DETERMINATION OF THE ALVEOLAR DEAD SPACE

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A method of obtaining the alveolar dead space (ADS), the part of the functional dead space (FDS) that is most difficult to determine, is suggested. The method of determination is based on the difference in the CO_2 concentration in the venous blood flowing to the lungs for oxygenation under quiet breathing conditions and the CO_2 concentration in alveolar portions of the expired air after breath holding for 10 sec at the level of ordinary inspiration. The mean volume of ADS (V_{DAl}) as a percentage of the alveolar part of the respiratory volume for 20 healthy subjects in the sitting position and for 12 of them in recumbency, with the corresponding sampling errors and dispersions, is: V_{DAl} (sitting) = 8.0 ± 1.5% (P = 0.95), σ = 3%; V_{DAl} (recumbency) = 5.0 ± 1.7% (P = 0.95), σ = 2.6%. It is suggested that first, the effectiveness of utilization of the inspired air for ventilation of the lungs can be judged on the basis of the FDS determined by the newly developed method; second, that ADS be determined for the diagnosis of pulmonary embolism; and third, that shunting of the pulmonary blood flow be estimated from the difference between the value found for FDS by Bohr's equation and for FDS determined by the suggested formula.

KEY WORDS: Ventilation of the lungs; functional dead space; anatomical dead space; alveolar dead space.

The functional dead space (FDS) is a measure of the degree of ineffectiveness of utilization of air entering the lungs and respiratory passages, in the gas exchange with the blood. It consists of two parts: anatomical and alveolar. The anatomical part is accounted for by inspired air entering the respiratory passages from which it is exhaled without having taken part in the gas exchange with the blood. This volume can be determined by Bohr's equation, as suggested for calculation of the anatomical dead space (AnDS) or planimetrically from the single expiration curve [1]. If the dead space is found planimetrically allowing for the alveolar gradient of the single expiration curve, the value obtained will include not only AnDS, but also part of the alveolar dead space (ADS), due to the presence of laminar heterogeneities of gas composition in the lungs as a result of the insufficiently uniform diffusion mixing of the inspired and alveolar air [2-5]. The fraction of ADS due to laminar heterogeneities can conveniently be found together with AnDS. The alveolar part of FDS which must be determined, and which will be considered from now on, consists of the volumes of inspired air entering the unperfused regions of the lungs at the end of inspiration (situation a) and entering the regions where a blood supply exists and may be within normal limits, but where the permeability of the lung membrane is disturbed (situation b). In these regions of the lungs gas exchange between air and blood is absent. Partial disturbances of the blood flow or diffusion of gases through the membrane also lead to some increase in ADS. Situations a and b are illustrated schematically in Fig. 1, where another case (case c), corresponding to lung volumes in which ventilation, blood flow, and gas exchange through the lung membrane are not disturbed, is also represent.

The method of determining ADS suggested in this paper is based on the difference between the CO_2 concentration (cCO_2) in the venous blood and cCO_2 measured in alveolar portions of the expired air after breath holding at the level of ordinary inspiration, for this difference is determined by the same causes as ADS existing in the lungs.

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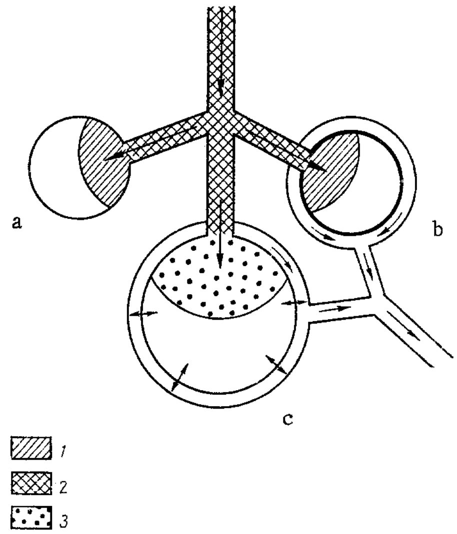

Fig. 1. Gas exchange in lungs represent schematically by 3 alveolar volumes: a) ventilation present, blood flow absent; b) ventilation and blood flow both present, gas exchange through lung membrane absent; c) normal gas exchange. 1) Volume of inspired air entering regions a and b of ADS at inspiration; 2) AnDS; 3) effective alveolar respiratory volume entering region c and taking part in gas exchange with blood.

EXPERIMENTAL METHOD

The value of cCO_2 was obtained by means of a capnograph (from Godart, Holland). The investigation began after the patient had rested. The subject was connected to the instrument and breathed air until the instrument began to record stable values of cCO_2 from one expiration to another. Then, in accordance to instruction, the patient took an ordinary inspiration and held his breath for 10 sec; in expiration cCO_2 was determined in the alveolar portion F_{10}. The breath holding was chosen on the basis of the following requirements: A time interval of 10 sec is sufficient to allow equalization of cCO_2 between the alveolar air and venous blood flowing to the lungs in the regions represented in situation c (Fig. 1); this interval is shorter than the blood recirculation time and, consequently, over this time interval no changes take place in the composition of blood flowing to the lungs. Satisfaction of the first demand was confirmed by the fact that in healthy subjects the gas concentration in the last portions of expired air showed little change with a change in breath holding from 10 sec to the blood recirculation time.

The true value of cCO_2 in venous blood flowing to the lungs for oxygenation of F_V was determined by the rebreathing method in two stages. The subject first produced a working mixture for himself with cCO_2 close to the venous level. After resting, the patient was connected to the bag containing the working mixture and, in accordance with instruction, took several (5-7) breaths with respiratory volumes (RV) close to the vital capacity of the lungs in the course of 15-20 sec. During this period, as a rule, recirculation of the blood did not take place but equilibrium was established between the alveolar gas and the blood. Otherwise the investigation was carried out in three stages (the third stage similar to the second)

When the time arises during rebreathing when no CO_2 is exchanged between the alveolar air and blood, the gas concentration in the alveolar air is known to be higher than its true concentration in the venous blood. However, it has been shown that this difference is small under quiet breathing conditions [6], when it can be disregarded. This was taken into account when F_V was determined by the rebreathing method. This value can also be found by direct measurement in mixed venous blood.

The difference between F_{10} and F_V obtained in this way is due to the same causes as ADS. In fact, during the period of breath holding cCO_2 in region c is equal to F_V. However, in expiration the CO_2 expelled from region c is diluted with air expelled from regions a and b,

TABLE 1. ADS Expressed as Percentage of Alveolar Part of RV, for Healthy Subjects in Sitting Position and Recumbency

Subjects	Sitting			Recumbency		
K.	6,8	7,0	2,86	7,0	7,0	0
S	6,2	7,0	11,43	6,3	6,9	8.7
Z	5,4	5,6	3,57	5,4	5,55	2,7
P-v	7,05	7,55	6,62	7,2	7,5	4,0
U.	6,63	7,0	5,29	6,8	7,0	2,86
K-va	5,4	6,2	12,9	5,4	6,2	12,9
A.	6,4	7,0	8,57	6,9	7,0	1,43
K-a	5,4	6,15	12,2	5,6	6,2	9,68
N	6,0	6,5	7,69	6,25	6,6	5,3
K-na	7,1	7,4	4,05	7,2	7,4	2,7
P	7,27	8,1	10,25	7,4	8,0	7,5
S-v	6,0	6,7	10.45	6,5	6,62	1.81
T.	6,45	6,8	5,15			
S-o	6,1	6,9	11,59			
T-v	5,95	6,65	10,53			
Sh	6,6	7,35	10,2			
P-a	6,8	7,4	5.41			
L	6,0	6,25	4.0			
K-n	5,95	6,3	5.56			
K-da	6,2	7,0	11,43			

when no CO_2 is entering from the blood (Fig. 1). Accordingly F_{10} is less than the value of F_V determined by the rebreathing method, for during determination of the latter, CO_2 enters regions a and b because of rebreathing and its concentration in them becomes equal to its concentration in the venous blood. The equation for calculating ADS is obtained from the following equation:

$$F_{10} \cdot V_{TAl} = F_v \cdot (V_{TAl} - V_{DAl}), \tag{1}$$

where $V_{TAl} = (V_T - V_{DAn})$ is the alveolar RV, V_T is the RV, V_{DAn} is the volume of AnDS, and V_{DAl} is the volume of ADS. Equation (1) is valid because both the right and left sides are expressions for the quantity of CO_2 eliminated from the blood into the lungs and breathed out during one expiration. On the right side it is expressed through the value of cCO_2 established over a period of 10 sec in region c, and equal to F_V, and the volume expelled from this region at expiration. On the left side it is expressed through cCO_2 averaged for the volume exhaled from regions a, b, and c, and through this volume itself. V_{DAl} is found from equation (1):

$$V_{DAl} = V_{TAl}(F_v - F_{10})/F_v. \tag{2}$$

It will be clear from equation (2) that to calculate the volume of ADS, besides F_V and F_{10} it is also necessary to know the alveolar part of RV or, what amounts to the same thing, RV itself and the volume of AnDS. It is thus necessary to have a second instrument to measure volumes and to connect it to the capnograph in order to record cCO_2 and volume simultaneously. This is not difficult, but when estimating ADS it is possible to manage with the capnograph alone, by expressing the value of ADS as a percentage of the alveolar part of RV:

$$V_{DAl}(\% V_{TAl}) = (F_v - F_{10})100/F_v. \tag{3}$$

In this paper, equation (3) was used to estimate ADS.

EXPERIMENTAL RESULTS

To test the suggested method of determining ADS, its value was calculated for 20 clinically healthy members of the hospital staff aged from 19 to 33 years. Some of them had a history of bronchopulmonary diseases, mainly of the nature of common colds, but four had a history of pneumonia. The value of ADS was determined for all subjects in the sitting position and for 12 of them in recumbency. The results of the tests and the values of ADS calculated as percentages of the alveolar part of RV are given in Table 1. Averaging of the results gives values of ADS and also sampling errors and dispersions of this parameter for healthy subjects in the sitting position and recumbency:

$$V_{DAl} \text{ (sitting)} = 8.0 \pm 1.5\% \ (P = 0.95),\ \sigma = 3\%$$
$$V_{DAl} \text{ (recumbency)} = 5.0 \pm 1.7\% \ (P = 0.95),\ \sigma = 2.6\%$$

The difference obtained for ADS in healthy subjects in the sitting position and in recumbency is significant (P > 0.999).

One of the most commonly used methods of determination of FDS at the present time is calculation by Bohr's formula intended for this purpose [1]. However, this formula can be used only when shunting of the pulmonary blood flow can be disregarded and there is no discharge of blood from right to left. If shunting is present, the value of FDS calculated by Bohr's equation may be significantly higher than the real value and, consequently, may not correspond to the parameter as measured [2]. An advantage of the parameter determined by Bohr's equation is that it reflects irregularity of the ratio of ventilation to blood flow for different lung volumes, whereas the true value of FDS does not reflect that part of the irregularity which exists when perfused but unventilated regions, i.e., shunts, are present in the lungs.

Having estimated ADS by equation (3) and knowing RV and AnDS, the value of FDS (V_{DF}) can be found:

$$V_{DF} = V_{DAn} + (V_T - V_{DAn})\,(F_v - F_{10})/F_v. \quad (4)$$

The value of FDS determined in this way is independent of shunting of the pulmonary blood flow and, through its second term (i.e., ADS), it reflects only that part of the irregularity of the ratio of ventilation to blood flow that is connected with a decrease in the blood flow relative to ventilation for certain regions of the lungs. Besides these irregularities, FDS also reflects the presence of regions in the lungs with disturbance of gas diffusion on account of a disturbance of the lung membrane, but it is considered that such situations are extremely rare [7]. The fact that ADS for healthy subjects in a sitting position was greater than in recumbency emphasizes a decrease in the inequality of the ratio of ventilation to blood flow that is reflected in the value of ADS on a change from the sitting position to recumbency.

Some promising ways in which the parameters of ADS and the associated FDS can be used may be mentioned: 1) estimation of the effectiveness of utilization of the inspired air for ventilation of the lungs, when two parameters can be used: the ratio of the difference between RV and FDS to RV and the ratio of effective alveolar ventilation (determined as the product of respiration rate and the difference between RV and FDS) to the minute respiratory volume; 2) the diagnosis of pulmonary embolism, in the presence of which ADS is considerably increased; 3) estimation of shunting of blood in the pulmonary circulation, which can be judged from the difference between the value for FDS determined by Bohr's equation and its value determined by equation (4).

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