The Lewis A. Conner Memorial Lecture

The Performance of the Heart

By Louis N. Katz, M.D.

Once again we are gathered to pay our respects to the memory of Dr. Lewis Atterbury Conner through this lectureship established by the American Heart Association in his honor. This was a fitting act, for Dr. Conner was one of its founders, served as one of its early presidents, and created the first official journal of the Association, the American Heart Journal, of which he was the first Editor. More than this, he played a continuing prominent role in the development of the Association for many years.

I came to know Dr. Conner in the last years of his distinguished career when he had become a legendary figure of the ideal internist and cardiologist. I remember him as tall and upright, reserved and poised, kindly and vigorous—a man one could readily admire. Over a long and active life, he showed by his writings and teachings that he was more than a bedside physician. He was a scholar with a broad interest in all aspects of medicine. It is perhaps significant of his personality that his first publication in 1895, at the age of 28, was entitled "Drifting, Who, How, Whither!" He was interested as much in the public health and psychosomatic aspects of heart disease as in the means of combining history, physical findings, and laboratory data in arriving at a proper diagnosis. Nor was diagnosis an end in itself for him, but rather it was the first step before proceeding judicially to evaluate the existing knowledge in order to manage his patient properly. In short, all aspects of the performance of the heart were his concern.

* * *

This occasion affords me the opportunity to review with you a number of aspects of the performance of the heart with which I have been concerned for many years and to which I have turned once again in the last few years.* Not all phases of the subject will be discussed. Information on the biochemical and enzymatic processes are still too incomplete although some aspects are slowly emerging. This is a challenging aspect that requires intensive investigation in the immediate future.

The similarity of the heart muscle to skeletal muscle in these regards serves as a good starting point. Differences between the 2 muscles do exist, however. Skeletal muscle may have long periods to rest and recover between its bursts of contractions. The heart, on the other hand, beats constantly from before birth until death, and in each diastole it must restore itself completely; otherwise it would not be long before it would be incapable of beating effectively. The heart cannot go into debt, as far as oxygen is concerned, to the extent skeletal muscle can, and it is more vulnerable to hypoxemia. In diabetes mellitus, the heart unlike skeletal muscle shows no sharp decrease in glycogen content nor in its respiratory quotient. The durations of its systole, of its refractory phase, and of its electrical action current are much longer than those of skeletal muscle, and it cannot readily be thrown into a

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*Some aspects of the subject have been reviewed recently elsewhere (see Reviews in References).
tetanic contraction. These differences indicate significant differences in their chemical and physical performance.

Today, I intend to present 3 aspects of the performance of the heart based on the work done by my associates and myself, at first chiefly on the isolated dog heart and heart-lung preparation, and more recently upon a special open-chest preparation with the heart in situ and subject to the usual neurogenic and hormonal influences. I shall use these data together with the pertinent facts in the literature to extrapolate to the performance of the heart in the unanesthetized animal and in man. Only time and further studies will tell how many of these generalizations will survive. I am aware of the hazards of attempting such an extrapolation but if it serves to stimulate more widespread interest in certain aspects of the performance of the human heart, hitherto somewhat neglected, then it will have been worth the risk.

The Manner by Which the Contractile Effort of the Heart Responds to the Work-Load Imposed upon It

The heart may be conceived as a compression pump. During its systole, the walls of the ventricles compress their content of blood—the work being done by the heart muscle (fig. 1). During diastole the blood content of the ventricular cavities is expanded—the work being done upon the heart wall (fig. 1). The possibility that work is done by the heart in diastole, exerting suction on the blood, has been proved, but this effect is small in comparison with the work done by the heart in systole, and special conditions are required for its demonstration. It can therefore be ignored as an aspect of the heart’s performance except under certain abnormal circumstances, which as yet are in need of better definition.

Not all of the work done by the heart in its systole is useful in the sense either that it is expended in the actual propulsion of blood through the blood vessels in systole, or in building up a pressure head in the aorta and pulmonary artery to make possible continued flow in the blood vessels in the subsequent diastole (fig. 2). The external useful work is calculated from the pressure change in the blood expelled (and from the velocity imparted to it) during the ejection.

\[
EW = P \cdot V + \frac{m \cdot ve}{2g}
\]

*EW* = External work  
*=P* = Mean arterial pressure during ejection  
*=V* = Blood volume ejected  
*=m* = Mass of blood ejected  
*=ve* = Mean velocity of blood in aorta during ejection  
*=g* = Gravitational constant

*Figure 1*
The 2 diagrams show the heart as a compression pump. During systole the ventricle does work by compressing its blood content; during diastole work is done upon the heart by the blood that enters and distends it.

*Figure 2*
The 2 diagrams show the aorta as a compression chamber. During systole blood from the ventricle distends the aorta, as well as passing through it; during diastole the aorta compresses the blood within it by virtue of its elastic recoil and maintains the onward flow into the periphery.
In order better to understand the heart as a compression pump certain of its characteristics should be stressed. It, like other muscles, is a viscous-elastic organ. Alterations of this property help determine how readily it relaxes and contracts. It has one setting when it is fully contracted and another when it is fully relaxed. These can be defined by plotting the pressure-volume relationships of these 2 cyclic states (fig. 3). In the relaxed heart, under steady conditions, the end-diastolic pressure rises with ever increasing magnitude as the end-diastolic volume enlarges progressively. Or, viewed contrariwise, the end-diastolic volume declines by ever increasing increments as the end-diastolic pressure falls. This relationship of end-diastolic volume and pressure defines the diastolic tone of a ventricle. A family of such curves can depict changes in diastolic tone, which may play as much of a role as the end-diastolic pressure in determining heart size in diastole (fig. 4).

A similar curve can be constructed for the contracted state with the use of the end-systolic pressures and end-systolic volumes (fig. 3). As expected, the change in viscous-elastic state with contraction is such that pressure in the ventricular cavity is greater in the contracted state than in the relaxed state at any given volume, or, conversely, that for any given pressure, the volume of the contracted ventricle is smaller than when it is relaxed. Without experimental determination, however, the shape of the relationship of end-systolic pressure to end-systolic volume could not be deduced. Actually, the curve is such that the rise of pressure with increasing volume slows progressively until a peak is reached, after which further increases in volume cause the pressure to fall until the systolic curve meets the diastolic one. In the first portion of the curve, the end-systolic volume rises by ever increasing increments as the end-systolic pressure rises, and the volume continues to increase even when the pressure has reached its peak and is again declining. The systolic pressure-volume curve defines what we have called the systolic tone of the ventricle, and a family of such curves can be constructed that depicts change in systolic tone.

Systolic tone is important, since along with peripheral resistance it determines the residue of blood remaining in the ventricle when contraction is complete, the systolic residue. Evidence is convincing that a ventricle does not empty itself completely, rather the systolic residue is normally about one half the diastolic volume in man and in the closed-chest unanesthetized animal. This systolic residue, together with that volume of blood in the atria, central veins, and lungs, can be called upon in beat-to-beat adjustment of the heart's output according to need above or below the venous return to the heart. This has been overlooked by many in analyzing the heart's performance because conditions are somewhat different in the isolated heart.

The curves of diastolic and systolic tone described above serve as the limits reached by
the heart in its cycle of contraction and relaxation. How the pressure and volume of the ventricle between these limits change from moment to moment during the heart cycle depends as much on the resistance to emptying in the arteries and the forces in the veins causing filling as upon the moment-to-moment changes in the physical properties of the heart’s contractile elements. A work-diagram can be inscribed relating the moment-to-moment changes of pressure and volume—which should be reminiscent of the vector loop of QRS in the frontal plane (fig. 5). Such work-diagrams have been recorded in the isolated cold-blooded and warm-blooded heart, and have been theoretically derived for the intact animal and man (figs. 6 and 7). It is relatively easy to record intracavity pressure accurately by catheterization of the intact animal and man, but such is not the case for ventricular volume. Some approaches to the recording of volume (circumference, cross-section area, or diameter) in intact animals have been made and will doubtlessly be improved and applied in the near future.

With these comments as a background, we are ready to consider the heart’s performance. The heart normally is so attuned that it pumps out, over any extended period, as much blood as it receives. In this respect it is no different from the peripheral circulation of the lung and systemic circuits. A number of servomechanisms are involved in this fine ad-

![Relative Amount of Volume Change at Different Diastolic Pressures When Diastolic Tone Changes](image1)

![Relative Amount of Pressure Change at Different Diastolic Volumes When Diastolic Tone Changes](image2)

**Figure 4**

Top. Segment A shows 2 graphs, calculated from segment B, showing the amount of diastolic volume change that will occur at different diastolic pressures when an alteration in diastolic tone takes place (upper curve), and the amount of diastolic pressure change which will occur at different diastolic volumes when similar alterations in diastolic tone take place (lower curve). Bottom. Segment B is a reconstruction of the diastolic curve shown in figure 3 (middle line) with the magnitude of the ordinate increased. The upper curve represents the effect on the diastolic pressure-diastolic volume relationship when diastolic tone increases; the lower one, when the diastolic tone decreases. The horizontal double arrows show the decline in magnitude of the volume change, with a like diastolic tone alteration at constant diastolic pressure, as the intracavity pressure rises—a distended heart shows less volume change than the more empty one. The vertical double arrows show the increase in magnitude of the pressure change, with a like diastolic tone alteration at constant diastolic volume, as the heart size increases—a distended heart shows more pressure change than the more empty one. The importance of these facts on the numerical significance of end-diastolic pressure as an index of end-diastolic volume is apparent.

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justment of the heart. One of the most important is end-diastolic volume.

End-diastolic volume is determined by 4 independent variables: (1) the systolic residue in the ventricles; (2) the ventricular diastolic tone; (3) the duration of the filling time; and (4) the filling pressure—the mean net difference between the pressures in the atrium and ventricle during the filling phases of diastole.

End-diastolic volume is not the only determinant of the stroke output of the heart. It has been stressed above that changes in systolic residue may independently contribute to the stroke output variations from beat to beat (fig. 7). The contracting and relaxing processes are subject to hormonal and neurogenic influences, as well as mechanical, chemical, and thermal ones, which can change the stroke output independently of their effect via the end-diastolic volume. Recent work in the intact animal shows forcefully that these effects are as important, if not more important, than end-diastolic volume in adjusting stroke output to need. Equally significant is the fact that the minute output of the heart is influenced as much, if not more, by changes in heart rate, as by changes in stroke output. The continued preoccupation exclusively with end-diastolic volume has been a handicap, in my view, to a clear understanding of the character of the heart’s performance.

What has been said about stroke output, applies equally well to cardiac external work and oxygen consumption. Even if stroke output were governed exclusively by end-diastolic volume—which it is not—it could not equally govern external stroke-work, since blood pressure, one of the factors in determining work, is set independently of the end-diastolic volume. Actual determinations have shown that both work and oxygen consumption of the heart, even when considered per stroke, vary independently of end-diastolic volume. It is important to stress these facts, since they show that the performance of the heart, whether measured as output, work, or oxygen consumption, is determined by several factors—not just one.

In consideration of the conversion of chemical to mechanical energy, one fact emerges. The ventricular pressure curve is determined not only by the end-diastolic volume but also by other factors. Thus, in each heart cycle, the onset of its pressure rise as well as its contour during ejection, is affected by the arterial resistance existing when ejection begins and that present from moment to moment during this phase. Furthermore, the pressure peak value depends in addition upon the end-systolic volume that is reached, or vice versa.

For completion of this aspect of the subject, it is necessary to deal with the ways by which the heart meets an increase in load, and the effect of this on its reserve. There are 4 mechanisms by which the heart adjusts to loading. These are (1) dilatation, (2) tachycardia, (3) change in its contractile power and distensibility produced by humoral, hormonal, and reflex effects, and (4), when the load is chronically maintained, hypertrophy. These compensatory mechanisms are interdependent; the more there is of one, the less need there is for the others to come into play. It would appear that dilatation, which alters end-diastolic volume along the diastolic tone curve, except when tone changes, comes into play at once. So do tachycardia and change in contractile power. Over any extended period of time, however, hypertrophy takes over and the other compensatory mechanisms abate. It is well known clinically that a patient who has an increased systolic (resistance) load on account of essential hypertension may show no tachycardia or dilatation. The compensatory mechanism drawn upon is hypertrophy, and this for many years may be adequate to meet the increased load. When hypertrophy no longer is adequate, the other mechanisms come into play.

Since there are limits to the extent of these 4 compensatory mechanisms beyond which further increases are detrimental rather than beneficial, it follows that any increased use of these compensatory mechanisms will bring this undesirable turning point closer at hand. Cardiac reserve can be considered to be the difference between the parameter as it exists and the maximum up to which increased per-
Figure 5

Upon the curves shown in figure 3 is constructed a work-diagram (shaded area—1) of the ordinary performance of the human left ventricle beating at 80 beats/min., having a stroke-output of 60 ml., a systolic residue of 60 ml., and a blood pressure in the aorta of 130/80 mm. Hg. The arrows show the direction that the pressure-volume changes take during the heart cycle. A-B represents isometric contraction; B-C, rapid ejection; C-D, reduced ejection; D-E, isometric relaxation; E-F, rapid inflow; F-A, diastasis. Work is done from A to D along the arrows by the heart in compressing (and ejecting) blood, and work is done from D to A upon the heart. The area of 1 is an index of the net compression-work done by the heart. This is not the same as the external useful work of the heart. It will be noted that points A and D are, respectively, on the curves of the fully relaxed and fully contracted ventricle, which set the limits of the work-diagram.

The performance of the heart can be expected and beyond which decreased performance ensues. For example, the difference between the existing heart size and the maximum heart size that can augment the heart’s performance is one measure of cardiac reserve. An estimate of cardiac reserve would be obtained, if the differences between the existing state and the maximum value beyond which performance declines could be evaluated for each of the following: heart size, heart hypertrophy, heart rate, and cardiac contractile power and distensibility—and the differences then added together. Unfortunately, this is not possible today, useful though it might be.

Time will not permit further discussion of this aspect of the subject. This has been dealt with in extenso elsewhere. It need only be added that significant cardiovascular disease cuts down cardiac reserve not only by increasing the load on the heart—i.e., by raising the resistance, by increasing venous return, or by producing shunts and obstructions,—but also by reducing the limits of benefit of the 4 compensatory mechanisms. When compensatory mechanisms approach inadequacy, the heart is no longer equal to the needs of the body and circulatory failure ensues as evidenced by inadequate minute output. At first this will occur during periods of stress, later also during ordinary activity, and ultimately even at bed rest. When the last happens, death will not be far away.

The Factors That Determine the Oxygen Requirements of the Heart as Its Performance Alters

The task of the heart, its external work, as stated earlier, is to propel blood through the arteries during systole and to store blood in them so that flow can continue in diastole. It is of value to the clinician to know the cost of this work in terms of energy expended, particularly since the heart has so small a capacity to go into debt as far as energy is concerned. Oxygen is the best index though a remote one of this energy cost, the cost of mechanical energy in terms of chemical energy. The ratio of external work done by the heart to the energy cost as represented by the oxygen used, in like units, is what is meant by the external mechanical efficiency of the heart.

\[
ME = \frac{EW}{O_C}
\]

Where
- \(ME\) = External mechanical efficiency
- \(EW\) = External work of heart
- \(O_C\) = Oxygen consumption of heart

\(ME\) is decreased minute output reduced by increased heart rate

It is little affected by changes in blood pressure.
Someday we will be able to compare the oxygen consumption with the heat production of the heart and thereby be in a position to relate it to the various chemical reactions going on in the heart at different moments of the heart cycle. It may soon be possible also to relate oxygen use to the heart's high-energy phosphate exchange, which appears to be so intimately linked with the conversion of chemical to mechanical energy.

But even without such detailed knowledge, we know that the heart in situ, subject to its usual hormonal and neurogenic influences, is a pump of low efficiency. Its external mechanical efficiency is such that only one tenth to one seventh of the oxygen used appears in the form of work related to the actual propulsion of blood. In this sense, the heart is a poor pump. But the task of the heart is to gear its machinery so as to adjust blood flow according to need, rather than to do this as inexpensively as possible in terms of energy cost.

The low external mechanical efficiency of the heart cannot be related to the amount of oxygen consumed in maintaining its architecture. This accounts for only 2 ml. per minute, which is about 15 per cent of the rate of oxygen consumed by the heart in its usual state of pumping. It is due rather to the fact that in addition to the dynamic effort actually used to propel blood, the heart exerts a large static effort (as a compression pump), which is necessary to create and maintain a comparatively high tension in the ventricular walls and a high pressure in their cavities. This we have shown recently by making the left ventricle contract isovolumically, thereby pumping out no blood. Under these circumstances, the oxygen consumed by the heart doing no external work is of the same order as when it does pump blood. This is not surprising when one considers that no more than one tenth to one seventh of the heart's oxygen consumption is converted to actual external work.

While the external mechanical efficiency is low, it has been found to alter when the conditions of the heart's performance change. And these alterations are of significance to the clinician. The external mechanical efficiency declines when the cardiac minute output is reduced and when the heart rate is accelerated. Alterations in the arterial pressure (the chief factor ordinarily setting the systolic resistance-load) influence the external mechanical efficiency very little per se. It follows from all this that variations in pumping efficiency when external work is altered depend on the accompanying changes in cardiac output, arterial pressure, and heart rate. Thus, with heart rate unchanged, the oxygen cost of an increase in cardiac output (output-work) is little, while for an increase in arterial blood pressure (pressure-work) of equivalent amount, the oxygen cost is large. In short, the change in oxygen consumed by the heart is set not so much by the work it does as by the manner in which work is accomplished.

It is also of significance that when heart rate, cardiac output, and blood pressure are maintained constant in our experiments, severe hypoxia causes the oxygen consumption of the heart to decline, so that utilization of the energy of the heart for propelling blood actually improves. A similar improvement in the external mechanical efficiency of the heart also has been noted by us, on occasion, when the heart has been put under great working stress. There appears to be, under these circumstances, a shifting of gears in the conversion of energy to external work, and such spontaneous improvement in the heart may persist for a matter of minutes or for an hour or so. It is not established whether this is due to the heart making better use of its chemical fuel, or to the heart size being reduced so that wall tension is more effectively converted to cavity pressure, or to the heart making more use of substrates passing to its muscles from the coronary vessels, while, at the same time, the degraded materials are returned to the blood for oxidative restoration elsewhere. However, both the "extreme hypoxemic" and the "stress-adjusting mechanisms" serve the useful purpose of conserving the heart's oxygen supply while maintaining the pumping capacity of the heart.
just when this conservation is most needed under the stimulus of oxygen lack or an excessive load.

The fact that external work accounts for such a small proportion of the energy exchange of the heart has led us to seek some other index that might correlate better with the oxygen consumed by the heart. Our first thought was, of course, to seek correlation with each of the parameters entering into the determination of the performance of the heart, namely minute cardiac output, arterial blood pressure, and heart rate. A comparison was therefore made of the effect of each of these 3 variables on the cardiac oxygen consumption. It soon became clear that the relation between minute cardiac output and oxygen consumption was a very poor one, while that between arterial blood pressure and cardiac oxygen consumption was good. Furthermore, an equally good correlation was found to exist between heart rate and oxygen consumption. It seemed natural, therefore, to correlate the oxygen consumption of the heart with the product of arterial blood pressure and heart rate—this we have designated as the curve. The result is that the end-diastolic pressure is 20 mm. Hg. The arterial pressure remains unchanged, 130/80 mm. Hg. In this case the net compression stroke-work has declined compared to curve 1 in figure 5—even though the external useful stroke-work is unchanged. Work-diagram 4 represents conditions in longstanding arterial hypertension in which ventricular hypertrophy has compensated adequately for the increased systolic resistance-load. The heart rate is 80, the heart is not dilated—its end-diastolic volume is 120 ml. The stroke output is normal at 60 ml. The arterial pressure is elevated to 155/120 mm. Hg. The net compression stroke-work is increased with respect to curve 1 in figure 5. Work-diagram 5 represents conditions in early arterial hypertension in which the compensatory mechanism is dilatation, not hypertrophy as in curve 4. The end-diastolic volume here is 180 ml. The stroke-output has been maintained at 60 ml. by virtue of Starling's law, but the systolic residue has doubled to 120 ml. from the normal value of 60 ml. (curve 1, fig. 5). The heart rate is still 80 and the arterial pressure is 180/120 mm. Hg. The difference in compensatory mechanisms for the arterial hypertension in work-diagrams 4 and 5 is worthy of note.
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BP × HR index of cardiac oxygen consumption. Cardiac output was ignored.

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<th>CARDIAC O₂ CONSUMPTION</th>
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<td>BP × HR</td>
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<td>is a constant when work-load alters.</td>
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<td>BP × HR is an index of cardiac O₂ consumption.</td>
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This BP × HR index was found to parallel the oxygen consumption of the heart in our preparation over a wide range of blood pressures (30 to 180 mm. Hg), heart rate (30 to 180 per minute), and cardiac outputs (½ to 2 liters per minute). It also applied over a wide range of blood oxygen and carbon dioxide contents and hydrogen ion concentrations, also when the heart was cooled to 27 C. (ordinary hypothermic conditions). It was found to apply also in the isovolumically contracting heart preparation where no external work was done, BP in this instance being determined from left ventricular pressure. So far, only 3 conditions have affected the quantitative relation of the BP × HR index to the cardiac oxygen consumption. These are marked hypoxemia, exhibition of catecholamines, and sometimes undue stress.

Further work along these lines needs to be done, since this is, at best, only a crude index. There are several reasons for this crudeness. In the first place, it would be better to obtain BP from some parameter of the ventricular pressure curve rather than from the arterial pressure, perhaps the best would be the mean pressure of the ventricular pulse or of its systolic portion. In the second place, it is logical to assume that oxygen consumption would be more nearly related to cardiac wall tension than to cavity pressure—the 2 not being synonymous. Wall tension determines cavity pressure and vice versa, but their quantitative relation is set by surface area of the cavity and by the curvatures of its boundaries. In the simplest terms: \( P = T/A \) where \( P \) is cavity pressure, \( T \) is wall tension and \( A \) is the area of the cavity surface. Thus, as the heart becomes larger, intracavity pressure becomes a smaller proportion of its wall tension. That wall tension is a better index of cardiac oxygen consumption than is intracavity pressure is shown by the fact that multiplying the BP × HR index by the cube root of the heart’s volume improved the correlation between the index and the cardiac oxygen consumption in the isovolumically contracting heart. The relation between wall tension and cavity pressure has been known for a long time, and has been precisely defined mathematically as the Laplace law.

The fact that changes in cardiac oxygen consumption appear to be mirrored by the BP × HR index, however crudely, is of value to the clinician, since both mean blood pressure and heart rate are readily determined at the bedside. He has, therefore, easily at hand some idea of the cardiac oxygen consumption in different states of the heart. If used with proper caution and with due regard to its limitations, this BP × HR index may help his thinking. In the coming years, it will, I am sure, be given further examination and its nature will be changed to give a better index as it undergoes the test “by fire.”

**How the Oxygen Needs of the Heart Are Met by Adjustments in Coronary Flow and in the Rate of Oxygen Extraction**

In order to complete this picture of the heart’s performance, consideration must be given to the way in which the oxygen requirements of the heart are met. In the following discussion only steady states will be considered. It would take us too far afield to present the more complicated situation existing while the heart is adjusting to a new steady state. Consideration will be directed to 2 aspects: (1) adjustments when the composition of the blood is altered, and related problems, and (2) the changes that occur under control or abnormal circumstances when the work-load is modified.

First off, it is well known that the oxygen capacity of the myocardium is very small and its oxygen debt low. Hence, it is essential that oxygen be supplied by the coronary vessels quickly as needed. It is, therefore, not surprising that the amount of oxygen available to the heart is readily adjusted to its consumption.
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KATZ

\[ \frac{O_2 \text{AVAILABILITY}}{O_2 \text{CONSUMPTION}} \]

is a homeostatic constant when work-load alters.

It is not altered by hypoxia. It is by acidemia, hypercapnia, catecholamines, and, sometimes, by undue stress.

\[ O_2 \text{AVAILABILITY} = \text{arterial} \ O_2 \text{ content} \times \text{coronary flow.} \]

\[ O_2 \text{CONSUMPTION} = \text{coronary flow} \times \text{coronary A-V O}_2 \text{ difference.} \]

This is a homeostatic mechanism whose nature needs to be discussed. This adjustment means primarily that the coronary flow rate is closely linked in a quantitative fashion with the rate of oxygen consumption of the heart—and the factors that alter the latter also simultaneously affect the former and to a like extent. This is apparent when the work-load of the heart changes. Thus, coronary flow adjustments are apparently little influenced by blood pressure except insofar as the latter modifies cardiac oxygen consumption. Apparently, intravascular and extravascular forces acting upon coronary flow balance each other rather closely.

The coronary flow is so finely attuned that it keeps the oxygen available to the heart almost precisely constant in relation to the oxygen being consumed by it. When the arterial oxygen content declines as in hypoxemia, and presumably in anemia, it is found that the coronary flow rate is augmented in an amount that still maintains the oxygen available to the heart attuned to the oxygen it consumes in a given time.

\[ \text{CORONARY FLOW} \]

\[ \frac{\text{CARDIAC O}_2 \text{ CONSUMPTION}}{\text{is a homeostatic constant when work-load alters.}} \]

It is altered by hypoxia, also by acidemia, hypercapnia, catecholamines, and sometimes, by undue stress.

These adjustments of coronary flow to oxygen need are paramount and supersede or are imposed upon all other kinds of adjustments in coronary flow. This must be appreciated thoroughly by the clinician in his day-to-day handling of cardiac cases. Only when the responsive elements of the coronary vessels became diseased and cannot adjust properly, or when occlusion of a major coronary vessel makes these adjustments of the bed inoperative, does the beautifully attuned, fine adjustment of the coronary flow to oxygen consumption break down.

We have found, however, that hypercapnia, acidemia, and catecholamine exhibition shift this fine adjustment. In these instances, the coronary flow is augmented and the oxygen available to the heart is thereby increased. However, this does not prevent coronary flow and oxygen availability rates from continuing to adjust as before to the rate of oxygen consumed, when the latter varies with work-load alteration, even when the ratios (coronary flow/oxygen consumption) and (oxygen availability/oxygen consumption of the heart) have been shifted from their control values. A similar shift, and in the same direction occurs when the "stress-adapting mechanism," mentioned earlier, appears.

It is important to reemphasize that the adjustments of coronary flow to the oxygen needs of the heart are of paramount importance. They are far more powerful than the mechanical factors to which so much attention has hitherto been paid. They represent, as mentioned, a homeostatic mechanism of prime importance. It may be stated categorically that in evaluating the benefit of any drug or procedure upon the coronary flow rate, any simultaneous effect upon the rate of oxygen consumption of the heart must first be ascertained. Only those drugs or procedures that improve coronary flow alone, or at least improve it out of proportion to their augmenting effect on the oxygen consumed by the heart, can be considered of value for the relief of coronary insufficiency. (Of course, drugs or procedures that lead to a decline of the oxygen needs of the heart are also useful.) Regrettably, this kind of evaluation has not been carried out often enough in the past.

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The only other way by which the oxygen supplied to the heart can be varied is by alterations in the amount of oxygen removed from each unit of blood passing through the coronary capillaries, the A-V oxygen difference. This is usually expressed as a ratio, A-V oxygen difference/arterial oxygen content, known as per cent oxygen extraction. The per cent oxygen extracted by the heart is greater than in most organs, so that coronary venous blood contains less oxygen than do the venae cavae, or most other veins.

**CORONARY A-V O₂ DIFFERENCE and CORONARY VENOUS O₂ content are constant when work-load O₂ content goes up.**

The coronary A-V oxygen difference and, with it, the coronary venous oxygen content were found to remain constant over a wide range of the heart’s performance so long as the stress was not excessive and the arterial blood oxygen and carbon dioxide contents and the hydrogen ion concentration remained normal. All the adjustments seem to reside in modification of the coronary flow rate. This is, one must reemphasize, a remarkable homeostatic mechanism.

The coronary A-V oxygen difference (and coronary venous oxygen content) are not constant under all circumstances. As mentioned earlier, arterial hypoxemia leads to a decline in the coronary A-V oxygen difference. In this state the coronary venous oxygen content falls less than the arterial. Actually, the per cent of oxygen extracted by the heart has been found to remain constant in hypoxemia, apparently because the increase in coronary flow is so nicely attuned as to keep the oxygen

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**Figure 7**

This diagram represents 3 things. First, it shows the alteration in the end-diastolic pressure-volume curve when the diastolic tone changes in the left ventricle of man. Second, it shows the alteration in the end-systolic pressure-volume curve when the systolic tone changes. It can be seen that a family of curves can be drawn on either side of the normal (norm.) to show increase (incr.) and decrease (decr.) of tone. Third, 3 work-diagrams are drawn to illustrate 2 ways by which stroke-volume may be increased. Work-diagram 1 is the normal and reproduces curve 1 in figure 5. Work-diagram 6 shows what happens when the end-diastolic volume increases from 120 to 160 ml. The result is an increase in stroke-output to 80 ml; the systolic residue rising from 60 to 80 ml. The increase in end-diastolic volume effect is an expression of the Starling law. It is associated with a rise in the end-diastolic pressure along the normal diastolic tone curve. Were the diastolic tone to decrease, a similar rise in end-diastolic volume might occur with less, with no, or with an actual decline in end-diastolic pressure depending on the amount of decline in diastolic tone. That is why end-diastolic pressure is not a necessary index of end-diastolic volume. Work-diagram 7 shows how an increase in stroke-output of a degree similar to that caused by the shift from work-diagram 1 to work-diagram 6 can take place without any change in end-diastolic volume. It can be seen that the end-diastolic volume is identical (120 ml) in work-diagrams 1 and 7. The increase in stroke-output from 60 to 80 ml. occurs in this case because the inotropic properties of the ventricle are augmented, its systolic tone is increased thereby, and as a result its systolic residue declines from 60 to 40 ml. In this case, therefore, the increased stroke-volume occurred by encroachment upon the systolic residue. The Starling law was not

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available to the heart constant. Only when the hypoxia becomes excessive will this adjustment become inadequate—and soon the heart's power will decline.

In hypercapnia, acidemia, and catecholamine exhibition, a decline in coronary A-V oxygen difference also accompanies the augmentation of coronary flow. But unlike hypoxia, the coronary venous blood oxygen content rises—that is the venous blood from the heart muscles becomes arterialized. This also occurs in the "stress adapting mechanism." Obviously, the adjustments to these conditions are different from those due to hypoxia or to a change in work-load. The adjustments to work-load and hypoxia may be considered basic, while these other adjustments are super-added as refinements under certain unusual conditions.

It would take us too far afield to enter into the intriguing question of how and by what mechanisms the adjustments of coronary flow and oxygen extraction occur. They are doubtlessly different in the various circumstances. In each case it is necessary to settle whether it is the oxygen extraction or the coronary flow that is primarily altered, or whether both are changed simultaneously. This is an intriguing subject—but I have talked long enough.

* * *

In concluding, I would like to emphasize that this presentation is one man's view of the present status of some significant aspects of the heart's performance. The views expressed are not those that I held 30 years ago, 20 years ago, or even 10 years ago (as a perusal of previous reviews will show) and, I am sure, they will not be the same 10 years hence. As more thought and study continue in this area, concepts will change, approaching, over the long pull, closer and closer to the ultimate truth. Analysis of the heart's performance is an exciting occupation, and I hope I have been able to get across to you some of the things that make it so fascinating to me.

**Summario in Interlingua**

Isto es le discurse memorial, presentate in honor de Lewis A. Conner, al occasione del trenta-secunde session scientific annual del Association Cardiologic American a Philadelphia, Pennsylvania, le 23 de octobre 1959. Le autor discute 3 aspectos del performance del corde, basante se super recercas effectuate initialmente super toto in le isolate corde e preparato de corde e pulmon del can e plus recentemente etiam in preparatos special a thorace aperte con le corde in sito e exponite al usual influentias neurogene e hormonal. Le datos assi colligite es suplementate per alteres ab le litteratura e usate como base de extrapolationes con respecto al performance del corde de canes intacte e etiam de subjectos human. Le 3 aspectos del tema que es principalmente tractate es: (1) Le maniera in que le effortio contractile del corde responde al cargo de labor imponite super illo; (2) le factores que determina le requirimentos oxygenic del corde quando su performance es alterate; e (3) le maniera in que le requirimentos oxygenic del corde es satisfacte per adjustmentes del fluxo coronari e del intensitate del extraction de oxygeno.

Le autor sublinea in conclusion que le opiniones presentate es le sues como recercator individuale e que ille mesme non considera los como definitive e absolute. Trenta e 20 e 10 annos retro, le opiniones del autor non essera illos exprimit per ille al tempore present, e un simile disvelloppamento debe esser expectate in le futuro. In tanto que le studios e le pensar in iste area continua, nostre conception del problematic va cambiar pro approachar de plus in plus—secundo le spero e le conviction del autor—le ultime veritate.

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Medical Eponyms

By Robert W. Buck, M.D.

Roentgen Ray. The discovery of the X-ray was announced at a meeting of the Physico-Medical Society in Würzburg in 1895. The paper by Wilhelm Konrad Roentgen (1845-1923), entitled "A New Ray" (Über eine neue Art von Strahlen) appears in the Sitzungsberichten der Würzburger Physik-med. Gesellschaft, 1895, pp. 132-141.

"If in a completely darkened room, one allows the discharges from a large Ruhmkorf coil to pass through a Hitotiff vacuum tube (or a sufficiently evacuated Lenard's, Crookes' or other similar apparatus) and covers the tube with a rather closely fitting jacket made of thin black cardboard, a paper screen which has been painted with barium platinum cyanide will be seen to glow brightly and become fluorescent when brought near the apparatus. It makes no difference whether the painted or the unpainted side of the screen is turned toward the source of the discharge. . . . In the presence of this phenomenon one is first struck by the fact that some agent is passing through the black cardboard jacket—a jacket which will not allow the passage of either the visible or ultraviolet rays of the sun or the rays of an electric light; further, that this agent is able to generate a marked fluorescence. . . . It will be found that all bodies are permeable. . . . Thick blocks of wood are also permeable. . . . Sheets of hard rubber several centimeters in thickness still permit the rays to pass through. . . .

"Note: For the sake of conciseness I should like to use the expression rays, and in order to distinguish them from others, the name X-rays."

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LOUIS N. KATZ

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