± 0.17</td>
<td>0.490 ± 0.15</td>
<td>0.552 ± 0.23</td>
<td>0.753 ± 0.30</td>
</tr>
<tr>
<td>Consumption (µmol/min/g)</td>
<td>0.264 ± 0.16</td>
<td>—</td>
<td>0.344 ± 0.21</td>
<td>0.342 ± 0.1</td>
<td>0.212 ± 0.11</td>
</tr>
<tr>
<td>Lactate/pyruvate</td>
<td>7.56 ± 2.31</td>
<td>6.79 ± 3.19</td>
<td>6.08 ± 2.6</td>
<td>6.43 ± 3</td>
<td>7.78 ± 3.32</td>
</tr>
<tr>
<td>Left ventricular</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blood flow (ml/min)</td>
<td>1.26 ± 0.35</td>
<td>—</td>
<td>1.19 ± 0.26</td>
<td>0.996 ± 0.12*</td>
<td>0.53 ± 0.15*</td>
</tr>
<tr>
<td>Endo/epi</td>
<td>1.41 ± 0.23</td>
<td>—</td>
<td>1.36 ± 0.19</td>
<td>1.38 ± 0.14</td>
<td>1.37 ± 0.24</td>
</tr>
<tr>
<td>MVO2 (ml/min/g)</td>
<td>1.26 ± 0.35</td>
<td>—</td>
<td>1.46 ± 0.43</td>
<td>1.22 ± 0.19</td>
<td>0.74 ± 0.27*</td>
</tr>
<tr>
<td>Oxygen content (ml/dl)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arterial</td>
<td>14.4 ± 1.3</td>
<td>—</td>
<td>14.8 ± 1.3</td>
<td>15.8 ± 0.9</td>
<td>16.5 ± 1.8*</td>
</tr>
<tr>
<td>Coronary venous</td>
<td>4.1 ± 0.6</td>
<td>—</td>
<td>3.2 ± 0.8</td>
<td>3.7 ± 0.3</td>
<td>3.1 ± 0.6*</td>
</tr>
<tr>
<td>Extraction (%)</td>
<td>71.0 ± 3</td>
<td>—</td>
<td>78.0 ± 6*</td>
<td>77.0 ± 2</td>
<td>81.0 ± 4*</td>
</tr>
<tr>
<td>Aortic blood flow (l/min)</td>
<td>5.37 ± 2.1</td>
<td>4.96 ± 2.0</td>
<td>4.14 ± 1.6*</td>
<td>3.33 ± 0.98*</td>
<td>1.79 ± 0.97*</td>
</tr>
<tr>
<td>Right atral BP (mm Hg)</td>
<td>1.59 ± 2.1</td>
<td>4.34 ± 2.1</td>
<td>7.1 ± 2.7*</td>
<td>10.2 ± 2.8*</td>
<td>15.1 ± 3.5*</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>124 ± 28</td>
<td>136 ± 31</td>
<td>162 ± 33</td>
<td>197 ± 21*</td>
<td>197 ± 49*</td>
</tr>
<tr>
<td>Arterial BP (mm Hg)</td>
<td>113.7 ± 10.9</td>
<td>113.7 ± 9.8</td>
<td>104.9 ± 12.8</td>
<td>98.1 ± 7.7*</td>
<td>73.8 ± 12.8*</td>
</tr>
</tbody>
</table>

*p < 0.05 vs baseline, mean ± SD. IPP = intrapericardial pressure, DCT = decompensated cardiac tamponade, MVO2 = myocardial oxygen consumption, BP = blood pressure.

Although studied, the lactate-pyruvate ratio remained constant, there was no evidence of myocardial lactate production, and the normal endocardial to epicardial blood flow ratio was maintained. Finally, in the 2 animals studied in Group II, a normal coronary reactive hyperemic response at all stages of cardiac tamponade confirmed that the potential for further coronary artery vasodilation was present even at the point of decompensation. These findings are consistent with the conclusion that despite a continuous, progressive decline during acute cardiac tamponade, coronary artery blood flow was at all times adequate to support aerobic myocardial metabolism in this conscious animal model. If epicardial coronary artery compression, coronary venous compression, tachycardia, or other mechanisms had resulted in myocardial ischemia during cardiac tamponade, one would have expected to see the lactate-pyruvate ratio decrease to levels less than 1.0, a decline in the myocardial endocardial to epicardial blood flow ratio, and an absent reactive hyperemic response to brief coronary artery occlusion.

The decrease in myocardial oxygen consumption during cardiac tamponade was associated with a significant trend toward increased myocardial oxygen extraction, which resulted from both increased arterial and decreased coronary venous oxygen content. This slight increase in oxygen extraction (from 71 to 81%) occurred in the presence of an adequate coronary arterial vasodilatory reserve, as evidenced by the normal reactive hyperemic responses seen in Group II animals throughout cardiac tamponade. This observation suggests that although myocardial oxygen supply was adequate to support aerobic metabolism, the ratio between myocardial oxygen supply and demand declined somewhat as intrapericardial pressure increased.

Although the reactive hyperemic response in Group II animals was normal throughout, the peak blood flow that occurred during reactive hyperemia at the time of decompensated cardiac tamponade was far less than at baseline. Several mechanisms may have contributed to the observed decrease in the maximum coronary artery blood flow. A decline in coronary perfusion pressure would have resulted if arterial blood pressure decreased and/or the effective downstream pressure increased. Mean arterial blood pressure is usually well maintained until late in cardiac tamponade in this animal model, and its late decline is shown in Table 1. A concomitant increase in the effective downstream pressure is an interesting possibility in this unique model.
hemodynamic situation. Uhlig et al. have concluded that under some conditions, a vascular waterfall is present in the epicardial venous system. Furthermore, in their open-chest, paced, and vasodilated canine preparation with the pericardium open, they found diastolic left ventricular pressure to be a determinant of venous waterfall pressure. They speculated that in situations in which left ventricular diastolic pressure exceeded right atrial pressure, the coronary venous waterfall may become the effective downstream pressure, thus reducing the driving pressure for coronary perfusion. During progressive cardiac tamponade in our animal model, mean intrapericardial pressure increased, exceeded, and remained greater than mean right atrial blood pressure (Table 1). The compliant epicardial veins are directly exposed to rising intrapericardial pressures during cardiac tamponade. Thus, the appropriate downstream pressure governing blood flow in the coronary bed may be determined by the increasing intrapericardial pressure. If this statement is true, the effective driving pressure for coronary perfusion during progressive cardiac tamponade would decrease continuously, even before the decline in arterial blood pressure.

An increase in diastolic coronary arterial resistance, even in the presence of maximal vasodilation, would have resulted if the epicardial coronary arteries were compressed by the increase in intrapericardial pressure as Jarmakani et al. have suggested. Prior studies from our laboratory have found no change in mid-diastolic coronary vascular resistance (calculated as the difference between aortic and right atrial blood pressures divided by coronary artery blood flow) during cardiac tamponade in this conscious model and a significantly increased myocardial requirements or impaired coronary vascular resistance might develop myocardial ischemia sufficient to alter the usual hemodynamic progression of cardiac tamponade. In the absence of such factors, our results demonstrate that the deterioration in cardiac function during acute cardiac tamponade in healthy conscious dogs is not caused by myocardial ischemia.

Our findings are inconsistent with the concept that the abrupt increase in coronary artery blood flow associated with rapid removal of pericardial fluid in conscious canine models of cardiac tamponade is reactive hyperemic in nature. It seems more likely that the change is appropriate and reflects a sudden increase in myocardial requirements at that time.

In conclusion, in this chronically instrumented conscious canine model of acute cardiac tamponade, the progressive decline in coronary artery blood flow during cardiac tamponade was appropriate to the decreasing needs of the myocardium. Thus, no evidence was found that myocardial ischemia contributes to the hemodynamic changes associated with acute cardiac tamponade in this otherwise normal conscious animal preparation.

Acknowledgments

The authors wish to acknowledge the technical assistance of Donna M. Siegesmund, B.S. and Dennis J. Janzer, M.S.B.E. We are indebted to Dr. Paul N. Uhlig for his thoughtful review of the manuscript. We wish to thank Jessica Provine for preparing the manuscript and Richard A. Ware, M.S., for analysis of lactate and pyruvate specimens.

References


key Words • coronary artery blood flow • myocardial ischemia
Coronary artery hemodynamics in conscious dog during cardiac tamponade.
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Circ Res. 1987;60:845-849
doi: 10.1161/01.RES.60.6.845

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

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