Effects of Heart Rate on Coronary Flow and Cardiac Oxygen Consumption

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ABSTRACT
The effects of electrically-induced heart rate (up to 300 beats/min.) on coronary flow and cardiac oxygen consumption has been studied in an open-chested intact preparation. A significant correlation between heart rate, coronary flow and cardiac oxygen consumption has been found at each level of cardiac work. Coronary flow and cardiac oxygen consumption increase with a rise in heart rate and seem to approach a limit at extremely rapid heart rates. Nomograms relating heart rate, work and oxygen consumption of the heart have been constructed. From these it is seen that heart rate is an important factor in determining the myocardial oxygen consumption; this is true at each level of cardiac work. The significance of these findings have been discussed relative to the unanesthetized animal. Under conditions of excessive heart rate or cardiac load which presumably lead to unusually high energy requirements, a radical departure from the expected 'normal' values was found in coronary flow, coronary A-V oxygen difference and cardiac oxygen consumption. This confirms the presence of 'spontaneous' change previously described by us. Its meaning and significance is discussed. Under these conditions of 'spontaneous' change coronary flow was increased, oxygen consumption decreased and coronary venous oxygen was raised as the coronary A-V oxygen difference declined. This 'spontaneous' change shifted the relationship of coronary flow to oxygen consumption. Furthermore, it led to a rise in coronary flow despite an elevation in coronary venous oxygen. It would seem that at this time the energy metabolism of the heart must change in that less oxygen is extracted from the blood despite an increase in its availability. The heart may therefore operate anaerobically in part or may make use of other hydrogen acceptors in the blood. The fact that this kind of metabolism may last as long as an hour or more, excludes the ordinary type of 'oxygen debt.'

The influence of arterial blood pressure and cardiac output on coronary flow and cardiac gaseous metabolism, and the interrelation between the latter two, have been studied recently in this department (1-3). The present study deals with the changes in coronary flow and cardiac oxygen consumption induced by changes in heart rate. No clear relationship of coronary flow to heart rate has emerged from the literature. This may be a result of the differences in physiological preparations employed to measure coronary flow (4-6) and the different methods used to obtain cardiac rate variations (7-11). In the heart-lung preparation oxygen consumption (12)

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coronary flow and heart rate (zapper curve), and between
needle electrode was inserted into the upper part of
such that a square-wave impulse of 20-msec. duration
to study the effect of heart rate on cardiac
metabolism independently of these two deter-
2 Artificial pacemaker was designed and constructed
by Mr. M. Tausig of the Dept. of Developmental
Engineering, Michael Reese Hospital. Details of the
pacemaker are being published in the J. Lab. & Clin.
Med.

curves were obtained with a catheter inserted into the
ventricle by way of the left auricular appendage. In
order to closely approximate the normal resistance of
the pulmonary tree, a variable Starling resistance was
introduced between the outflow of the right ventricle
and the coronary flowmeter, which by itself offers little
resistance to flow. This pressure was recorded with a
needle inserted into the inflow arm of the flowmeter
and designated as ‘pulmonary arterial pressure.’
Ordinary limb and aV limb leads were recorded and
used to check the induced heart rates. The dog was
kept in a steady state with regard to heart rate, arterial
pressures and coronary flow for 10-15 minutes before
simultaneous arterial and coronary venous blood sam-
3 Ten mongrel dogs, ranging in weight from 13.0-17.7
kg, anesthetized with sodium pentobarbital (30 mg/kg)
were used in these experiments. The coronary flow was
measured by the method previously described (16, 3)
and expressed in cc/min/100 gm of heart weight (HW).

METHODS

Ten mongrel dogs, ranging in weight from 13.0-17.7
kg, anesthetized with sodium pentobarbital (30 mg/kg)
were used in these experiments. The coronary flow was
measured by the method previously described (16, 3)
and expressed in cc/min/100 gm of heart weight (HW).
Variations in heart rate were induced by sino-auricular
or auricular stimulation. Platinum wire electrodes
attached to a curved hemostat were used. After making
a small slit in the pericardium these electrodes were
clamped with slight tension to the area of junction
between the superior vena cava and the right auricle.

The characteristics of the artificial pacemaker1 were
such that a square-wave impulse of 20-msec. duration
could be delivered at any desired frequency. The
voltages and milliamperages as delivered varied from
8-10 and 1-2, respectively, but were kept constant
during each experiment. In one experiment a stimulat-
ing needle electrode was inserted into the upper part of
the interventricular septum and an indifferent needle
electrode was inserted into the hind leg of the animal;
however, the results of the stimulation were similar
and the data of this experiment were used.

Pressures and electrocardiograms were recorded on a
Sanborn twin-viso direct writer. Aortic blood pressures
were obtained with a catheter inserted into the carotid
artery. In some instances left ventricular pressure

4 The hematocrits in these experiments were within
the normal range in all animals and did not vary by
more than 10% in any given experiment. The arterial
O₂ saturations rarely fell below 90%, and when it
did the corresponding data were discarded.

In each experiment two, and sometimes three,
levels of cardiac output were used, varying between
300 and 1600 cc/min. The cardiac output was ad-
justed by altering the speed of the pump delivering
blood through the lungs to the left heart. The aortic
pressure was kept constant in each experiment by
adjusting a clamp regulating the degree of constric-
tion of the aorta. The mean blood pressure range in the
different experiments was between 52 and 108 mm Hg.
The ‘pulmonary arterial pressure’ was kept within
a relatively narrow range in each experiment by adjust-
ing the Starling-resistance. The range in all but two
of the experiments was between 5 and 25 mm Hg;
in the two exceptions it varied between 25 and 40
mm Hg. In this way, the variations of calculated
values of total work for any stated work level were
within ±5%.

Effect of Electrical Stimulator. A true pulsus
alternans, accompanied by a left ventricular but not
by an electrical alternans, was often seen when the
heart was beating at rates of 200 beats/min. or more.
This alternans was often transitory and varied in degree even at the same rate of stimulation. Our experiments do not support the concept that the alternation is necessarily a sign of heart failure and necessarily associated with an increase in the venous return or end-diastolic pressure (or volume) above a critical level, because: a) this alternans was transitory and reversible; b) there was no evidence of a rise in the left ventricular end-diastolic pressure when alternans occurred; c) the same pattern of cardiac oxygen consumption change with heart rate occurred in the presence of alternation as in its absence. However since the calculations of work are based on electrically integrated pressures, small differences in ‘efficiency’ might have been overlooked.

Several experiments were carried out to test the effect of electrical stimulation per se on coronary flow and cardiac oxygen consumption. In two experiments the electrically induced heart rate (197 and 205 beats/min., respectively) was maintained for at least 30 minutes, while cardiac output and systemic and ‘pulmonary arterial’ pressures were kept constant. It was found that during this period, coronary flow did not vary and coronary A-V oxygen differences checked within ± vol. %. This would indicate that electrical stimulation of the heart per se does not lead either to progressive coronary vasomotor changes or to progressive changes in cardiac oxygen consumption.

The coronary flow was seen to change immediately when the rate of cardiac stimulation was altered at constant work levels, and it reverted to its previous value immediately when the heart rate returned to its previous level. The speed with which the coronary flow, and presumably the cardiac oxygen consumption, changed precludes any lasting effect of the previous rate of stimulation.

When electrical stimulation was utilized to obtain a heart rate identical with the dog’s own basal rate (without stimulation) no change in coronary flow occurred. Unfortunately these comparisons were possible only at rates below 150 beats/min. Therefore, this generalization has not been demonstrated for higher heart rates. However, a comparison of oxygen consumption utilization values in animals with electrically driven hearts at a rate below 150 beats/min. with those observed in other dogs setting their own pace revealed no significant differences; this is in accord with a report by others (12).

RESULTS

Heart Rate, Coronary Flow and Myocardial Oxygen Consumption. The present experiments, incorporating 60 observations at heart rates between 77 and 310 beats/min., showed a definite relationship between heart rate and coronary flow, and between heart rate and myocardial oxygen consumption. Figure 1 illustrates a single experiment at a relatively constant work level (61 ± 6 kg m/hr/100 gm IWW). Curves A and B are, respectively, the plots of coronary flow and oxygen consumption against heart rate. It can be seen that the slope of both curves decreased at extremely rapid heart rates. When treated statistically the 60 experimental observations of the three variables—heart rate, cardiac oxygen consumption and coronary flow—show a significant correlation2 regardless of the work load.

Despite wide variations in heart rate and work, the arteriovenous oxygen difference fluctuated within a narrow range. Thus, the increment of oxygen extraction by the myocardium was determined primarily by an increase in coronary flow rather than by an increase in coronary A-V oxygen difference.

Heart Rate, Cardiac Work and Myocardial Oxygen Consumption. At a given heart rate, the cardiac oxygen consumption and the coronary flow increased as the work level increased. The variation in work used in these experiments ranged from 25-130 kg m/hr/100 gm HW, a range wider than previously reported by us (3). These variations in heart work involved change in both cardiac output and blood pressure. This does not preclude differ-

2 Regression equations showing these relationships are best expressed logarithmically:

\[
\log O_2 = 0.306 + 0.420 \log R (r = 0.611)
\]

\[
\log CF = 1.035 + 0.483 \log R (r = 0.540)
\]

where \( O_2 \) = oxygen consumption cc/100 gm IWW/min.; \( R \) = heart rate beats/min.; \( CF \) = coronary flow cc/100 gm HW/min. Both coefficients \( r \) are statistically significant.
consumption at high work levels than at low ones, but the percent of the oxygen consumption increment remains the same. For example, at a work level of 20 kg m/hr/100 gm HW an increase in rate from 75 to 300 beats/min. leads to an increase in oxygen consumption from 8.5 to 18 cc/100 gm HW, which represents a rise of 112% \( \frac{(18 - 8.5)}{8.5} \times 100 \); the same increment of heart rate at a work level of 60 kg m/hr/100 gm HW results in a greater increase in oxygen consumption (i.e. 11.5–24 cc/100 gm HW), but this rise represents 108% \( \frac{(24 - 11.5)}{11.5} \times 100 \).

The similarity of percent increase (33%) in cardiac oxygen consumption when the work is tripled at a low rate (75 beats/min.) or at a high rate (300 beats/min.) is striking. When this is compared to the percentage increase (110%) obtained when the rate is increased fourfold at a low work level or a high work level, the greater cardiac oxygen requirement for work done at a higher rate level is emphasized.

Heart Rate, Efficiency and Work. As noted in previous experiments with this preparation (3) the ‘efficiencies’ were low. However, the values change sufficiently under the conditions of these experiments to permit certain conclusions. Figure 4 is a plot of ‘efficiency’ against heart rate in one isowork experiment. Efficiency declines and approaches a level asymptotically as the heart rate increases to about 200 beats/min. The highest efficiencies, in confirmation of earlier experiments (2, 19), were found at the highest work levels.

Heart Rate and Stroke-Oxygen Consumption. Figure 5 illustrates a single experiment in which the total work was kept constant. The stroke-oxygen consumption—the oxygen consumed by the heart per stroke—is seen to decrease rapidly when the heart rate increases. The plots of stroke-oxygen consumption against heart rate exhibited the same trend in each experiment, approaching a level asymptotically as the heart rate increases to about 250 beats/min.

Coronary Flow and Total Oxygen Consumption. There was a good correlation between coronary flow and oxygen consumption. This general relationship can be expressed as follows:

\[
\log CF = 1.161 + 0.774 O_2 (r = 0.600).
\]
correlation is valid beyond the physiological heart rates and work levels; but the closer the heart rate and work levels are to physiological conditions, the better is the correlation.

**DISCUSSION**

**Oxygen Consumption Alterations With Heart Rate Changes.** The results clearly demonstrate—at least under these experimental conditions—that oxygen utilization of the heart, as well as the coronary flow, are closely regulated by the conditions of performance of the heart. Cardiac work and heart rate are the most obvious factors in this regard. The effect of each of these was investigated separately in these experiments as far as blood supply and oxygen utilization (and presumably oxygen requirements) of cardiac muscle are concerned.

The heart rate per se was shown to have an effect upon the oxygen extraction by the heart muscle, in confirmation of other reports (12-14). No matter how this relationship is expressed, either as the increment of total oxygen consumption at the fast heart rates, the decrement of stroke-oxygen consumption in tachycardia, or the lower ‘efficiency’ of the fast beating heart, the phenomenon cannot be explained entirely on the basis of the change in stroke-work, or of alteration in the relative durations of systole and diastole, at the different heart rates.

The stroke-oxygen consumption of the heart is not solely a function of the stroke-work. If this were the case, then each beat having the same stroke-work would consume the same quantity of oxygen regardless of the heart rate. That this relationship does not hold is seen clearly from figure 4. At a heart rate of 300 beats/min., cardiac work of 80 kg m/hr/100 gm HW, and stroke-work of 0.0044, the oxygen consumed per beat per 100 gm HW is equal to 25.0 or 0.08 cc; and at a heart rate of 75, cardiac work of 20 kg m/hr/100 gm HW, and the same stroke-work, the stroke-oxygen consumption is equal to 8.5 or 0.11 cc. Thus, with the same stroke-work different stroke-oxygen consumption occurs.

If the major part of energy utilization takes place during diastole as has been postulated recently (20), then stroke-oxygen consumption should be a function of diastolic duration at constant cardiac work. At a heart rate of 150 beats/min. the total period of diastole per minute is 33 seconds, while at a rate of 300 beats/min. it is 36 seconds (21), an increase of 3 seconds (or approximately 10%). Yet our experiments have demonstrated that cardiac oxygen consumption increase about 50% between 150 and 300 beats/min. The wide difference between expected and observed increments of oxygen consumption emphasize the unlikelihood of a cause and effect relationship between duration of diastole and cardiac oxygen utilization.

The greater work/oxygen consumption ratio at slow heart rates can not be based upon a simple mechanical concept. It would appear instead that heart rate acceleration augments the energy metabolism of the heart without the manifestation of the extra energy as output- or pressure-work. The interrelationship between work, heart rate and oxygen consumption can be more clearly understood on the assumption that the heart rate effect per se acts independently of the effect of heart work upon the cardiac oxygen consumption. Thus, the percentage rise in cardiac oxygen consumption for a given increment of heart work was unchanged at four widely different heart rates. Furthermore, the percentage rises in cardiac oxygen consumption for a given increment of heart work was unchanged at four widely different heart rates. Such an independence between the cardiac oxygen utilization induced by change in heart rate and that induced by change in work, is in keeping with the possibility that heart rate and cardiac work compete for the oxygen.

One of the most important physiological adjustments in trained athletes is the ability to perform a greatly augmented amount of...
body work without much increment in heart rate. This adjustment, on the basis of our results, may depend in part on the decreased energy requirements of the heart in doing this intense work at the slower heart rates maintained by athletes. Indeed some of the deleterious effects of sustained tachycardias may be explained in terms of the metabolic cost of performing heart work at excessive heart rates.

The same type of relationship between oxygen consumption, heart rate and cardiac work, found in our experiments, may exist in the normal animal, as well as under certain abnormal conditions in man, as for example in paroxysmal auricular tachycardia. It seems unlikely that the degree of reduction in cardiac output and blood pressure occurring in paroxysmal auricular tachycardia (15, 22) will decrease cardiac work sufficiently to offset the energy cost of increased heart rate. 

Coronary Flow With Heart Rate Changes. Dynamic factors have been suggested as an explanation for augmented coronary flow during tachycardia. Wiggers concluded that the increased coronary flow when heart rate increased was not due to increased massaging of the coronary vessels (21). Gregg could not relate the increase in coronary flow with increase heart rate to changes in the relative duration of diastole and systole (23). Alteration in coronary vasomotor tone could be considered in view of the possible interference of the autonomic nervous system in order to explain the coronary flow changes immediately following the change in heart rate. However, this is not likely since the same coronary dilatation follows acceleration of the heart induced either spontaneously (24), by direct electrical pacing (9-11, 15), or in recovery from central vagal stimulation (14). Furthermore, the good correlation found in these experiments between cardiac oxygen consumption and coronary flow within and outside the physiological range, requires an explanation which relates the vascular tone of the coronary bed with the cardiac metabolism (3, 23). Increased heart rate, like increased cardiac work, requires coronary vasodilatation to meet the augmented oxygen needs of the heart muscle.

There appears to be a maximum capacity for oxygen uptake on the part of the myocardium under ‘normal’ conditions. When the needs for oxygen surpasses that supplied by the existing rate of blood flow through the myocardium, an increase in blood flow results. This increase in coronary flow seems to have a physiological limit as evidenced by the small increment observed at extremely rapid heart rates. When the limit of normal physiological adjustment of cardiac oxygen consumption to oxygen availability is surpassed as with an increasing load or an extremely high heart rate, then the mechanism by which the myocardium obtains its oxygen may change qualitatively. This we have previously described as ‘spontaneous’ change (1, 2).

‘Spontaneous’ Change. In some experiments of the present series we were able to observe a phenomenon to which we have referred in previous work (1) as ‘spontaneous’ change in coronary flow. This phenomenon consists of: a) an abnormal increase in coronary flow, and b) a concomitant arterIALIZATION of coronary venous blood, of such a degree that it is readily seen visually on observing the coronary flowmeter measuring the coronary venous blood flow. In addition it has been previously reported (2) that under these conditions cardiac oxygen consumption declines even if work increases. All this we have confirmed in the present study.

In our present studies, the blood gaseous determinations showed, in every case, a striking increase in venous oxygen content associated with a marked decrement in the coronary A-V oxygen difference. No clear pattern of change of the respiratory quotient of the heart was seen under such conditions. The cardiac oxygen consumption for a given cardiac work
## Table I. Summary of the factors involved in the 'spontaneous' change

<table>
<thead>
<tr>
<th>Duration of Stimulation</th>
<th>Possible Contributory Factors</th>
<th>Parameters</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HR, beats/min.</td>
<td>W, kg m/hr/100 gm HW</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 hr.</td>
<td>45 min.</td>
<td>C.O. rise 1200-1500</td>
<td>132 (15.9)</td>
</tr>
<tr>
<td>1 hr.</td>
<td>45 min.</td>
<td>C.O. rise 850-1200 St. &gt; 207 failed</td>
<td>114 (12.3)</td>
</tr>
<tr>
<td>Sample 8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 hr.</td>
<td>30 min.</td>
<td>Ao. const.</td>
<td>133 (15.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>St. &gt; 257 failed</td>
<td>[252]</td>
</tr>
<tr>
<td>Sample 12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 hr.</td>
<td>60 min.</td>
<td>St. &gt; 257 failed</td>
<td>133 (15.3)</td>
</tr>
<tr>
<td>1 hr.</td>
<td>50 min.</td>
<td>St. &gt; 179 failed</td>
<td>[179]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exp. 6, sample 7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 hr.</td>
<td>70 min.</td>
<td>Ao. const.</td>
<td>[237]</td>
</tr>
<tr>
<td>Exp. 7, sample 12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 hr.</td>
<td>40 min.</td>
<td>Ao. const.</td>
<td>[241]</td>
</tr>
</tbody>
</table>

St. > ... failed = stimulation unsuccessful when rate is over ... beats/min.; Ao. Const. = aortic constriction which increased aortic pressure over 5 mm Hg; C.O. = cardiac output (the figures following C.O. are the values expressed in cc/min.); HR = heart rate; W = work; (A-V) O₂ diff. = coronary A-V oxygen difference; O₂ cons. = oxygen consumption; CF = coronary flow; T = transient; P = permanent; End = experiment terminated; HW = heart weight.

The numbers written in the column ‘Duration of Stimulation —> 150%’ indicate the time elapsed from the onset of a rate > 150% of the dog’s natural basic heart rate to the occurrence of the ‘spontaneous’ change. Parameters represent the physiological conditions (work and rate) at the onset of the ‘spontaneous’ change, when the first sample is drawn and ‘Data’ represent the O₂ and CF values in the same period. The heart rate figures in brackets below the other figures indicate the heart rate values prior to the first sampling of the period of ‘spontaneous’ change. The figures in parentheses below the other figures represent the theoretical values derived from the nomograms at the experimental conditions of work and rate for the sample and from the correlation between O₂ cons. and CF. In exp. 4, sample 8 is also included in order to show the accentuation of the phenomenon initiated with sample 6.

Load and heart rate were much reduced in comparison with periods not displaying these combination of changes. The conditions in which these so-called ‘spontaneous’ changes were seen are summarized in Table I. An attempt has been made to evaluate the factors that could be responsible for them, and a comparison was made between the actually observed and expected values of coronary flow, coronary A-V oxygen differences and cardiac oxygen consumption, as shown by the nomograms.

This ‘spontaneous’ change was sometimes transient (cf. exp. 3 and 5), in which case the coronary flow gradually decreased to the expected ‘normal’ value. In these cases, however, no oxygen data was obtained during recovery. More often the ‘spontaneous’ change persisted for over an hour, or until the experiment was terminated. In these latter cases we were able
In one experiment (exp. 5) the ‘spontaneous’ change persisted for 1 hour and 30 minutes, and nine determinations were made at three different levels of work. In this experiment coronary A-V oxygen differences under normal conditions were 18 ± 1 vol. %, while during the ‘spontaneous’ change the difference became 11 ± 2 vol. %, and finally 7 ± 1.5 vol. %. The coronary flow values did not follow the same stepwise progressive deviation, and although consistently high, they varied from sample to sample. The cardiac oxygen consumption, by and large, showed the same shifting pattern as the coronary flow.

No single factor or group of factors were consistently implicated as the stimulus for the ‘spontaneous’ change. Various factors which may have been contributory (table 1) are briefly considered: a) in every case, ‘spontaneous’ change was observed to occur when electrically induced heart rates were greater than 150% of the dog’s own basic heart rate. While the phenomenon did not always occur at such extremely high heart rates, it seemed to appear more frequently when the excessive rate lasted more than 30 minutes. Even at lower rates, electrical stimulation lasting more than 1 hour also seemed to be contributory. b) In four instances, ‘spontaneous’ change occurred when an unsuccessful attempt was made to obtain a rapid ventricular regular rate with electrical stimulation. In fact the ‘spontaneous’ change persisted even when the ventricular rate was slowed and after the electrical stimulation was discontinued. c) More than one factor may have been operating simultaneously. In two instances, the change could have been triggered by an increment of work imposed by increasing cardiac output to a level ½ higher than that previously existing. In two instances, the change could have been aided by an induced increase in aortic resistance, even though the resulting increase in work was not large. However, alternans was not necessarily associated with the ‘spontaneous’ change.

In any discussion of ‘spontaneous’ change it is necessary to integrate the findings of this laboratory relating work, coronary flow and oxygen consumption with reference to the ‘normal’ state. The data presented in this report extends the correlation of coronary flow rate to oxygen consumption to include a }
sideration of the effect of heart rate. When heart rate is taken into consideration, along with cardiac output and blood pressure, the cardiac oxygen consumption can be fairly accurately predicted within the range of rate, output and pressure studied. It was shown by us previously that changes in myocardial oxygen requirement is met by an alteration in coronary flow rather than a change in the coronary A-V oxygen difference (2, 3). Since the coronary A-V oxygen difference remains relatively constant it is possible to predict coronary flow from cardiac oxygen consumption by using the above-mentioned correlation between these two variables.

The factors that are active in the transition from the above physiologic adjustments to the 'spontaneous' change appear to be those which impose an excessive work load on the heart. Under these new conditions the heart seems to shift from the normal 'unstressed' adjustment just described to a different mode of adjustment, probably by alteration of myocardial metabolism. However, even under conditions of 'spontaneous' change the relationship between cardiac oxygen consumption and work, and between coronary flow and work, are qualitatively the same, i.e. an increase in work is followed by an increment of coronary flow and an increment of cardiac oxygen consumption but the quantitative relationship noted above no longer pertains.

The significance of the 'spontaneous' change lies perhaps in the decreased oxygen cost of myocardial work done under such conditions although it is fallacious to closely correlate cardiac work done with oxygen consumed by it since unknown portions of oxygen are utilized for heat, synthesis and maintenance of the myocardial architecture. Nevertheless it is noteworthy that the usual pattern of increased cardiac work associated with increased oxygen consumption is altered with 'spontaneous' change. The heart seems to be able to perform the same or excessive work at a decreased oxygen cost as manifested by the decrease in its oxygen consumption.

It has been pointed out in this report that as work increases to attain excessive levels the coronary flow seems to approach a maximum while the coronary A-V oxygen difference remains constant. However, under conditions of 'spontaneous' change a qualitative shift occurs wherein coronary flow values range far in excess of the usual range made in response to cardiac work. During this interval the coronary A-V oxygen difference falls to very low levels. However, the full dilatation potential of the coronary vessels has not yet been obtained since under the conditions of hypoxia even greater flow rates have been observed (1) — (these flow rates are associated with increased coronary A-V oxygen difference and extremely low coronary venous oxygen).

It is tempting to formulate a hypothesis which poses the 'spontaneous' change as an intermediate stress-adapting mechanism, such that excessive and sudden cardiac work loads can be met by an alteration in cardiac metabolism with decreased oxygen requirements and near minimal resistance to coronary flow. On the other hand, under conditions of hypoxia, the heart responds with all of its resources (by opposing no resistance to coronary flow and increasing the amount of oxygen it removes in each cubic centimeter of blood perfusing it). Eventually even this fails and the cardiac metabolism then decays rapidly.

This hypothesis it must be noted is far in advance of our available knowledge relating metabolism and work performed. At this point in our development no frame of reference exists into which this phenomenon readily fits. It can perhaps be said that the heart has recourse to a stage of anaerobiosis, and can obtain energy for work by utilization of its storage products or by making more efficient use of substrates available to it from the blood. Still another possibility is the diversion of energy to mechanical work while such processes as synthesis and repair are reduced to a minimum. It must be noted that this phenomenon is long-lasting and reversible, and that no permanent damage has been associated with its occurrence. It is different from 'oxygen debt' since it can persist for an hour or more. Certainly, this observation places the 'spontaneous' change within the realm of available adaptive mechanisms compatible with survival and not with the last gasps of a dying system.

We are indebted to Dr. Harold Feinberg for his valuable suggestions in connection with the preparation of this manuscript.
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