CLXXII. AN APPARATUS FOR THE GRAPHIC RECORDING OF OXYGEN CONSUMPTION AND CARBON DIOXIDE OUTPUT, ESPECIALLY ADAPTED FOR CLINICAL WORK.

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EXPERIENCE with Krogh's [1923] recording respiration apparatus has shown clearly that it is a very great advantage in clinical work to have oxygen consumption graphically recorded, because the graph makes it possible to see whether the respiration and metabolism are uniform or not, a control which is specially necessary in studying subjects untrained in metabolic experiments, such as most patients will be.

While the determination of a patient's oxygen consumption is relatively easy to obtain, there are certain special difficulties in determining the carbon dioxide, arising from the fact that a slight change in the ventilation may give rise to a considerable change in the carbon dioxide content of the body; therefore metabolic experiments of short duration with patients often give very misleading results regarding the respiratory quotient, as patients still more than other untrained persons tend to alter their ventilation when breathing through a mask or mouthpiece.

An apparatus which could record not only the oxygen consumption but also the carbon dioxide output would be helpful in clinical metabolic work, because it would permit the observation during the experiment of every change in ventilation, oxygen consumption and carbon dioxide output, and therefore give much safer results than an ordinary apparatus.

Under many circumstances it would also be convenient to avoid gas analyses.

In the following pages an apparatus of this type will be described.

Hanriot and Richet [1891] have invented and used an apparatus for measuring both oxygen consumption and carbon dioxide output; they use three equal gas meters; one measures the inspired air, the second the expired air, and a third the expired air after absorption of the carbon dioxide in a suitable absorber. The difference in reading between the second and the third meter shows the amount of carbon dioxide eliminated during a certain time, while the difference between the first and the third shows the oxygen absorbed. The method of Hanriot and Richet has not been generally adopted, undoubtedly because there are special sources of error in gas meters which are difficult or even impossible to overcome with the arrangement described.

Closer investigations have led the writer to the opinion, that the most serious errors arise from changes in the air pressure affecting the water level. An example will show the importance of this. An air current is led through a gas meter at a constant rate, the volume of air per revolution being measured independently of the meter; if now a sort of braking effect is exerted on the shaft of the gas meter the result will be, first that the air pressure just great enough to run the drum will increase, and therefore the water level in the drum will be changed, and hence the volume of air corresponding to the revolution of the meter will also be considerably changed.

Fig. 1.

Fig. 1 shows an arrangement partly based on the principle of Hanriot and Richet, in which the sources of errors arising from the gas meters have been reduced to such an extent that accurate determination of the human respiratory exchange can be made.

The apparatus is of the closed circuit type, the air being circulated by two symmetrical gas meters, arranged on a common shaft, which is revolved at a suitable rate (one to three revolutions per minute) by a small electric motor fitted with a simple governor to secure constancy of the rate. The gas meter drums are placed in a common water-bath, and as this water-bath is mounted on levelling screws it is easy to obtain such an angle between the axis of the double gas meters and the water level that the two parts of the gas meters are giving exactly the same volume of air for a full revolution. (If the volumes of the drums are exactly identical the axis of course has to be parallel to the water level.)

Gas meter I pumps air at a certain rate from the pipe (*a*) to the recording spirometer (*A*), which is of the type described by Krogh and used in his recording respiration apparatus. The box of the spirometer is filled with moist soda lime to absorb CO_2 , and the pressure of the air in it remains constant whatever the position of the spirometer bell. Gas meter II pumps just that quantity of air out from spirometer (*A*) which was put in by meter I and delivers it to the pipe (*d*). When therefore the ingoing air contains CO_2 the quantity of this gas will be recorded by the downward movement of the spirometer bell (*A*).

The pipe (*d*) carries the air through a second recording spirometer (*B*) back to meter I, but at (*f*) the pipe is provided with a side tube which can be connected through a mouthpiece or mask with the respiratory system of a patient.

If this side tube is closed and the gas meter motor and recording drums started each spirometer will write a wave line, each wave corresponding to one revolution of the double gas meter. The waves arise from small irregularities, *e.g.* eccentricity in the two gas meters' drums, but if the levelling screws of the water-bath are correctly adjusted the wave lines will be horizontal.

If a person is breathing into the side tube the spirometer (*B*) will record the respirations of the subject, but the graph will show a slight decline corresponding to the difference between the volume of air inspired and expired. It is well known that this difference is due to the volume of CO_2 eliminated being (as a rule) smaller than the volume of O_2 absorbed, and if the decline of the graph is measured by means of a scale divided in litres over a period of, say, 10 minutes the resulting figure represents the oxygen absorbed — the CO_2 eliminated during that period. Simultaneously spirometer *A* records directly the CO_2 output, and the oxygen consumption is therefore easily calculated: oxygen consumption = carbon dioxide output + difference between oxygen consumption and carbon dioxide output.

The air current in the apparatus is running so fast that the volume passing through a transverse section in one minute is not less than thrice the ventilation of the subject in the same time; if this condition is maintained valves are superfluous.

Fig. 2 shows the apparatus in a convenient form which has been in use for about two years with entire satisfaction. The gas meters and spirometers are arranged in a common water-bath, the spirometers recording on a common drum, most conveniently with ink of different colours. The water-bath is fitted with an overflow tube to secure constant water level; it contains about 100 kg. water, and the expired air is led through a pipe of considerable length which is immersed in the bath to cool the air to the temperature of the bath before it enters the gas meter. From the service pipe to the spirometer (*B*) there is a wide pipe to secure that every change in air pressure caused by the respiration is taken up promptly by the spirometer (*B*), so that there can be an absolutely constant pressure in the gas meter I.

The accuracy of the results largely depends upon the care with which the spirometers are balanced; every change in the air pressure in one of the spirometers will affect the water level in the corresponding gas meter and so disturb its accuracy. The spirometers therefore are arranged on special bearings and balanced with a double set of counterbalances, a large one for gross and a small one for fine adjustment. The counterbalances are adjustable horizontally and vertically, this allowing convenient compensation for buoyancy of the spirometer.

The accuracy of the measurements is greatly increased by dissolving 1 litre glycerol and 5 g. sodium glycocholate in the water in the bath, this securing a homogeneous film of liquid on the spirometer bells and gas meter drums, when these parts are moving from the water into the air; this liquid also gives only a relatively small resistance when a dry spirometer bell is dipping in it. To secure that the liquid is slightly acid a small amount of salicylic acid may be useful.

Fig. 2.

The apparatus is tested for tightness by placing a weight of 100 g. on the spirometers and recording, without running the meters; if the apparatus is tight the lines written will be horizontal.

Then it is adjusted with the meters running, by means of the screws, so that the two gas meters give the same volume of air per revolution; the spirometers will in such case record horizontally.

The balancing of the spirometers is correct, when the wave lines are horizontal, whether the spirometers are filled with air or nearly empty; this

securing that the buoyancy is correctly compensated. It is of course the safest plan to let the apparatus record for some time before or after each experiment, to be sure that it is correctly adjusted. If the wave lines are not quite horizontal, it is not necessary to adjust the apparatus. The change in level can be measured and allowed for in calculating the result. If, for instance, spirometer *A* rises during a complete revolution 0.15 litre, the position of spirometer *B* will (when the apparatus is closed and air-tight) be lowered to the same extent, as shown in Fig. 3. A corresponding correction must therefore be added to the recorded volume of CO₂ and subtracted from the record of the difference O₂ - CO₂.

Special tests have been made to make sure that the respiratory movements and the high temperature of the expired air cannot influence the records. On the side tube was attached a large rubber ball which was forcibly compressed, corresponding to a frequent deep breathing. The recorded line was parallel to the wave line recorded, when the rubber ball was not in use. In another experiment the rubber ball was inserted on a tin spiral tube immersed in very hot water to secure that the temperature of the expired air had no disturbing influence; the line of "respirations" recorded was parallel.

Finally several experiments were made by burning alcohol in the apparatus. The side tube was removed and the air current conducted through a suitable container enclosing a small alcohol-burner, which was supplied with alcohol from a burette. At the moment when the alcohol level passes a division on the burette, the pens are moved from the recording drum for a few seconds, and so a convenient record of the rate of combustion of the alcohol can be obtained. The table gives a series of such experiments:

No.	T.	Bar.	Spirometer		R.Q.	Oxygen
						0° 760 mm. (litres)
1	17°	763	„	<i>B</i> 160	.665	4.42
				<i>A</i> 317		
				477		
2	17°	763	„	<i>B</i> 161	.664	4.44
				<i>A</i> 318		
				479		
3	19°	763	„	<i>B</i> 163	.663	4.46
				<i>A</i> 321		
				484		
4	19°	763	„	<i>B</i> 162	.662	4.42
				<i>A</i> 319		
				481		
5	19°	763	„	<i>B</i> 162	.666	4.46
				<i>A</i> 323		
				485		
6	19°	763	„	<i>B</i> 162	.667	4.48
				<i>A</i> 325		
				487		
Mean					.664	4.45

In each experiment 3.10 g. alcohol $\left(d \frac{15^\circ}{15^\circ} = 0.7970\right)$ were burned corresponding to $\frac{310 \times 99.1 \times 67.23}{46} = 4.49$ litres oxygen.

Theoretical oxygen consumption 4.49 litres.

Theoretical R.Q. 0.667.

The table shows the great uniformity of the measurements, and the agreement between the measured and theoretical quotients is also very good. There is a difference of about 1 % between the calculated and measured oxygen consumption, but it is doubtful whether this is due to an error of the measurement with the apparatus or to an error in the determination of the amount of alcohol burned.

Fig. 3. Curves of respiration experiment and control.

- S. Special scale for measuring curves divided in litres; right for measuring CO_2 (spirometer A), left for measuring differences $\text{O}_2 - \text{CO}_2$ (spirometer B).
 O—O. Zero line for measurements.
 C. Control curves drawn by spirometers. Heavy line spirometer A, faint line spirometer B. The lines are seen to be nearly horizontal. Two controls are made, one with A in top position and B nearly empty, another with positions reversed. The error per revolution is in both positions and for both spirometers the same (0.15 litre), showing correct compensation for buoyancy.
 A. Curve from experiment. Spirometer A showing CO_2 absorption in 10 min. (distance 18.8 cm.).
 B. Curve from experiment. Spirometer B showing respiration of subject and difference $\text{O}_2 - \text{CO}_2$ in 10 minutes. For calculation of results see below.

Fig. 3 shows the graph of an experiment and the special scale used for the measurements; the readings in litres are written on the paper and the calculation is as follows:

T. 18° , Bar. 752 (reduction factor 0.909).

Correction:	Litres		Litres
for a total revolution of the drum		CO_2 before experiment	4.20
(30 minutes)	0.15	CO_2 after experiment	2.80
for 10 minutes	0.05	Difference	1.40
		+ correction	0.05
		CO_2 output	1.45
$\text{O}_2 - \text{CO}_2 = 0.51$		$\text{O}_2 - \text{CO}_2$ before experiment	5.38
$\text{CO}_2 = 1.45$		$\text{O}_2 - \text{CO}_2$ after experiment...	4.82
O_2 1.96	R.Q. = 0.740	Difference	0.56
O_2 reduced to 0° 760 and		- correction	0.05
$0.909 \times 1.96 = 1.78$ litres		Difference between O_2 consumption	
CO_2 reduced to $0.909 \times 1.45 = 1.32$ litres		and CO_2 output	0.51

The heat production can be calculated with the help of tables compiled by Zuntz and Schumburg [1901].

The calculation and tables are also given by Krogh [1916].

The ventilation can be calculated in the following manner. With a good planimeter the total area between inspirations and expirations in an experiment is measured; this is easily obtained by moving the pin of the planimeter from top to top of all the expirations in the experiment, following the last respiration down to the inspiration and then through all the deepest points of the inspirations and up to the point in which the measuring has started; the reading of the planimeter will then give an area, and this area divided by the length of the experiment in centimetres on the abscissa will give the mean depth of respiration in centimetres; which can be transformed into litres by means of the special scale. The average respiration multiplied by the number of respirations during the experiment and divided by the duration of the experiment in minutes will give the ventilation per minute.

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