Alveolar Air, Respiratory Dead Space, and the "Ventilation Index." (17787)

J. B. BATEMAN*

From the Division of Physics, Biophysical Research, Aero Medical Laboratory, Mayo Foundation, Rochester, Minn.

The purpose of this paper is to report an experimental result of unexpected simplicity obtained in the course of an attempt to devise tests for respiratory impairment. The ideas that led to this finding were somewhat as follows: The search for tests of adequacy of ventilation reduces essentially to the attempt to relate measurable respiratory characteristics to a more or less abstract system of unknown "alveolar" partial pressures and respiratory dead space, and to relate this, in turn, to the composition and distribution of blood entering and leaving the vessels of the lungs. A dilemma immediately arises, for the unknown quantities are interdependent; one way or another, one is always faced with the choice between alveolar partial pressures obtained by assuming a value for the respiratory dead space, and the converse. It is true that methods have been developed for the more direct measurement of both alveolar partial pressures and dead space, but as these are open to theoretical and practical objections, especially when they are used in conjunction with experiments involving muscular exercise, it is desirable to circumvent them. One is thrown back on the dilemma, to which such partial solutions are available as that offered by Krogh and Lindhard(1) who advocated the calculation of alveolar partial pressures from those of whole expired air by means of the Bohr equation, with the adoption of a value for the respiratory dead space such as that obtained for a limited number of normal persons in the very careful measurements of Krogh and Lindhard. The relevance of this is, however, open to question, since in those measurements an inspiratory pause was introduced to ensure complete intrapulmonary mixing.

The difficulty is expressed algebraically by 2 equations which can be derived very simply from the Bohr(2) equations:

$$V_t = \frac{qO\ [1 - (1 - Q)\cdot fO]}{m} \cdot \frac{1}{fO - fO''} + V_d \qquad (1)$$

$$V_t = \frac{qC}{m} \cdot \frac{1}{fC''} + V_d \qquad (2)$$

where V_t is tidal volume; m is number of breaths per minute; qO and qC are oxygen and carbon dioxide turnover per minute, respectively; fO is the fraction of oxygen in the inspired gas; fO'' and fC'' are "effective" alveolar oxygen and carbon dioxide fractions, respectively; Q is respiratory quotient, and V_d is "effective" respiratory dead space.

The unknown quantities in these 2 equations are 3 in number: fO'', fC'', and V_d; the remainder are readily measured in the laboratory. If a change in physiologic state is brought about—for example, by muscular exercise—a solution is still impossible, since one is not entitled to assume that any of the 3 unknown quantities remain unchanged. It is clear that no progress is possible along these lines without either a knowledge of the physiologic factors which might permit formulation of an additional equation, or empirical observation of the operation of those factors.

The latter approach seemed preferable, and muscular exercise the most suitable means of bringing about physiologic change. Accordingly, the measurements indicated by equations

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* Present address Camp Detrick, Frederick, Md.

1. Krogh, A., and Lindhard, J., *J. Physiol.*, 1917, v51, 59.

2. Bohr, Christian, *Skandinav. Arch. f. Physiol.*, 1890, v2, 236.

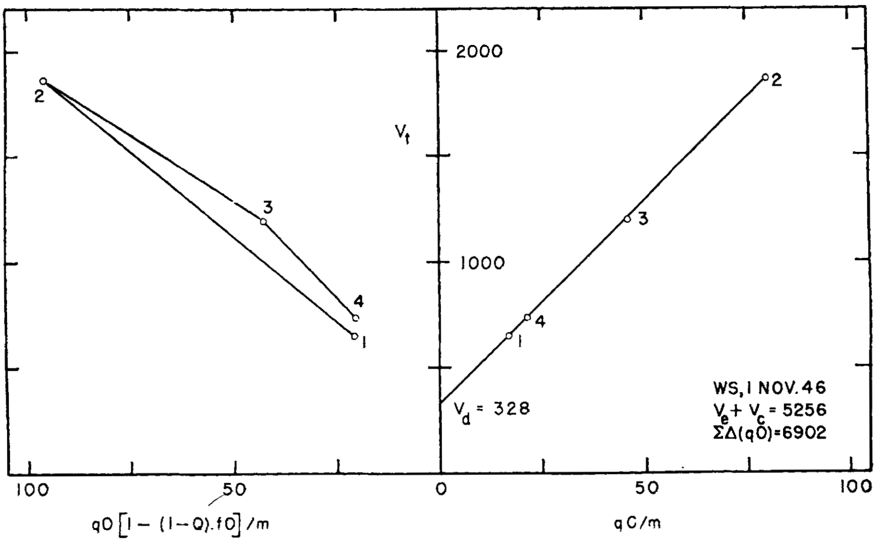

FIG. 1.
Response of tidal volume, oxygen and carbon dioxide turnover, and breathing rate to muscular exercise, plotted in accordance with text equations (*1*) and (*2*). Points marked 1 are for the person sitting at rest; 2 refers to a 2-minute exercise period (4 miles per hour, 10% grade), 3 to the first 4 minutes of recovery, 4 to the second 4 minutes. The subject's vital capacity was 5,256 cc BTPS; the extra oxygen consumption during exercise and 8 minutes of recovery was 6,902 cc BTPS. Symbols are explained in text.

(*1*) and (*2*) were performed on a group of normal persons at rest, during muscular work, and during recovery. The measurements were made by a standard open-circuit method; the exercise was done on a treadmill for a period of 2 minutes, and the recovery was followed for 2 consecutive periods of 4 minutes each. The amount of exercise varied widely and its severity was assumed to be related to the excess consumption of oxygen associated with it during the entire ten minutes of observation.

The data were examined graphically, the tidal volume being plotted against $qO\ [1-(1-Q)\cdot fO]/m$ and qC/m, respectively. It was consistently observed that the values of qC/m were linear with V_t, while those of the oxygen factor usually were not (Fig. 1). The most convenient interpretation of this result is to suppose that the effective partial pressure of carbon dioxide in the alveoli and the effective respiratory dead space both remain constant in normal persons during muscular exercise of some severity and the ensuing period of recovery. In seeking any other interpretation one would be obliged to assume the linear relationship to be the result of a fortuitous compensation of changes in alveolar carbon dioxide and respiratory dead space. Accepting the simpler explanations as the more expedient, one can at once derive from the experimental data values for (1) the effective respiratory dead space, represented by the value of the tidal volume when qC/m is extrapolated to zero; (2) the effective partial pressure of carbon dioxide in the alveoli, and (3) the effective partial pressures of oxygen in the alveoli during each of the 4 experimental periods.

The numerical data thus obtained in the entire series of 13 experiments on 9 normal persons are given in Table I, together with the vital capacities and the excess oxygen consumed during exercise and recovery. It is evident that the absolute variation in pO'' is generally rather greater, and often much greater, than that of pC''; this is true also of the percentage variation in $pO—pO''$, in agreement with the conclusion already drawn from inspection of the graphical data. The figures showing the constancy of pC'' provide good evidence that experiments of this kind can be of value in obtaining reliable

TABLE I.
Effective Respiratory Dead Space and Alveolar Partial Pressures Calculated From Respiratory Response to Exercise.*

Subject	Vital capacity	Excess O_2 uptake	V_d	pC'' Rest	pC'' Exercise	pC'' Recovery		pO'' Rest	pO'' Exercise	pO'' Recovery	
Men											
JB	5145	5806	370	39.6	39.9	40.6	40.8	92.8	90.2	102.8	104.7
	4717	5180	310	36.9	37.2	38.7	38.2	94.6	91.9	101.4	103 8
	5012	2252	260	34.5	34.9	35.3	37.5	100.6	98.8	97.2	98.0
	4855	1674	280	33.2	33.1	35.0	35.0	99.5	100.2	96.2	98 3
	4917	1668	300	35.9	35.5	37.8	40.2	99.8	99.8	95.8	94.6
JH	5098	4766	280	35.1	34.9	35.3	35.9	102.6	96.3	105.4	105.8
W	5265	6902	330	36.0	35.7	36.0	35.7	98.8	100.2	109.1	108.3
R	6449	5640	295	35.3	34.7	33.9	36.0	103.7	101.9	108.0	104.6
H	6268	1956	330	34.0	33.4	33.7	36.1	103.3	101.8	102.3	103.6
JM	3737	3872	195	34.3	33.8	34.8	34.6	103.9	106.3	106.5	108.0
Women											
R	3380	1958	205	29.6	29.6	29.3	29.4	107.5	106.5	108.0	109.0
L	3078	2370	180	30.0	29.8	30.1	30.6	105.5	106.5	109.0	109.5
P	3395	3522	155	28.3	28.1	30.4	27.8	110.5	110.5	113.0	117.0

* Vital capacity and excess oxygen uptake in ml BTPS. Excess oxygen uptake is amount consumed in 2 min. exercise and 8 min. recovery, minus resting consumption over 10 minutes. V_d is effective respiratory dead space obtained by plotting qC/m against tidal volume. pC'' and pO'' are effective alveolar partial pressures (in mm of mercury) of carbon dioxide and oxygen, respectively, calculated from the experimental data by means of text equations (*1*) and (*2*). The 4 figures in each case correspond to rest, exercise, and the two 4-minute recovery periods. Values of effective dead space have not been corrected for dead space of face mask.

information concerning the effective partial pressures in the alveoli and the effective respiratory dead space. Such information is perhaps to be considered superior to that gained by other methods, in respect both to technical simplicity and to lack of dependence on dubious assumptions. The effective alveolar partial pressures are related in a clearly defined manner to accurately measurable quantities, on the one hand, and to a simple model of the respiratory process, on the other; consequently they should constitute an acceptable definition of the state of the gaseous phase at the site of respiratory interchange, with which can be compared the effectiveness of the lungs as judged by the gaseous exchanges of the blood.

The effective dead space obtained by the present method likewise has definite advantages as an index of ventilatory efficiency, since it represents a physiologically effective, rather than an anatomically defined, dead space, and can be expected to be sensitive to anomalies in distribution and mixing of the intrapulmonary gases. This is true also of the effective dead space obtained from lung clearance measurements, but such measurements are technically so demanding as to have little value in a routine laboratory. In view of the high degree of consistency of the present measurements, the fact that they can most easily be interpreted in terms of a constant dead space is of particular significance. It has been rather generally supposed that increased ventilation brings about an increase in the respiratory dead space, and even Krogh, who was inclined to oppose this view, was forced to concede that a moderate increase may occur.

The present considerations also point to what may be a valid form of ventilation index. The respiratory volume per unit of oxygen consumed has been used widely as a ventilation index in clinical circles and almost as widely criticized. Equation *(1)* shows that an index involving oxygen consumption would have to be calculated in the form $m(V_t - V_d)/qO$, instead of mV_t/qO, but would then be constant only as long as the other quantities in the equation—notably the respiratory quotient and the alveolar oxygen partial pressure—remained unchanged. A valid index, as the data in Table I demonstrate, would be $m(V_t - V_d)/qC$, the *effective* respiratory volume per unit of *carbon dioxide* produced; but calculation of such an index is equivalent to a partial analysis along the lines of Table I and would be superfluous if the data permitted the complete calculation of V_d, fO'' and fC''.

Summary. The ventilatory response of 9 normal persons to muscular exercise can be described in part by a linear relationship between tidal volume and carbon dioxide output per breath. The intercept (Fig. 1) is the effective respiratory dead space and the slope is the reciprocal of the effective alveolar carbon dioxide partial pressure. Thus, during exercise and recovery, involving large changes in oxygen consumption and tidal volume, both effective respiratory dead space and effective alveolar carbon dioxide remain remarkably constant. This circumstance makes possible the calculation of dead space and alveolar partial pressures without recourse to direct sampling methods.

Received March 28, 1950. P.S.E.B.M., 1950, v73.