A Continuous Cardiac Output Recorder Employing the Fick Principle

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A continuous cardiac output recorder has been developed utilizing an oxygen consumption recorder, an arteriovenous oxygen difference recorder and a computer. The computer continuously derives and records the cardiac output by dividing the rate of oxygen consumption by the A-V oxygen difference. Calibration of the continuous cardiac output recorder against a Ludwig stromuhr showed that under many different conditions and many different levels of cardiac output the 305 individual calibration points had a mean deviation from the regression line of ± 7.7 per cent. This correlation is as satisfactory as previously reported correlations between the intravenous dye method for recording cardiac output and the direct Fick method.

DURING the past two years a continuous recorder for cardiac output has been employed in this laboratory for studying different factors that affect venous return and cardiac output. This apparatus utilizes the direct Fick principle for measuring output. It employs three separate components (fig. 1) including an arteriovenous oxygen difference recorder, a continuous oxygen consumption recorder and an analog computer that derives the cardiac output continuously from the measurements made by the first two components. Two models of the arteriovenous oxygen difference recorder have been described previously,1-2 and many uses other than that of recording cardiac output have been demonstrated for this apparatus. The continuous oxygen consumption recorder also has been described previously,3 and it too, has many other probable uses as important as that of recording cardiac output. The present paper describes a method for recording cardiac output continuously using these two instruments along with a computer system. It also gives the calibration of the system and examples of results obtained.

DESIGN

The details of the arteriovenous oxygen difference recorder and of the continuous oxygen consumption recorder have been described in previous reports. The general principles of their operation are as follows: The A-V oxygen difference recorder has two cuvettes. Venous blood is pumped through one and arterial blood through the other. A light source provides a beam of light that passes first through the arterial cuvette, then through the venous cuvette, alternating back and forth between the two. The beams transmitted through both cuvettes are focused on the same photomultiplier tube. When they are out of balance with each other, a circular optical wedge, the optical density of which increases as the wedge turns, is automatically rotated by a servosystem until they are rebalanced again. The A-V oxygen difference is directly proportional to the degrees rotation of the wedge and the wedge is coupled to a potentiometer so that the difference can be recorded in electrical units.

In the continuous oxygen consumption recorder, normal room air is pulled by a vacuum pump at a constant rate into the recorder. This air enters by way of the coiled tube (fig. 1) and passes continuously through the T tube that connects with the animal's tracheal cannula. The animal breathes in and out of the flowing stream of air, but in doing so it does not alter the rate of air flow to the
OXYGEN CONSUMPTION RECORDER

Regulated to within 0.1%

Input Signal from Oxygen Consumption Recorder

Input Signal from A-V O₂ Difference Recorder

FIG. 1 Top. Schema of the continuous cardiac output recorder, showing recording of arteriovenous oxygen difference between the blood of the right ventricle and the blood of the carotid artery, recording of oxygen consumption by means of an intratracheal tube, and continuous computation of cardiac output from these two recordings by an analog computer.

FIG. 2 Middle. Circuit diagram of the analog computer.

FIG. 3 Bottom. Calibration of the continuous cardiac output recorder against a Ludwig stromuhr.

GUYTON recorder. A continuous sample of the air entering the recorder is passed through a Beckman recording oxygen analyzer. When no oxygen at all is being used by the animal the oxygen analyzer measures a voltage output that is equal to that measured for normal room air; when the animal removes oxygen from the flowing stream of air, the deviation of the output voltage is directly proportional to the rate of oxygen utilization per minute.

The electrical outputs of the A-V oxygen difference recorder and of the continuous oxygen consumption recorder are fed into an analog computer (fig. 2). It employs a servo-type division circuit in which the input voltage from the oxygen consumption recorder is automatically balanced against the input voltage from the arteriovenous oxygen difference recorder by means of a servo-driven potentiometer $R_2$. The position of potentiometer $R_2$ at which the two voltages balance is a measure of the ratio of the two voltages and when properly calibrated also depicts the quotient of oxygen consumption divided by A-V oxygen difference. Since cardiac output is proportional to this quotient, the position at which potentiometer $R_2$ balances can be calibrated directly in terms of cardiac output.

To allow direct recording on a D.C. recorder the shaft of potentiometer $R_2$ is connected also to potentiometer $R_4$. The position at which $R_4$ balances is also a measure of cardiac output. This potentiometer is coupled by means of an appropriate electrical circuit to any high resistance D.C. recorder.

The calibration of the instrument has purposefully been made nonlinear (fig. 3), so that very wide ranges in cardiac output can be recorded on the same record. To achieve this type of calibration the computer has been arranged, first, to divide A-V oxygen difference by oxygen consumption. The output of this gives a linear relationship between the meter deflection and the reciprocal of cardiac output. Then by reversing the polarity of the output terminals, the reciprocal of the reciprocal of cardiac output or, in other words, the cardiac output itself is recorded, but this recording is nonlinear. The nonlinearity allows the record to become progressively compressed at the higher ranges of cardiac output.

Another computer has also been constructed that divides the A-V oxygen difference directly into the oxygen consumption. This gives a linear recording of cardiac output, but it does not have as wide a range as the arrangement shown in figure 2.

OPERATION OF THE SYSTEM

To operate the instrument heparinized arterial blood and venous blood are pumped through the
 CONTINUOUS CARDIAC OUTPUT RECORDER

Euvettes of the A-V oxygen difference recorder and air flow through the oxygen consumption recorder is adjusted to a constant rate. Before connecting the animal to the apparatus, switch $S_1$ of the computer is placed in position 1. Then $R_1$ and $R_2$ are adjusted, respectively, for coarse and fine zeroing of the output signal from the oxygen utilization apparatus at the beginning of the experimental run—that is, before any oxygen begins to be used. This preliminary adjustment compensates for different atmospheric conditions and for instrumental drift from day to day. To find the appropriate balance point, $R_1$ and $R_2$ are adjusted until the servo-motor of the computer reverses itself from forward to backward or backward to forward. In other words, the servosystem is used as a galvanometer to determine the nullpoint for the zero adjustment.

Once the zero baseline for oxygen consumption has been established the animal is allowed to breathe into the system and switch $S_2$ is turned to position 2. The computer then divides the two input signals, giving a continuous record of cardiac output. Drift of the instrument is essentially zero in all components except for the zero baseline for oxygen consumption, and it too is usually negligible if the Beckman oxygen analyzer is maintained at constant temperature.

CALIBRATION

Figures 3 illustrate the calibration of the continuous cardiac output recorder against a Ludwig stromuhr used simultaneously for measuring cardiac output. This was accomplished as follows: Using an open-chest dog anesthetized with pentobarbital (30 µg./Kg.), the right atrium was cannulated and all the blood entering the right atrium was passed through an external circuit consisting of a pump, a heater circuit, appropriate pressure regulating devices, and a Ludwig stromuhr. Heparin was injected in an initial dose of 5 µg./Kg. and supplementary doses were given as required. After passing through this circuit the blood was returned to the pulmonary artery. In other words, all blood bypassed the right ventricle and the blood flowing through the external flowmeter included all the venous return to the heart (even that from the coronary system except for a very minute amount flowing by way of the Thebesian vessels into the left heart).

The cardiac output was increased or decreased by transfusing blood into the animal or hemorrhaging the animal, by administering varying doses of epinephrine at continuous rates of infusion, and by infusion of Tyrode’s solution. The individual points in figure 3 represent 305 simultaneous determinations of cardiac output by the stromuhr and by the continuous cardiac output recorder. This calibration curve is a composite of measurements made in 10 successive dogs. Many additional measurements have been made comparing a Shipley rotameter with the continuous cardiac output recorder, but for calibration purposes the stromuhr has been used because of its inherent accuracy.

The mean deviation of the individual points from the regression curve of figure 3 is ± 7.7 per cent, and the standard error of the deviation from the mean of all the points is ± 0.7 per cent. From these results it can be seen that the cardiac output recorder has sufficient accuracy for most studies on cardiac output. Indeed, this correlation is better than previous reports of correlation between the direct Fick method for recording cardiac output and dye injection methods.

TYPICAL RECORDS

Figures 4 and 5 illustrate typical recordings of cardiac output using the continuous cardiac output recorder. Simultaneous recordings of arteriovenous difference and rate of oxygen consumption are also shown. Figure 4 illustrates the effect of blood transfusion into a dog, showing an immediate very marked elevation in cardiac output, and elevation in oxygen consumption, and a decrease in arteriovenous oxygen difference. In this figure, the rate of oxygen consumption soon returned almost to normal while the cardiac output was still about twice the control value. Yet, over a period of 25 min. all 3 measurements returned almost exactly to control values.

Figure 5 illustrates the effect on the cardiac output of hemorrhage. In this record the
cardiac output did not reapproach the control value nearly as rapidly as it did following transfusion. This observation correlates well with previous studies that have shown that blood volume reapproaches the control value far more rapidly following transfusion than it does following hemorrhage. Also important is the course of oxygen consumption following hemorrhage. This did not decrease to nearly the same degree as the cardiac output, but, instead, the A-V oxygen difference increased greatly, providing a considerably enhanced oxygen utilization coefficient which was almost, but not quite, sufficient to compensate fully for the tendency of decreased blood flow to reduce oxygen consumption.

**SUMMARY**

A continuous cardiac output recorder employing the Fick principle has been developed and used for the past two years. The apparatus employs an arteriovenous oxygen difference recorder that automatically measures the A-V oxygen difference by a photometric principle, a continuous oxygen consumption recorder that measures the rate of oxygen consumption by means of a paramagnetic oxygen analyzer, and an analog computer that continuously derives cardiac output from the A-V oxygen difference and oxygen consumption measurements. Calibration of the apparatus indicates that its accuracy is highly suitable for most physiologic measurements. Several are presented.

**SUMMARIO IN INTERLINGUA**

Un continue registrator del rendimento cardiac, utilisante le principio de Fick, esseva disveloppate e se trova in uso a iste laboratorio deposit duo annos. Le apparato utilisa (1) un registrator del differentia arterio-venose de oxygeno que mesura le differentia arterio-venose de oxygeno automaticamente per medio de un principio photometric, (2) un continue registrator del consumption de oxygeno que mesura le intensitate del consumption de oxygeno per medio de un analyzator paramagnetic de oxygeno, e (3) un computator analoge que computa continuemente le rendimento cardiac super le base del differentia arterio-venose de oxygeno e le mesuration del consumption de oxygeno. Le calibration del apparato indica que su accuratia es altemente appropriate pro le majoritate del mesurationes physiologic. Plure exemplos es presentate.

**REFERENCES**


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