Effect of Alterations of Coronary Blood Flow on the Oxygen Consumption of the Working Heart

By John Ross, Jr., M.D., Francis Klocke, M.D., Gerard Kaiser, M.D., and Eugene Braunwald, M.D.

The finding that the oxygen consumption of the empty, nonworking heart could be influenced by the rate of coronary blood flow was at variance with the concept that myocardial oxygen consumption is determined primarily by the mechanical activity of the heart. Furthermore, the results of these studies in the nonworking heart were not in accord with the preliminary results of experiments in the isolated supported heart made available to us by Dr. S. J. Sarnoff. The latter experiments suggested that, in the heart performing external work at a constant level, the myocardial oxygen consumption was not altered by variations in coronary blood flow. These considerations made it interesting to study the effects of altering coronary blood flow on the oxygen consumption of the working heart, utilizing a preparation similar to that which had been employed to study the heart which performed no external work.

Methods

The basic experimental plan consisted of retroperfusion of the coronary circulation of a dog maintained on total cardiopulmonary bypass, while a constant level of work was performed by the left ventricle (fig. 1). The methods employed for inducing anesthesia and for instituting cardiopulmonary bypass have been described. The experimental dogs weighed between 13.6 and 20.5 kg, and averaged 16.5 kg. Both vagus nerves were sectioned in the neck. The thoracic aorta was occluded distal to the left subelavian artery, the brachiocephalic artery was ligated, and the head was perfused through the cannulated distal end of this vessel from the arterial line of the pump oxygenator. The coronary arterial bed was perfused with oxygenated blood through the cannulated left subelavian artery by means of a Simmamotor pump. The pulmonary artery was ligated and the coronary venous return was collected by means of a large-bore cannula placed into the right ventricle; this chamber was thus maintained in a collapsed state. The left atrium was cannulated and perfused at a constant rate with oxygenated blood from the arterial line of the pump oxygenator. The blood perfusing the left atrium passed into the left ventricle and was ejected through a large-bore cannula containing a ball valve; the cannula was introduced through the ventricular apex. Resistance to left ventricular outflow was regulated by varying the height of the distal orifice of the tubing attached to this cannula. The heart rate was controlled by means of an electrical pacemaker attached to the right atrium. During each experiment the left ventricular output, left ventricular systolic pressure, and heart rate were maintained at a constant level; the heart rates ranged from 98 to 185 beats per minute and varied by no more than seven beats per minute during any experiment.

Coronary venous return was continuously recorded gravimetrically by means of a pressure transducer attached to a graduated cylinder. The oxygen contents of arterial and coronary venous blood were determined in duplicate by the method of Van Slyke and Neill, and myocardial oxygen consumption ($\dot{M}V_{\text{O}_2}$) was calculated as the product of the coronary blood flow and the coronary arteriovenous oxygen difference. Pressure was measured in the aortic root by means of a catheter introduced through the brachiocephalic artery and left ventricular pressure was measured by means of a catheter inserted through the ventricular wall. The temperature of the blood perfusing the coronary circulation was maintained constant by means of a heat exchanger in the perfusion line. The hematocrit values ranged from 36 to 45 and averaged 40.

Coronary blood flow was varied by changing the output of the pump perfusing the coronary circulation. The direction of change in coronary blood flow was randomized. Prior to each measurement...
OXYGEN CONSUMPTION OF WORKING HEART

Hemodynamic Observations and Myocardial Oxygen Consumption following Alterations in Coronary Blood Flow in the Working Heart

<table>
<thead>
<tr>
<th>Expt. no.</th>
<th>Heart weight g</th>
<th>Determination no.</th>
<th>Art. O₂ content vol %</th>
<th>Ven. O₂ content vol %</th>
<th>(A-V)O₂ diff.</th>
<th>Cor. blood flow ml/min</th>
<th>MV_sm VOL</th>
<th>O₂ extraction %</th>
<th>Cor. perf. pressure (mean) mm Hg</th>
<th>LV pressure syst./diast. mm Hg</th>
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Note: Determinations in each experiment were performed in the order indicated.
Art. = arterial; Ven. = venous; (A-V) = arteriovenous; Cor. perf. pressure = coronary perfusion pressure; LV = left ventricular; Syst. = systolic; Diast. = diastolic; MV_sm = myocardial oxygen consumption.

of oxygen consumption, the coronary blood flow was maintained at the new level for a period of 7 to 15 minutes in order to insure a steady state.

**Results**

In the ten experiments, the effect of a change of coronary blood flow on MV_sm could be determined in a total of 23 instances (table 1). In general, alterations of coronary blood flow did not result in any consistent changes of MV_sm (fig. 2). In 21 of 23 instances, the values for MV_sm at the two levels of coronary blood flow differed from one another by less than 1.0 ml O₂/min. In 14 of these 21 instances the MV_sm was higher at the higher level of coronary blood flow, while in seven instances the MV_sm was lower at the higher...
Diagrammatic illustration of the preparation employed. R.A. = right atrium. R.V. = right ventricle. L.A. = left atrium. L.V. = left ventricle. I.V.C. = inferior vena cava. P.A. = pulmonary artery. Tp P.T. indicates the lines to the pressure transducer. The arrow at the lower left indicates the return of blood from the vena cava (V.C.) to the oxygenator, from which it is pumped to the femoral artery (F.A.), brachiocephalic artery (B.C.A.), and left atrium (L.A.).

level of coronary blood flow. In the two instances in which the values for \( \text{MV}_0^2 \) differed from one another by more than 1.0 ml O\textsubscript{2}/min, the \( \text{MV}_0^2 \) was higher at the higher level of coronary blood flow.

**Discussion**

The preparation employed for the experiments described herein was similar to that utilized to study the effects of coronary blood flow on the \( \text{MV}_0^2 \) of the empty heart which performed no external work.\(^1\) In both preparations, the coronary blood flow was controlled and varied by means of a pump which perfused the aortic root. The fundamental difference between the two preparations was that in the empty heart a drainage cannula prevented the left ventricle from developing pressure during systole, while in the present investigation the left ventricle was permitted to develop a constant level of pressure during systole. A composite graph of the results obtained in the two series of experiments is reproduced in figure 3. It is evident that in the working heart the lowest values of coronary blood flow were, in general, higher than the lowest values in the nonworking heart.
it was not possible to lower coronary blood flow to extremely low levels in the working heart since under these circumstances the aortic valve opened, permitting the left ventricle to eject into the aorta and thereby to contribute to coronary perfusion.

It is also apparent from figure 3 that in the working heart, the rate of coronary blood flow had no apparent influence on the $\dot{M}V_{0}$, while in the nonworking heart $\dot{M}V_{0}$ and coronary blood flow varied in the same direction. However, it may be noted that at comparable levels of coronary blood flow, the differences between the two groups of experiments are less obvious; at the higher levels of coronary blood flow achieved in the nonworking heart the influence of coronary blood on $\dot{M}V_{0}$ was appreciably less than at lower levels of coronary blood flow. While it seems possible that when coronary blood flow is markedly restricted, changes in flow may play an important role in determining $\dot{M}V_{0}$, the observations in the present experiments are consistent with the view that when the left ventricle is permitted to develop pressure and to expel blood, $\dot{M}V_{0}$ cannot be altered by variations in coronary blood flow.

Summary

The effects of varying coronary blood flow on the $\dot{M}V_{0}$ of a heart permitted to perform external work at a constant level were determined in 10 experiments. No consistent changes of $\dot{M}V_{0}$ occurred with alterations of coronary blood flow. These results were in contrast with those previously obtained when coronary blood flow was altered in a heart which performed no external work.

References


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