SOME ASPECTS OF DETERMINATION OF THE CARDIAC OUTPUT BY THE REBREATHING METHOD

R. S. Vinitskaya and N. A. Koganova

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It is shown that the rebreathing method can be used to study the cardiac output even when the ventilation does not correlate with the pulmonary blood flow. pCO_2 was measured in mixed venous blood by equilibrating it with pCO_2 in the alveolar air by the rebreathing method. A gas mixture with a CO_2 concentration close to that in venous blood was produced by the subject himself during rebreathing into a bag with a capacity of 2-3 liters, filled with oxygen. Irregularity of distribution of ventilation relative to blood flow was judged from the shape of the CO_2 concentration versus time curve. If signs of irregularity are present, it is impossible to make $p_{et}CO_2$ equal to p_ACO_2 and for that reason pCO_2 of arterialized blood was determined. By means of this correction it is possible to determine the cardiac output of patients with cardiac and pulmonary diseases. The possibility of using standard nomograms for calculating the CO_2 concentration in the arterial and venous blood in the presence of appreciable disturbances of the acid–base balance is discussed.

KEY WORDS: *carbon dioxide; rebreathing; cardiac output.*

Carbon dioxide can be used as an indicator gas by means of which the cardiac output can be determined by the indirect Fick method. The method is based on the equilibration of pCO_2 of mixed venous blood with pCO_2 of the alveolar gas during rebreathing. Although this method has been known for a long time, it began to be used on a wide scale only with the appearance of low-inertia CO_2 gas analyzers [1, 3, 4, 6, 8, 9, 15]. Not withstanding all the temptations to use a bloodless method and simple indicator gas for determining cardiac output, the reliability of the method has been criticized [7, 10, 12, 15]. Doubts have been expressed about the accuracy of equilibration of $p_{\bar{v}}CO_2$ and p_ACO_2 during rebreathing; an extremely interesting phenomenon, the nature of which has not yet been adequately explained, has been discovered when pCO_2 has been found to be higher in the alveoli air than in the blood flowing from and into the lungs [10, 13, 16]. Moreover, incorrect results can be obtained if it is assumed that pCO_2 of arterial blood is always equal to pCO_2 of the spinal portion of the expired air, i.e., if $p_{et}CO_2$ is taken for p_ACO_2. Errors always arise during the calculation of the CO_2 concentration from the corresponding partial pressure without allowing for many factors involved in the binding of carbon dioxide in the blood. All these matters have repeatedly been discussed in the literature; nevertheless, in most papers in this field good correlation has been found between the values obtained by the rebreathing method and by other methods [17, 19].

The accuracy and reproducibility of the method are largely dependent upon the procedure used in the test and, in particular, on allowance for the concrete details of the air of the investigation and of the subject studied. The object of this paper is to show that the rebreathing method can be used even when p_ACO_2 and the indices of the acid–base balance differ considerably from normal and when there is irregularity of the pulmonary ventilation. This can be observed in healthy subjects working under special conditions and is frequently found in patients with diseases of the heart and lungs.

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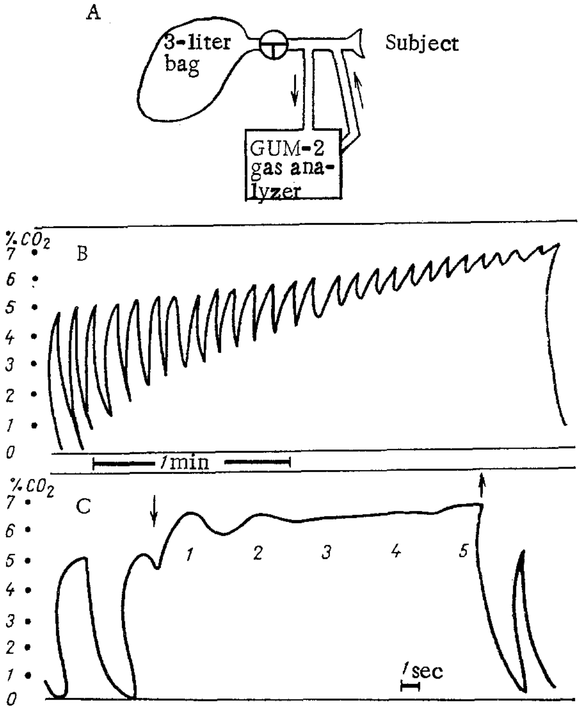


Fig. 1. Determination of cardiac output by the CO_2 rebreathing method: A) scheme of investigation; B) recording of concentration of CO_2 as it accumulates in the bag (preparations of the mixture); C) recording of CO_2 concentration during equilibration of p_ACO_2 with $p_{\bar{v}}CO_2$ (numbers in Fig. 1C denote successive expirations during equilibration).

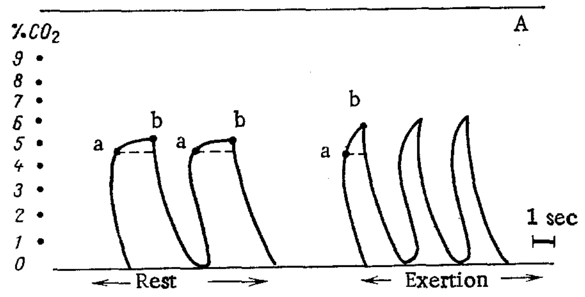
PROCEDURE

After the subject has rested for 30 min the expired air is collected for 3-5 min in a Douglas' bag; the gas mixture is analyzed in a gas analyzer (the GUM-2 Capnograph, Smolensk Factory, USSR) and passed through a gas meter. By this ordinary procedure the rate of elimination of CO_2 can be determined ($\dot{V}CO_2$, ml/min). This value can also be calculated on the basis of a spirographic test: $\dot{V}O_2$ is determined in ml/min and, assuming RQ = 0.825, $\dot{V}CO_2$ can be calculated.

STAGES OF REBREATHING

1. The bag from an anesthetic apparatus, connected to a 3-way stopcock, is filled with 2-3 liters of oxygen (Fig. 1A). 2) The subject breathes the ordinary room air for a few minutes, during which the CO_2 concentration is recorded continuously. 3) By turning the stopcock, the subject is connected to the bag, from which he rebreathes for 1.5-2 min. A record of this stage of the investigation is given in Fig. 1B. The expired mixture is returned to the bag from the gas analyzer. CO_2 gradually accumulates in the bag and its concentration approximates that in the venous blood. When the difference $F_{(e-i)}CO_2$ is about 0.5%, the subject is disconnected from the bag by turning the stopcock and he reverts to breathing room air. This rest lasts 3-5 min until the initial value of F_ACO_2 is restored. 4) The subject is then again connected to the bag; for 15-20 sec he inhales and exhales the prepared mixture and the CO_2 concentration is recorded at this time at a speed of 0.5 cm/sec (Fig. 1C). Complete equilibrium between the inspired and expired gas is observed after 2, 3, or 4 inhalations: This is the so-called equilibration plateau. The last stage is repeated a few minutes after normalization of F_ACO_2.

In the method as described above the subject himself prepares a mixture close in its pCO_2 value to mixed venous blood. This is particularly important in cases when, because of constant hyper- or hypoventilation, pCO_2 differs appreciably from normal. In such cases the use of standard mixtures containing 7-8% CO_2 is unsuitable. During rebreathing and individually prepared mixture the equilibration plateau is reached at the 3rd or 4th expiration, and as



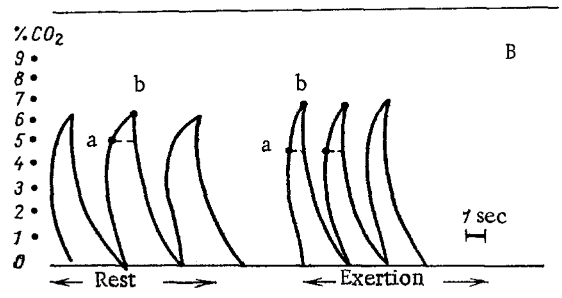


Fig. 2. CO_2 concentration during rebreathing measured at rest and during physical exertion: A) healthy subject K.; B) patient N. Point a indicates beginning of alveolar phase, point b final CO_2 concentration in expired air.

a rule when the procedure is repeated, the pCO_2 values of these plateaux coincide. At the beginning of the investigation, when the subject is breathing air, the shape of the CO_2 concentration curve can be used to judge the irregularity of ventilation with respect to the blood flow in the lungs. If the rate of change of CO_2 in the alveolar phase of expiration is low (1-3 mm Hg/sec) the final pCO_2 ($p_{et}CO_2$), the mean alveolar pCO_2 (p_ACO_2), and pCO_2 of the arterial blood (p_aCO_2) are very close; the difference between these values is not more than 2 mm Hg (Fig. 2A). However, if there is an irregular distribution of ventilation relative to blood flow, the rate of rise of pCO_2 in the alveolar phase of expiration increases sharply (Fig. 2B). In that case $p_{et}CO_2$ cannot be taken as equal to the mean alveolar or, still less, to the arterial pCO_2. The writers have found that in patients with pulmonary diseases $p_{et}CO_2$ could be higher than in the arterial blood by 8-10 mm or even more [5]. If the course of the CO_2 concentration curve is altered, p_aCO_2 must therefore be determined directly by analysis of a sample of arterialized blood with a micro-Astrup or similar instrument.

CALCULATION OF THE VENO-ARTERIAL DIFFERENCES IN CO_2 CONCENTRATIONS

In healthy subjects this calculation is usually done using standard nomograms for CO_2 [20] . However, if the buffer properties of the blood are disturbed, the quantity of bound CO_2 may vary considerably. We accordingly studied the possibility of errors arising when standard nomograms are used when there are appreciable deviations of the blood bicarbonate and hemoglobin concentrations from normal. For this purpose, indices of the acid–base balance and hemoglobin concentrations were determined in arterialized blood from 20 patients with various heart defects; next, using the Siggaard–Andersen nomogram (i.e., allowing for the actual bicarbonate and hemoglobin concentrations), the CO_2 concentration was calculated in arterial and venous blood; the corresponding values also were obtained by the use of the standard nomogram. In the patients of this group the hemoglobin concentration varied from 10.2 to 17.5 g% and pH from 7.36 to 7.45; the buffer bases (BB) varied from 36 to 56 meq/liter. We found that the CO_2 concentration, calculated from the actual data, may differ by 14-15 vols.% from the value obtained by the standard nomogram. Meanwhile the difference in the calculated veno-arterial difference was about 0.5 vol.%, rising only rarely to 1-1.5 vol.%. The standard nomogram can thus be used for approximate calculations. In some cases, however, when there are sharp fluctuations in the concentrations of buffer bases and hemoglobin, the error in the determination of cardiac output can be reduced by the use of factual data. This can be done if the state of the acid-base balance is known.

The above remarks apply not only to sick but also to healthy persons spending long periods under special conditions, e.g., at high altitudes.

The rebreathing method is extensively used for determination of the cardiac output not only in tests in the resting state, but also during physical exertion. The individual mixture prepared by the subject at rest at the beginning of the investigation will no longer be close in its composition to venous blood during physical exertion and, accordingly, the equilibration plateau is not obtained at the 3rd or 4th expiration. In such cases it is most convenient to extrapolate in order to find $p_{\bar{v}}CO_2$ [9].

During exertion one other source of distortion which can substantially affect the results of determination of cardiac output must be considered. With an increase in the respiration rate even in healthy subjects the shape of the CO_2 concentration curve reflects a high rate of rise of this parameter in the alveolar phase of expiration (Fig. 2A). If marked changes in the CO_2 concentration are present in the alveolar phase of expiration, it is therefore better to analyze the arterialized blood during exertion.

REPRODUCIBILITY OF RESULTS OF DETERMINATION OF CARDIAC OUTPUT

Cardiac output was determined in 18 healthy subjects and patients by the rebreathing method several times on different days. The period of rest between the investigations, which were carried out in recumbency, was strictly observed. The mean difference between the two CO_2 determinations ($\bar{v}$ – a) was 0.32 vol. % and the difference in cardiac output 0.33 liter/min, or under 10% of the mean measured value. This reproducibility of the results obtained in the resting state indicates that the rebreathing method is suitable for use when determining cardiac output.

This bloodless and comparatively simple method, which does not inconvenience the subject, can be used with advantage to study not only healthy subjects but also patients of various kinds, when the use of the Fick method is contraindicated or impossible. Irregularity of the ventilation with respect to the blood flow and disturbance of the buffer properties of the blood may distort the value of the cardiac output obtained, but the error can be reduced if the shape of the CO_2 concentration curve in the expired air and the indices of the acid-base balance of the arterialized blood are taken into consideration.

LITERATURE CITED

1. B. E. Votchal and O. A. Votchal, Trudy Kazan. Med. Inst., 41, 350 (1972).
2. N. N. Kanaev, Fiziol. Zh. SSSR, No. 4, 431 (1966).
3. V. L. Karpman, R. A. Merkulova, and B. G. Lyubina, Teor. Prakt. Fiz. Kul'tury, No. 6, 69 (1974).
4. B. S. Katkovskii, Yu. D. Pometov, and G. V. Machinskii, in: Development of Physiological Instrumentation for Scientific Research in Biology and Medicine [in Russian], Moscow (1968), p. 300.
5. T. S. Tsuzmer, R. S. Vinitskaya, and N. A. Koganova, Exper. Khir., No. 3, 22 (1967).
6. I. S. Breslav, A. M. Shmeleva, and B. N. Volkov, Fiziol. Zh. SSSR, No. 7, 1139 (1973).
7. P. Ceretelli, Y. C. Cruz, L. E. Farhi, et al., Resp. Physiol., 1, 258 (1966).
8. C. R. Collier, J. Appl. Physiol., 9, 25 (1956).
9. J. G. Defares, J. Appl. Physiol., 13, 159 (1958).
10. D. Denison, R. H. T. Edwards, G. Jones, et al., Respir. Physiol., 7, 326 (1969).
11. D. Denison, R. H. T. Edwards, G. Jones, et al., Respir. Physiol., 11, 186 (1971).
12. S. Godfrey and E. Wolf, Clin. Sci., 42, 345 (1972).
13. G. H. Gurtner, S. H. Song, and L. E. Farhi, Respir. Physiol., 7, 173 (1969).
14. W. F. Hamilton, in: Handbook of Physiology. Section 2, Circulation, Vol. 1, Washington (1962), pp. 551-584.
15. R. Jernerus, G. Lundin, and D. Thomson, Acta Physiol. Scand., 59, 390 (1963).
16. N. L. Jones, E. Y. M. Campbell, R. H. T. Edwards, et al., J. Appl. Physiol., 27, 356 (1969).
17. K. Klausen, J. Appl. Physiol., 20, 763 (1965).
18. G. Y. McHardy, Clin. Sci., 32, 299 (1967).
19. G. Muiesan, C. A. Sorbini, E. Solinas, et al., J. Appl. Physiol., 24, 424 (1968).
20. R. Root, in: Handbook of Physiology, Respiration, Philadephia (1958), p. 64.
21. F. J. W. Roughton, in: Handbook of Physiology, Section 3, Respiration (ed. by W. O. Fenn and H. Rahn), Vol. 1, Williams and Wilkins, Baltimare, Maryland (1964), pp. 767-825.