MIXING OF GASES IN THE DEAD SPACE OF THE RESPIRATORY TRACT

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The effect of diffusion processes on the boundary between alveolar gas and the dead space (DS) gas on the size of the DS was established. Breath holding experiments also indicate that diffusion processes influence the size of the DS. The size of the DS increases with an increase in the respiration rate if the tidal volume and functional residual capacity remain constant.

It can be taken as established that the dead space (DS) of the respiratory tract is not a constant value. It has been shown, for example, that the diameter and shape of the bronchi vary in healthy persons during respiration in connection with changes in the gas pressure in the air passages. It has also been found that the DS depends on the tidal volume if the volume of the lungs at the end of inspiration is fixed, on the volume of the lungs at the end of inspiration if the tidal volume is fixed, on the difference between the pressure in the lungs and in the mouth, and finally, that it decreases with an increase in the duration of breath holding [3].

The object of the present investigation was to study the role of diffusion processes at the boundary between the alveolar gas and the DS gas with different breathing patterns. It was shown previously [3] that DS is a function of the respiration rate, but this fact was associated with differences in the functional residual capacity at different respiration rates. In the present investigation the tidal volume and functional residual capacity of the lungs were therefore kept constant.

EXPERIMENTAL METHOD

The apparatus consisted of two instruments: a gas-flow meter and nitrogen gas analyzer. Having a gas-flow meter in the system enabled the results of nitrogen analysis to be recorded on a drum moving at a speed proportional to the volume of expired gas. This was done by means of a mechanical connection between the drum of the gas-flow meter and the siphon into which the expired gas mixture passed. Fluctuations of pressure proportional to the nitrogen concentration at expiration were transmitted from the nitrogen analyzer to the recording system of the gas-flow meter. A nonuniform time scale was also recorded by a time marker.

TABLE 1

Tube no	Length (in cm)	Diam. (in mm)	Inertia time (in sec)
1	100	10,2	0,085
2	68	18,7	0,086
3	140	20	0,084
4	63	19	0,082
5	116	10,5	0,083

To determine true values of the DS on the record of nitrogen analysis, the error due to inertia of the system had first to be determined. Two series of experiments accordingly were carried out: on models to discover the inertia time of the system (with glass tubes of different known volumes and recording of the nitrogen analysis results obtained by displacing the air contained in them with oxygen) and on healthy subjects in which the results of nitrogen analysis were recorded under different patterns of respiration (different respiration rates and holding the breath for different periods at inspiration).

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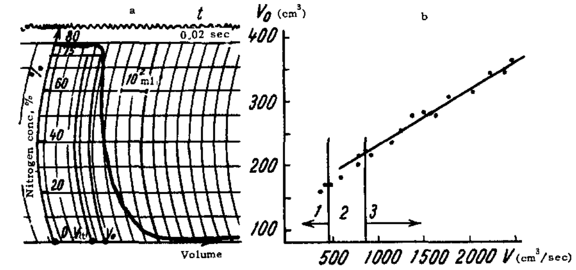

Fig. 1. Nitrogen analysis during expulsion of air from a tube by a flow of oxygen (a) and volume V_0 calculated from the record of this nitrogen analysis as a function of rate of ventilation of the tube with oxygen (b). In b: 1) region of laminar flow; 2) region of unstable flow; 3) region of turbulent flow. Explanation in text.

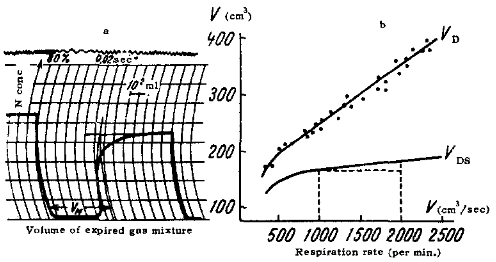

Fig. 2. Nitrogen analysis in man (a) and V_D and V_{DS} as functions of the maximal rate of expiration (b). Explanation in text.

EXPERIMENTAL RESULTS

In the experiments of series I the inertia time of the system was determined by means of live tubes of different lengths and diameters (see below).

Air in the tubes simulating dead spaces of different sizes was expelled with oxygen. This process was recorded on the drum (Fig. 1a). The air was displaced at different velocities v, at which either a laminar or a turbulent flow of oxygen was created. (At $Re < 1000$ the flow is laminar, at $Re > 2000$ the flow is turbulent, and at $1000 < Re < 2000$ the flow is unstable. Re denotes the Reynolds' number.) The volume V_0 corresponding to a decrease in the nitrogen concentration to 75% was determined by the nitrogen analyzer. This volume did not coincide with the volume of the ventilated tube V_t. If the flow of oxygen with which the tube was ventilated was turbulent, V_0 was found to be greater than V_t. This result can be explained because if the gas flow is turbulent, when its front can be regarded as straight, the excess of the measured volume over the true volume is determined by the inertia of the system (by delay in recording the nitrogen concentration).

The results of the experiments with tubes ventilated at different rates enabled the relationship between the value of $V_0 - V_t$ and the rate of ventilation V to be established within the region of turbulence (Fig. 1b). The tangents of the slope of the curve within the linear region give the inertia time of the system τ. From the results of five experiments (see above) its mean value is 0.084 sec.

If the tube was ventilated by a laminar flow of oxygen, the measured volume, allowing for the inertia of the system, was smaller than the true volume of the tube. This result is explained by the "tongue-shaped" front of the gas with a laminar flow.

An effect analogous to a decrease in V_0 within the region of laminar flow was observed on examination of the nitrogen analysis curves of human respiration in which case the value of DS fell more rapidly than by the linear rule, at velocities of expiration within the laminar region (see below).

The experiments of series II were carried out on three healthy subjects (the results of 30-40 measurements were analyzed for each subject). The subject initially breathed air, then pure oxygen. The process of expulsion of the nitrogen from the lungs by oxygen was recorded by a nitrogen analyzer (Fig. 2a). The segment V_D corresponds to the dead space of the respiratory tract. It is determined by the point of intersection of two tangents: one to the alveolar plateau of the curve, the other to the point of inflection of the curve, i.e., at the point of maximal rise of nitrogen concentration.

The nitrogen analysis curves for high rates of expiration had a higher value of V_M than at low rates of expiration. Allowing for the inertia time of the system did not obliterate this difference. The value of V_{DS} (the value of DS allowing for the inertia time) is given by:

$$V_{DS} = V_D - v\tau$$

and it depends, as before, on the maximal rate of expiration (Fig. 2b). In the turbulent region of expiration velocities this relationship approximates to a straight line. The mean-square scatter of the points from a straight line is not more than ± 3 ml.

With a change in the velocity of expiration from 1000 to 2000 ml/sec the value of DS was found to increase by 13-15 ml for all subjects. This dependence of DS on the respiration rate can be explained by diffusion processes at the border between the alveolar gas and the gas in DS. In the case of low rates the

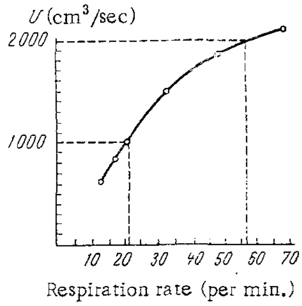

Fig. 3. Maximal rate of expiration as a function of respiration rate with constant tidal volume.

diffusion time was greater than for high respiration rates, and, consequently, on account of diffusion gas from DS can participate in the gas exchange.

It is clear from Fig. 2b that in the case of low rates the value of DS falls faster than would be expected from the linear function for the turbulent region. This can be attributed to the laminar "tongues" of the gas mixture at expiration.

To replace one variable (the maximal rate of expiration) by a more convenient variable (the respiration rate), a graph of one as a function of the other was plotted (Fig. 3). If used in conjunction with Fig. 2b, Fig. 3 enables the effect of diffusion on the size of DS to be estimated at different respiration rates. For instance, DS is increased by 13-15 ml with an increase in the respiration rate by 33 per minute. During physical exertion, when the respiration rate rises sharply, DS increases substantially on account of changes in the tidal volume and in the functional residual capacity [3, 4]. As the results show, diffusion processes also make their own contribution to the increase in DS during work.

The following experiments also indicate the importance of diffusion in the mixing of gases at the boundary between DS and the alveolar region. Nitrogen analysis curves were recorded during breath holding at inspiration for different periods. The results showed that DS is reduced by 30-35 ml if the breath is held at inspiration for 2.5 sec, by 40-50 ml if it is held for 5 sec, and by 60-80 ml if it is held for 10 sec. The longer the breath is held, therefore, the smaller the DS or, more precisely, the longer the duration of diffusion the smaller the measured value of DS. It can accordingly be concluded that diffusion processes at the boundary between DS and the alveolar regionhave some effect on the size of the DS.

LITERATURE CITED

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