THE INTERRELATIONS BETWEEN BLOOD FLOW AND METABOLIC RATE: A GRAPHIC REPRESENTATION

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Cardiovascular physiology exhibits a number of instances in which the product of two variables yields a third. Among these are: cardiac output times the peripheral resistance gives the mean arterial pressure, the transmural pressure in a vessel times the radius gives at equilibrium the wall tension (Leplace's law), and, the case dealt with in this note, the blood flow times the arteriovenous oxygen difference gives the tissue metabolic rate. All such relations can be graphically represented in the form $\underline{y} = \underline{ax}$, in which $\underline{a}$ is the slope of the line obtained by plotting $\underline{y}$ against $\underline{x}$. Burton (1), for example, has done this in his equilibrium diagrams for blood vessels wherein the abscissae represent vessel radius, the ordinates wall tension, and the slope of a line through the origin, the transmural pressure. It is suggested in this paper that a similar representation of the relation between blood flow and metabolic rate might be useful.

The fundamental equation for the Fick principle relative to oxygen is

$$\dot{V}_{O_2} = (Ca_{O_2} - Cv_{O_2})\,\dot{Q}$$

where $\dot{V}_{O_2}$ is the oxygen consumption rate (ml oxygen per min), Ca_{O_2} is the arterial oxygen constant (ml oxygen per 1 blood), Cv_{O_2} is the venous oxygen content (ml oxygen per 1 blood), $Ca_{O_2} - Cv_{O_2}$ is the arteriovenous oxygen difference (ml oxygen per 1 blood) and $\dot{Q}$ is the blood flow (1 per min). Rearranging this equation so as to make $\dot{V}$ the independent variable and dropping the subscripts for oxygen, we have

$$\dot{Q} = \frac{1}{C_a - C_V}\,\dot{V}$$

The quantity $\frac{1}{C_a - C_V}$ represents the blood flow (in liters) required to deliver one ml of oxygen (which we might call the metabolism-specific blood flow).

If for one set of values, $\dot{V}$ be plotted as abscissa, $\dot{Q}$ as ordinate, and the resulting point connected to the origin by a straight line, that line will have the slope $\frac{1}{C_a - CV}$, as shown in Fig. 1.

Numerical values for the arteriovenous difference can readily be noted by drawing a circle with center at the origin and radius sufficiently great so that all plotted points lie inside its circumference. For any such point, the line drawn through it, and the origin can be produced to intersect this circle. At this point the appropriate calculated values for $C_a - C_V$ may be written along the circumference. In a sense, such a line might be thought of as representing the pointer of a dial indicating $C_a - CV$ values.

In the same manner any physiological situation in which the blood entering an organ delivers some or all of a constituent can be represented by a point in the above quadrant. Further, if the organ delivers a substance to the blood for removal, $\dot{V}$ becomes negative and such situations may be represented by points in the left upper quadrant. Again, if clearance of a constituent from the blood is complete, obviously the slope of the line concerned will be $\frac{1}{C_a}$, i.e., the volume of blood required to contain one unit of the constituent.

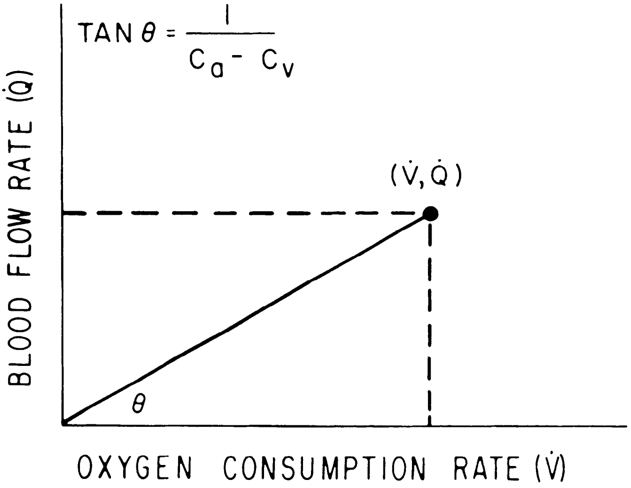

Fig.1. Graphic representation of the relation between blood flow and oxygen consumption. The slope of the regression line is equal to the reciprocal of the arteriovenous oxygen difference.

A simple example of the use of this graphic method is given in Fig. 2. The brain of a human subject is assumed to consume 46 ml oxygen per minute and to have a blood flow of 0.75 1 per min. The arteriovenous oxygen difference would be 61 ml per 1 blood.

This approach can be extended to represent additional physiological variables concerned with oxygen transport. Thus, if the physiological situation is such that the arterial blood oxygen content (C_a) can be regarded as constant and known (as is commonly true), then for each C_a-C_V value the venous oxygen content (C_V) can be calculated - and a second concentric circle inscribed outside that for these values.

Again, if also we can legitimately assume that the blood oxygen capacity is constant and known, for each value of C_V there can be calculated the percentage oxygen saturation of the venous hemoglobin. These values can be placed on a third circle. Finally, if we can also take as constant and known the applicable hemoglobin dissociation curve of the venous blood, then for each percentage of venous hemoglobin saturation we can read off the venous P_{O_2} value at equilibrium, and plot such values on a fourth circle. Such values may be taken as representing the level of tissue P_{O_2}, a valuable index of the degree of tissue oxygenation.

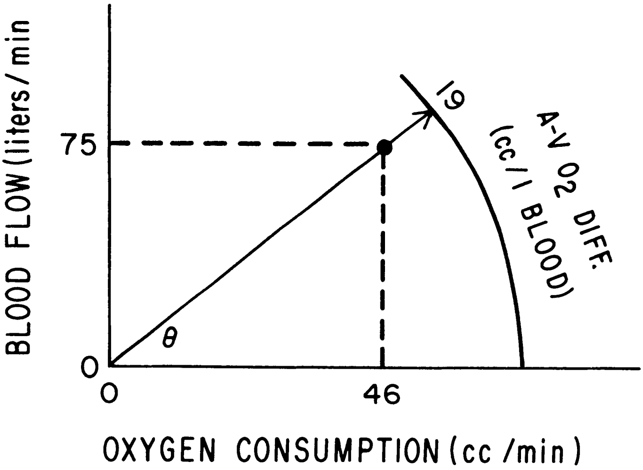

Fig.2. The relation between the blood flow and oxygen consumption of a human brain.

Thus it is possible with such diagrams to see at a glance the status of these physiological values in situations where comparisons are to be made. Two examples are now given.

First, the relation of cardiac output to metabolic rate in exercise is represented in Fig. 3, plotted by Barger et al. (2) from data derived from several sources for man at rest and during exercise at various levels of intensity. This relation is clearly representable by a straight regression line. If we select three points in this line, A for the resting state, B for moderate exercise (oxygen consumption of 1000 ml per min) and C for severe exercise (oxygen consumption of 3000 ml per min), and draw straight lines from the origin through these points to intersect the circles of the diagram, we see immediately and quantitatively that tissue oxygenation, as indicated by a rising arteriovenous oxygen difference, by a fall in venous oxygen content in oxygen saturation, and in venous P_{O_2}, is reduced progressively with increasingly vigorous exercise.

Second, the marked differences in the oxygenation of the various tissues of the body at rest can be represented as in Fig. 4. Here each point represents the oxygen consumption (ml per min) and the blood flow (1 per min) of one of six of the major organs of the body, based on the data assembled by Bazett (3). Note that the values of the metabolic and flow rates for each organ are not weight-specific, but are the absolute values. It is interesting to see how the organs with oxygenation below average (skeletal muscle, brain and heart) are those in which blood flow regulation is predominantly metabolic; and those with oxygenation above average (the liver, skin and kidneys) are those in which nervous regulation of blood flow is predominant.

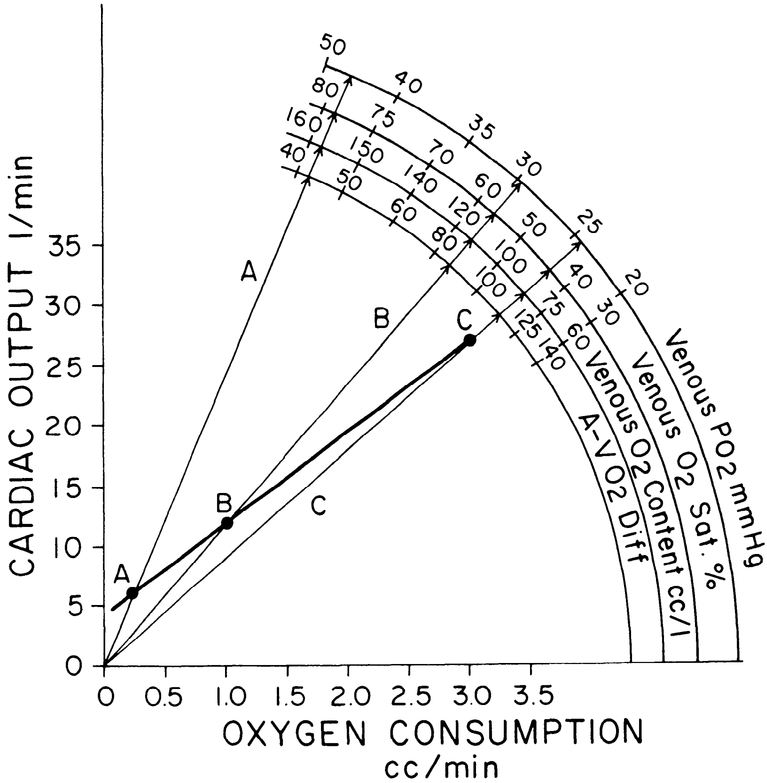

Fig.3. The relation between the blood flow and oxygen consumption of human subjects at rest and in exercise; together with derived measures.

A final word of warning is in order. The estimates of tissue P_{O_2}, venous oxygen saturation and venous oxygen content obtainable from the diagrams described above all rest on assumptions of the constancy of arterial oxygen content, the oxygen capacity of the blood, and the course of the hemoglobin dissociation curve. Thus, it is inapplicable (beyond the representation of the arteriovenous oxygen difference) to such conditions as arterial hypoxemia, anemia, polycythemia, acidosis and alkalosis.

Summary. A graphic method is described whereby, from knowledge of the oxygen consumption and blood flow rates of organs (or of the whole body), there can be represented simultaneously the arteriovenous oxygen difference, and, if certain assumptions are justified, also the venous oxygen content, the venous hemoglobin saturation, and the tissue P_{O_2}. Its value in portraying the changes of these values during exercise, and the distribution of degree of oxygenation of the various organs is shown by several examples.

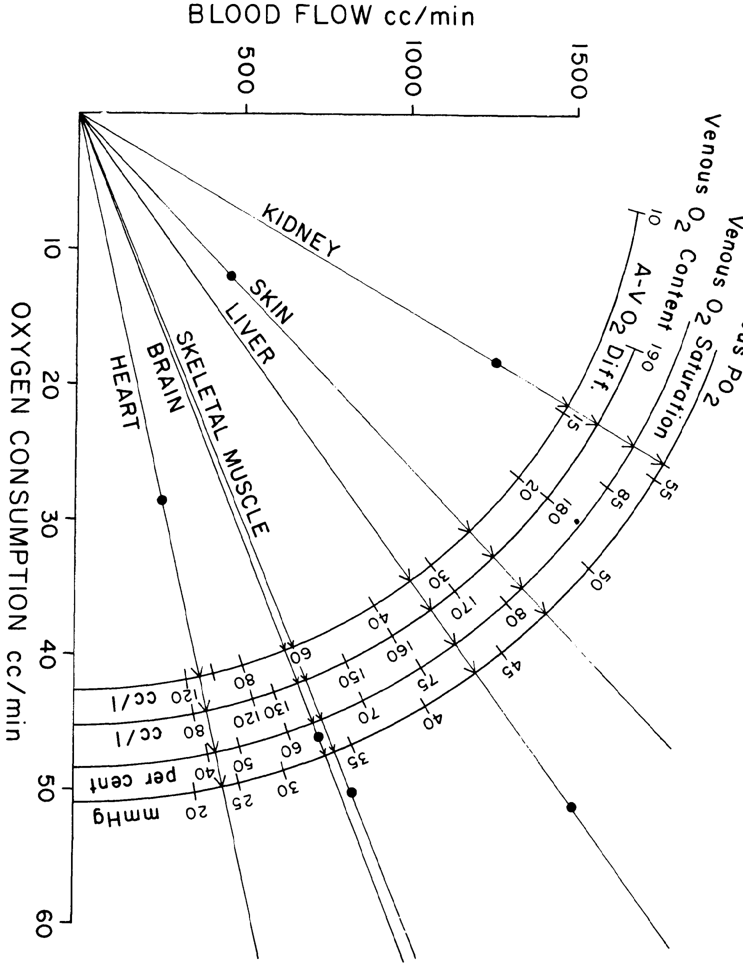

Fig.4. The relation between the blood flow and oxygen consumption of various human organs at rest.

REFERENCES

1. Burton, A. C. Physical equilibrium of small blood vessels. Am. J. Physiol. 164: 319-329, 1951.
2. Barger, A. C., V. Richards, J. Metcalfe, and B. Gunther. Am. J. Physiol. 184: 613-623, 1956.
3. Bazett, H. D. In P. Bard, Medical Physiology. 10th Edition, p. 221. St. Louis: Mosby Co.

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