Mechanism of Attenuated Pressure-Flow Autoregulation in Right Coronary Circulation of Dogs

Shuji Yonekura, Noriyasu Watanabe, James L. Caffrey, John F. Gaugl, and H. Fred Downey

Right coronary autoregulation was assessed in 14 open-chest, anesthetized dogs. In Group 1 (n = 5), the left common and right coronary arteries were cannulated and perfused independently. As coronary perfusion pressures varied simultaneously between 70 and 120 mm Hg, right coronary blood flow changed by 48%, whereas left coronary flow changed by 13%. In this pressure range, the autoregulatory closed-loop gain of the right coronary circulation averaged 0.37 ± 0.01, reflecting a modest autoregulatory capability but significantly less than that of the left coronary circulation, 0.78 ± 0.08. In Group 2 (n = 9), only the right coronary artery was perfused, and right coronary venous blood was collected for determining arteriovenous oxygen extraction. Autoregulatory gain was similar to that of Group 1, indicating that collateral flow associated with intercoronary pressure gradients does not mask right coronary autoregulation. Right ventricular myocardial oxygen consumption varied directly with perfusion pressure, ranging from 7.1 ± 1.0 to 2.9 ± 0.8 ml O₂/min/100 g as pressure was reduced from 160 to 40 mm Hg. Thus, right coronary autoregulation is masked by an opposing change in oxygen demand. When right ventricular oxygen consumption was altered by pacing, a linear flow-oxygen consumption relationship was observed (8.2 ± 0.4 ml/min/100 g per ml O₂/min/100 g). Subtraction of flows associated with pressure-induced changes in metabolism revealed a potential autoregulatory capability of the right coronary circulation similar to that manifested by the left coronary circulation. (Circulation Research 1987;60:133–141)

The intrinsic tendency of an organ to maintain constant blood flow despite changes in arterial perfusion pressure is called autoregulation. Under conditions of stable cardiac function, left coronary blood flow remains relatively constant while coronary perfusion pressure is varied over a wide range. Since the left and right ventricles differ markedly in work performed, oxygen consumption, coronary blood flow, and transmural pressure, differences in autoregulation between the left and right coronary circulations might be expected. The relation between changes in right coronary blood flow and right coronary perfusion pressure has not been specifically investigated, but some data suggest that autoregulation is absent in the right coronary circulation. Murray and Vatner reported that a 34% rise in aortic pressure increased right coronary blood flow 55%. Urabe et al reported a linear decline in right coronary flow as perfusion pressure was reduced from 125 to 25 mm Hg.

Despite recognized differences between the left and right ventricles, it is not apparent why autoregulatory capabilities of the left and right coronary circulations should be strikingly different.

This investigation was conducted to compare simultaneously autoregulation in the canine right and left ventricles. Since right coronary autoregulation was significantly less potent than left coronary autoregulation, additional experiments were conducted to determine the reason for this difference.

Materials and Methods

Fourteen dogs of either sex, weighing 15 to 24 kg, were anesthetized with sodium pentobarbital, 30 mg/kg i.v. initially, and supplemented as needed to maintain stable anesthesia. After tracheotomy, the dogs were ventilated with room air supplemented with oxygen to maintain normal arterial oxygen tension. A vinyl catheter was positioned in the inferior vena cava via a femoral vein for administration of supplementary anesthetic, heparin, and fluids. A second catheter was advanced into the thoracic aorta via a femoral artery to monitor aortic blood pressure. Left ventricular pressure was measured with a Millar catheter-tip pressure transducer introduced through an incision in the left atrial appendage and advanced across the mitral valve. Right ventricular pressure was measured with a second Millar catheter-tip transducer inserted via the left jugular vein and across the tricuspid valve. The right ven-
tricular pressure signal was differentiated electronically, and the positive derivative dP/dt was recorded. The animals were then prepared to evaluate both left and right coronary autoregulation simultaneously (Group 1), or right coronary autoregulation and right ventricular oxygen consumption (Group 2). When all surgical procedures were completed, heparin (500 U/kg) was administered intravenously to prevent blood coagulation.

In Group 1, 5 of the 14 dogs, a thoracotomy was performed in the fifth left intercostal space, and the fourth rib was removed. The proximal left common and right coronary arteries were dissected and freed, and loose ligatures placed under them. It was possible to isolate the right coronary artery through the left thoracotomy by gently retracting the right ventricle.

A modified Gregg stainless steel cannula (4.9 mm o.d., 3.0 mm i.d.) was introduced via the left subclavian artery into the left common coronary artery and secured with the previously positioned ligature. The left coronary circulation was perfused with oxygenated blood from a pressurized reservoir that was supplied with blood from a femoral artery by a roller pump. The right coronary artery was cannulated just distal to its origin and a loose ligature was placed under it. The right coronary circulation was independently perfused with arterial blood from a second, controlled pressure system. Left and right coronary arterial pressures were sensed at the tip of each perfusion cannula through small-bore, fluid-filled catheters within the perfusion cannulas. All fluid-filled catheters were connected to Statham P23Db pressure transducers. Blood flows in the left and right coronary perfusion lines were measured electromagnetically with FM501 flowmeters and EP612 cannulating flow transducers (Carolina Medical Electronics Inc., King, N.C.). Pressure and flow signals were recorded on a Beckman R611 eight-channel polygraph. A schematic diagram of the left and right coronary perfusion systems is shown in Figure 1.

In Group 2, 9 of the 14 dogs, the heart was exposed through a thoracotomy in the fourth right intercostal space. The right coronary artery was dissected and freed at its origin and a loose ligature placed under it. An anterior right coronary superficial vein was also isolated. After heparinization, the right coronary artery was cannulated and perfused with a controlled pressure system similar to the right coronary portion of the system used in Group 1 experiments. In 7 dogs, the right coronary vein was successfully cannulated with PE-50 tubing and allowed to drain continuously into a beaker. The coronary venous blood was returned intermittently to the animal through a femoral vein cannula.

At each coronary blood flow determination within the projected autoregulatory range and at selected pressures above and below this range, samples of right coronary arterial and venous blood were collected anaerobically for determination of right coronary arteriovenous oxygen content differences. Arterial and venous Po2, Pco2, and pH were measured with an Instrumentation Laboratory blood gas analyzer and oxygen content was determined with a LEX-O2-CON.

Oxygen consumption for the right ventricle was computed from the Fick equation:

\[ \text{MV}O_2 = \text{MBF} \times (\text{Cao}_2 - \text{Cvo}_2), \]

where \( \text{MV}O_2 \) is myocardial oxygen consumption (ml O2/min/100 g), \( \text{MBF} \) is myocardial blood flow (ml/min/100 g), \( \text{Cao}_2 - \text{Cvo}_2 \) is the right coronary arteriovenous oxygen content difference (ml O2/100 ml blood).

India ink was infused into the right coronary artery at the end of each experiment (Groups 1 and 2) to define the portion of the right ventricular wall perfused by this artery. In Group 2 experiments, India ink was
Experimental Protocols

Group 1. Left and right coronary perfusion pressures were simultaneously decreased in 10 mm Hg steps from 160 to 40 mm Hg. At each step, steady-state coronary blood flows and other hemodynamic parameters were recorded.

Group 2. Right coronary perfusion pressure was reduced in 10 mm Hg steps from 160 to 40 mm Hg with recordings of coronary blood flow and other hemodynamic parameters as in Group 1. Samples of arterial blood from the perfusion line and of right coronary venous blood were collected as described above for determining the right coronary arteriovenous difference in oxygen content.

In 4 dogs, right ventricular myocardial oxygen consumption was also measured while myocardial metabolic activity was altered by atrial pacing after autoregulation had been evaluated. After the sinoatrial node was crushed, the hearts were paced at rates from 87 to 214 beats/min while right coronary perfusion pressure was held constant at 100 mm Hg.

To ascertain that blood collected from the superficial right coronary vein was not contaminated with blood from the left coronary circulation, Evans blue dye was administered systemically to 3 dogs during perfusion of the right coronary artery with blood from the isolated, dye-free reservoir. The concentration of Evans blue dye in blood collected from the right coronary venous catheter was less than 3% of that observed in coincident samples of systemic arterial blood.

Quantitation of Autoregulation

The autoregulatory capabilities of the right and left coronary circulations at each perfusion pressure were expressed as the autoregulatory closed-loop gain, Gc:

\[ Gc = 1 - \left( \frac{[\Delta F/F]}{[\Delta P/P]} \right) \]

\( \Delta F \) is the change in coronary blood flow observed when coronary perfusion pressure is changed by \( \Delta P \). F is the flow observed at pressure P prior to the change in perfusion pressure. Values of Gc between 0–1 indicate partial autoregulation and reach a maximum value of 1 if flows stays constant despite changes in perfusion pressure.

Statistical Analyses

Data are reported as means ± standard errors of the mean (SE). Differences between observations made at different perfusion pressures within groups were tested with an analysis of variance, randomized complete block design (ANOVA), and the Student-Newman-Keuls procedure. Group means that did not differ by ANOVA were subjected to linear regression analysis to determine if the means varied systematically as a function of coronary perfusion pressure. Comparisons of autoregulatory gains at corresponding perfusion pressures between left (Group 1) and right coronary (Groups 1 and 2) circulations were tested with the Student's t test for unpaired data. The relation between pressure and flow in the autoregulatory range and between flow and myocardial oxygen consumption of paced hearts was determined by linear regression analysis. The autoregulatory slopes of the right and left coronary circulations were compared by analysis of covariance. These statistical procedures have been described by Zar. Differences were regarded as statistically significant at \( p < 0.05 \) unless otherwise stated.

Results

Group 1. Left and right coronary perfusion pressures were altered simultaneously to evaluate pressure-flow autoregulation without producing pressure gradients between left and right coronary circulations. Systemic arterial blood was analyzed frequently to ensure that blood gas values of the coronary perfusate remained physiological (\( \text{PO}_2 = 119.1 ± 12.8 \text{ mm Hg}, \text{PCO}_2 = 28.3 ± 2.7 \text{ mm Hg}, \text{pH} = 7.42 ± 0.01 \)). Figure 2 shows a typical tracing of hemodynamic parameters as right and left coronary perfusion pressures were decreased from 160 to 40 mm Hg. Mean aortic blood pressure, right ventricular peak systolic and end-diastolic pressure, right ventricular \( \text{dP/dt}_{\text{max}} \), and heart rate were determined for each coronary perfusion pressure. The effects of changes in coronary perfusion pressure on these parameters were examined by ANOVA and linear regression analyses. Since these parameters were generally stable as coronary perfusion pressure was varied, only values observed at 100 mm Hg are presented in Table 1. Heart rate and right ventricular peak systolic pressure were unaffected by changes in coronary perfusion pressure. Mean values of right ventricular \( \text{dP/dt}_{\text{max}} \) for each perfusion pressure were not significantly different by ANOVA, but linear regression analysis detected a small but significant overall decline as coronary perfusion was lowered.

Average values of mean aortic pressure were similar for coronary perfusion pressures from 160 to 50 mm Hg but fell significantly at 40 mm Hg. Likewise, right ventricular end-diastolic pressure was constant for coronary perfusion pressures from 160 to 50 mm Hg but increased significantly at 40 mm Hg.

Right and left coronary blood flows are plotted as functions of coronary perfusion pressure in Figure 3. For the left coronary circulation, effective autoregulation was evident between coronary perfusion pressures of 120 and 70 mm Hg. For the right coronary circulation, autoregulation was much less pronounced, with mild inflections at 130 and 50 mm Hg. The slope of the pressure-flow relationship for the right coronary circulation between 130 and 50 mm Hg was 0.39 ± 0.05 ml/min/100 g/mm Hg. This was significantly greater than the slope of the left coronary relation between 120 and 70 mm Hg, 0.12 ± 0.04 ml/min/100 g/mm Hg.

Closed-loop gains for left coronary autoregulation were significantly greater than 0 between perfusion
pressures of 120 and 70 mm Hg (Figure 4). In this pressure range, left coronary Gc averaged 0.78 ± 0.08 and reached its maximum value of 0.92 ± 0.04 between 100 and 90 mm Hg. Right coronary Gc's were significantly greater than zero between perfusion pressures of 110 and 80 mm Hg. In this pressure range, right coronary Gc averaged 0.37 ± 0.01, 47% of the average positive left coronary Gc (p < 0.01).

**Group 2.** Blood gas measurements of the right coronary arterial perfusate, mean aortic blood pressure, right ventricular peak systolic and end-diastolic pressures, right ventricular dP/dt\(_{max}\), and heart rate were determined for each coronary perfusion pressure. Mean values of these measurements were examined by ANOVA and by linear regression analysis to evaluate their stability during changes in right coronary perfusion pressure. These parameters were generally stable, as in Group 1, so that only values at 100 mm Hg perfusion pressure are presented in Table 1. Mean aortic blood pressure, heart rate, coronary perfusate Po\(_2\), oxygen content, Pco\(_2\), and pH remained constant throughout the experiments. As right coronary perfusion pressure was reduced from 160 to 40 mm Hg, right ventricular peak systolic pressure and right ventricular dP/dt\(_{max}\) decreased and right ventricular end-diastolic pressure increased. These changes were small but significant by linear regression analysis (Table 1).

Right coronary blood flow as a function of right coronary perfusion pressure is presented in Table 2. This relation was similar to that observed in the right coronary circulations of Group 1 (Figure 3). Likewise, Gc's for the right coronary circulations of Group 2 were similar to those computed for the right coronary circulations of Group 1. Thus, average values of right coronary Gc's for each pressure change were computed for all 14 dogs (Groups 1 and 2) and are plotted in Figure 4 along with the left coronary Gc's of Group 1. The autoregulatory gain curves of the two coronary circulations have similar shapes, but right coronary Gc's are significantly less than left coronary Gc's, ranging from 120–70 mm Hg.

Coronary venous blood was successfully collected from the right coronary perfusion field in 7 of the dogs of Group 2. Venous blood gas values for each perfusion pressure are presented in Table 3. Coronary venous Po\(_2\) decreased significantly from 33.8 ± 3.6 mm Hg at a right coronary perfusion pressure of 160 mm Hg to 20.8 ± 2.0 mm Hg at a right coronary pressure of 40 mm Hg. Over this range of perfusion pressures, coronary venous oxygen content decreased from 9.2 ± 1.3 to 4.7 ± 0.7 ml O\(_2\)/100 ml blood, right coronary venous Pco\(_2\) increased significantly from 35.8 ± 2.3 to 40.7 ± 3.1 mm Hg, and coronary venous pH decreased significantly from 7.37 ± 0.01 to 7.33 ± 0.03. From the right coronary arteriovenous differences in oxygen content, right ventricular oxy-
oxygen extractions and consumptions were computed at each perfusion pressure (Table 3). Right ventricular oxygen extraction increased significantly from 7.7 ± 1.0 to 12.3 ± 0.8 ml O₂/100 ml blood as coronary perfusion pressure was reduced from 160 to 40 mm Hg, and right ventricular myocardial oxygen consumption fell significantly from 7.1 ± 1.0 to 2.9 ± 0.8 ml O₂/min/100 g. Right ventricular myocardial oxygen extraction and consumption changed continuously as perfusion pressure was varied, but the largest changes were observed at both extremes of perfusion pressure. They were more constant over the range of perfusion pressures where significant right coronary autoregulation was evident.

In 4 of the animals, right ventricular myocardial oxygen demand was altered by atrial pacing at a constant coronary perfusion pressure. The resulting relation between coronary flow and right ventricular oxygen consumption was determined by linear regression analysis for each dog. The linear fit was significant for each animal. The slopes of these relations ranged from 7.1–8.7 and averaged 8.2 ± 0.4 ml/min/100 g per ml O₂/min/100 g.

After determining the relation between right coronary blood flow and right ventricular myocardial oxygen consumption in paced hearts, the portion of coronary blood flow due to pressure-induced changes in right ventricular myocardial oxygen consumption in the autoregulation experiments was estimated. This approach is illustrated in Figure 5. Taking 100 mm Hg as the baseline condition, the flow change due to altered metabolism is shown by the dashed straight line derived from regression analysis of the pacing experiments. The curved line illustrates the right coronary blood flows now plotted vs. right ventricular myocardial oxygen consumptions for the Group 2 autoregulation experiments. The shaded area between the two curves represents the flow deficit or excess due to imperfect autoregulation. For each flow determination at a right coronary perfusion pressure different from 100 mm Hg, the change in right ventricular myocardial oxygen consumption was noted (Table 3). The difference in blood flow associated with this change in metabolism independent of pressure-flow autoregulation was determined by utilizing the relation between flow and myocardial oxygen consumption in paced hearts (Figure 5). This change in flow due selectively to altered metabolism was subtracted algebraically from the observed flow caused by altered perfusion pressure. In this manner, a “corrected” flow was computed for each right coronary perfusion pressure below and above 100 mm Hg. The corrected flows are plotted in Figure 6, where a pronounced regulatory plateau from 50–90 mm Hg is now evident. Autoregulatory closed-loop gains computed from these corrected flows are also illustrated in Figure 6. After changes in flow associated with pressure-induced changes in metabolism were taken into account, the maximum potential autoregulatory gain of the right coronary circulation was similar to that observed in the left coronary circulation.
Discussion

There were four important findings in this study: 1) Pressure-flow autoregulation is significantly less potent in the right coronary circulation than in the left coronary circulation. 2) Right coronary autoregulation is not masked by collateral flow between the right and left coronary circulations. 3) Right ventricular oxygen consumption rises with right coronary perfusion pressure, and, thus, right coronary autoregulation is masked by vascular adjustments required to balance oxygen supply with altered demand, i.e., metabolic regulation. 4) When changes in flow are corrected for pressure-induced changes in metabolism, the potential autoregulatory capability estimated for the right coronary circulation is similar to that observed in the left coronary circulation.

This investigation was prompted by the recent studies of Murray and Vatner and Urabe et al. Although neither group specifically assessed right coronary autoregulation, measurements of right coronary flow were reported as right coronary perfusion pressure was altered. Murray and Vatner found that a 34% increase in mean aortic pressure due to aortic constriction in normal conscious dogs was accompanied by a 55% increase in right coronary blood flow. Urabe et al examined right ventricular performance during coro-

Table 2. Right Coronary Blood Flows and Autoregulatory Closed-loop Gains (Gc) of Group 2

<table>
<thead>
<tr>
<th>Perfusion pressure (mm Hg)</th>
<th>Flow (ml/min/g)</th>
<th>Gc</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>0.96 ± 0.05</td>
<td>-0.46 ± 0.16</td>
</tr>
<tr>
<td>150</td>
<td>0.87 ± 0.04</td>
<td>-0.36 ± 0.14</td>
</tr>
<tr>
<td>140</td>
<td>0.79 ± 0.03</td>
<td>-0.58 ± 0.22</td>
</tr>
<tr>
<td>130</td>
<td>0.70 ± 0.03</td>
<td>-0.13 ± 0.16</td>
</tr>
<tr>
<td>120</td>
<td>0.64 ± 0.03</td>
<td>0.05 ± 0.13</td>
</tr>
<tr>
<td>110</td>
<td>0.59 ± 0.03</td>
<td>0.40 ± 0.07*</td>
</tr>
<tr>
<td>100</td>
<td>0.56 ± 0.03</td>
<td>0.38 ± 0.09*</td>
</tr>
<tr>
<td>90</td>
<td>0.52 ± 0.03</td>
<td>0.11 ± 0.18</td>
</tr>
<tr>
<td>80</td>
<td>0.48 ± 0.04</td>
<td>0.15 ± 0.16</td>
</tr>
<tr>
<td>70</td>
<td>0.43 ± 0.04</td>
<td>0.02 ± 0.21</td>
</tr>
<tr>
<td>60</td>
<td>0.38 ± 0.04</td>
<td>-0.03 ± 0.24</td>
</tr>
<tr>
<td>50</td>
<td>0.32 ± 0.05</td>
<td>-0.17 ± 0.17</td>
</tr>
<tr>
<td>40</td>
<td>0.26 ± 0.05</td>
<td></td>
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</table>

Values are means ± SE, n = 9.

*Greater than zero, p < 0.05.
Table 3. Coronary Venous Blood Gas Values, Right Ventricular Oxygen Extraction, and Right Ventricular Myocardial Oxygen Consumption in Seven Dogs of Group 2

<table>
<thead>
<tr>
<th>Perfusion pressure (mm Hg)</th>
<th>P_{VO_2} (mm Hg)</th>
<th>C_{VO_2} (ml/100 ml)</th>
<th>P_{CO_2} (mm Hg)</th>
<th>pH</th>
<th>C_{aO_2} - C_{vO_2} (ml O_2/100 ml)</th>
<th>Myocardial oxygen consumption (ml O_2/min/100 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>33.8±3.6</td>
<td>9.17±1.25</td>
<td>35.8±2.3</td>
<td>7.37±0.01</td>
<td>7.71±0.98</td>
<td>7.06±0.95</td>
</tr>
<tr>
<td>140</td>
<td>32.6±3.1</td>
<td>8.75±1.18</td>
<td>37.4±1.6</td>
<td>7.35±0.01</td>
<td>8.51±1.17</td>
<td>6.52±0.95</td>
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<tr>
<td>120</td>
<td>28.4±3.3</td>
<td>7.76±1.05</td>
<td>38.3±1.8</td>
<td>7.37±0.02</td>
<td>9.30±1.17</td>
<td>5.79±0.88</td>
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<tr>
<td>110</td>
<td>27.9±3.1</td>
<td>7.31±1.09</td>
<td>38.4±1.4</td>
<td>7.36±0.03</td>
<td>9.60±1.05</td>
<td>5.50±0.81</td>
</tr>
<tr>
<td>100</td>
<td>26.7±2.6</td>
<td>7.09±1.01</td>
<td>38.4±1.8</td>
<td>7.35±0.02</td>
<td>9.86±1.17</td>
<td>5.33±0.83</td>
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<tr>
<td>90</td>
<td>27.7±2.1</td>
<td>6.79±0.81</td>
<td>36.6±2.0</td>
<td>7.36±0.02</td>
<td>10.44±1.07</td>
<td>5.25±0.79</td>
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<tr>
<td>80</td>
<td>25.4±2.0</td>
<td>6.29±0.52</td>
<td>38.2±2.1</td>
<td>7.32±0.00</td>
<td>10.77±0.95</td>
<td>4.89±0.78</td>
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<tr>
<td>70</td>
<td>25.4±1.6</td>
<td>6.39±0.90</td>
<td>37.3±2.4</td>
<td>7.32±0.03</td>
<td>10.97±0.78</td>
<td>4.33±0.75</td>
</tr>
<tr>
<td>60</td>
<td>23.4±1.5</td>
<td>5.89±0.97</td>
<td>39.5±2.4</td>
<td>7.34±0.03</td>
<td>11.21±0.87</td>
<td>3.93±0.75</td>
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<tr>
<td>40</td>
<td>20.8±2.0</td>
<td>4.74±0.66</td>
<td>40.7±3.1</td>
<td>7.33±0.03</td>
<td>12.29±0.80</td>
<td>2.88±0.77</td>
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</table>

Linear regression analysis

<table>
<thead>
<tr>
<th>Intercept</th>
<th>Slope*</th>
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<tbody>
<tr>
<td>17.2</td>
<td>0.10†</td>
</tr>
<tr>
<td>3.57</td>
<td>0.036†</td>
</tr>
<tr>
<td>40.7</td>
<td>−0.027†</td>
</tr>
<tr>
<td>7.31</td>
<td>0.0004†</td>
</tr>
<tr>
<td>13.6</td>
<td>−0.037†</td>
</tr>
<tr>
<td>1.97</td>
<td>0.033†</td>
</tr>
</tbody>
</table>

Values are means ± SE.

C_{aO_2} and C_{vO_2} are coronary arterial and venous oxygen contents, respectively.

*Slope units are parameter units/mm Hg.

†Different from zero, p < 0.05.

Cardiovascular autoregulation in anesthetized dogs. At normal and reduced right coronary perfusion pressures, right coronary blood flow correlated linearly with pressure, although the slope of this relation was decreased slightly at higher pressures. The apparent absence of effective autoregulation in the right coronary circulation contrasts markedly with the potent autoregulation found in the left coronary circulation.

Autoregulation of flow measured in individual arteries can be masked by collateral flow if pressure gradients exist between adjacent perfusion fields. This phenomenon might have obscured autoregulation to some degree in the study of Urabe et al. but not in the study of Murray and Vatner since the latter group increased both left and right coronary perfusion pressures simultaneously by aortic constriction. Likewise, we observed blunted right coronary autoregulation in Group I with no pressure gradients between the right

![Figure 5](http://circres.ahajournals.org/)

**Figure 5.** Changes in right coronary flow associated with pacing (dashed line) and pressure-induced (solid line) changes in myocardial oxygen consumption. Shaded area between the two curves represents the flow changes due to pressure-induced changes in right ventricular metabolism. RCPP = right coronary perfusion pressure.
and left coronary circulations. Also arguing against an important role for collateral flow in masking right coronary autoregulation is the finding of Scheel et al\textsuperscript{12} that collateral flow between the right and left coronary perfusion fields was less than 3\% of right coronary blood flow. Thus, it is not surprising that similar values were found for right coronary autoregulatory gains in Group 1, with no pressure gradients between left and right coronary circulations, and in Group 2, with pressure gradients between left and right coronary circulations. These findings also agree with the earlier observation that autoregulation in the left coronary circulation is not affected by pressure gradients between major vessels.\textsuperscript{13}

Implicit in the definition of autoregulation is the assumption that changes in arterial perfusion pressure do not produce changes in organ metabolism. In the left ventricle of the working heart, pressure-induced increases in myocardial oxygen consumption do not compromise autoregulation below 125 mm Hg,\textsuperscript{14} but in isolated, nonworking hearts, this effect is evident at lower pressures.\textsuperscript{15} A coherent explanation for increased myocardial oxygen consumption at elevated perfusion pressures is that coronary distension alters cardiac fiber length.\textsuperscript{16} Reports of prior investigations of this phenomenon in the right coronary circulation are lacking, probably due to difficulty in collecting right ventricular venous blood for determination of right ventricular myocardial oxygen consumption. We were successful in cannulating superficial veins on the right ventricular free wall to accomplish this purpose. Absence of dye in this venous blood following selective administration of dye to the left coronary circulation confirmed that these veins drained myocardium perfused by the right coronary artery.

Right ventricular oxygen consumption of the preparation used in this study perfused at 100 mm Hg was similar to that reported by others,\textsuperscript{17,18} but, in addition, we found that right ventricular myocardial oxygen consumption varied directly with right coronary perfusion pressure (Table 3). Thus, for the right coronary circulation, the autoregulatory prerequisite of constant metabolic activity was absent over the entire range of pressures (40–160 mm Hg) examined in this study. Metabolically coupled regulation of right coronary blood flow has previously been described,\textsuperscript{19} so changes in oxygen consumption caused by changes in coronary perfusion pressure would be expected to alter right coronary blood flow. These changes in flow would counteract any autoregulatory mechanism for holding flow constant. Thus, this difference in metabolic sensitivity to changes in coronary perfusion pressure could account for the difference in autoregulatory capabilities of the right and left coronary circulations. The greater sensitivity of right ventricular myocardial oxygen consumption to altered perfusion pressure probably results from more readily distensible vessels exposed to lesser intramural pressures in the right ventricular free wall.\textsuperscript{6} Furthermore, the pressure-induced increase in oxygen demand may be more readily apparent in the right ventricle because of its lower baseline oxygen consumption.

With knowledge of the relation between metabolically induced changes in right coronary blood flow and right ventricular myocardial oxygen consumption, it should be possible to correct the pressure-induced changes in coronary blood flow for the component of flow due to metabolic regulation. Although this relation has been well characterized for the left ventricle,\textsuperscript{19} it was not available for the right ventricle. Therefore, we measured right coronary blood flow and right ventricular oxygen consumption at constant perfusion pressure while metabolic demand for oxygen was varied by altering heart rate.
We found a linear relation between right coronary blood flow and right ventricular oxygen consumption (Figure 5), and the slope of this relation was similar to that described for the left ventricle. As expected, we found that changes in right coronary flow induced by altered metabolism associated with altered perfusion pressure exceeded those caused by altered metabolism at constant pressure (Figure 5). Subtraction of the metabolically induced change in flow at each right coronary perfusion pressure revealed the residual flow due to imperfect pressure-flow autoregulation. These corrected flows were then subjected to closed-loop gain analysis, and the gains were compared with those observed in the left coronary circulation. By this approach, it was observed that the potential for autoregulation of the right coronary circulation was similar to that of the left coronary circulation, although the peak autoregulatory gain for the right circulation occurred at lower perfusion pressures. This finding is consistent with the fact that right coronary blood flow is only 40 to 60% of that observed in the left coronary circulation. Since the vascular resistance of the right coronary circulation normally exceeds that of the left coronary circulation, less vasoconstrictor reserve is available for autoregulation of right coronary blood flow. Thus, it is not surprising that the potential peak autoregulatory capability of the right coronary circulation is expressed at lower perfusion pressures.

Acknowledgments

We are grateful for the expert technical assistance of Arthur G. Williams and Wendi M. Randall, and for the excellent secretarial assistance of Betty L. Elliott.

Dr. William P. Dole, University of Iowa, suggested the approach for correcting the pressure-flow relation for pressure-induced changes in metabolism.

References


Key Words • autoregulation • right coronary circulation • myocardial oxygen consumption • metabolic regulation
Mechanism of attenuated pressure-flow autoregulation in right coronary circulation of dogs.
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Circ Res. 1987;60:133-141
doi: 10.1161/01.RES.60.1.133

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