MIXING OF GASES IN THE LUNGS BY DIFFUSION

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During forced breathing there is too little time for uniform mixing of the inspired gas by diffusion with the gas remaining in the lungs after expiration, the unevenness of ventilation increases, and this is manifested as a marked increase in the steepness of rise of the alveolar plateau on the nitrogen concentration curve obtained by the single-breath technique (oxygen is used as the test gas; the nitrogen concentration is recorded). The respiratory dead space is considerably increased during forced breathing.
KEY WORDS: forced breathing; diffusion of gases in the lungs; dead space of the lungs.

After inhalation of a gas its concentration differs in two samples of alveolar air taken at different depths of expiration [4]. This fact has been explained by regional inhomogeneity, i.e., the unevenness of ventilation of different parts of the lungs [5], for the dimensions of the respiratory lobule are such that the mixing of gases in it by diffusion is sufficient to balance out any unevenness of concentration in the process of breathing. However, recent investigations have indicated the existence of "stratified" inhomogeneity, i.e., unevenness of the concentration of gases in the consecutive orders of the distal segments of the bronchial tree [3], in addition to regional inhomogeneity.

It was shown previously that during quiet breathing the duration of the respiratory cycle is sufficient to ensure practically uniform mixing of the inspired gas and the alveolar gas remaining in the lungs after expiration [1]. The diffusion process ensures that the size of the respiratory dead space (DS) is kept sufficiently small on account of the passage of alveolar gas into the distal part of the DS.

The object of this investigation was to study the relationship between the size of the respiratory DS and pattern of breathing.

EXPERIMENTAL METHOD

The apparatus consisted of a nitrogen gas analyzer and the single-breath technique was used [1]. After breathing atmospheric air, the subject was given pure oxygen to breathe. During expiration the nitrogen concentration and the expired volume were recorded. The nitrogen concentration curves obtained during breathing under different conditions were subjected to further analysis. At the beginning of expiration 0% nitrogen was recorded, after which the nitrogen concentration rose rapidly and flattened out on the alveolar plateau. A planimetric method of determining the respiratory DS is illustrated in Fig. 1: the horizontal line is drawn as a tangent at the point of the highest nitrogen concentration (usually this is the extreme right point on the alveolar plateau) and the vertical line so that the two shaded triangles in Fig. 1 were equal in size. The region from the beginning of expiration to the vertical line, allowing for inertia of the instrument, corresponds to DS. Clearly the steeper the slope of the alveolar plateau, the greater the effect of the upper right triangle on the shift of the vertical line to the right.

The effect of diffusion on the size of the respiratory DS was investigated in six healthy subjects. Two types of breathing were chosen for comparison: 1) deep, slow breathing; 2) rapid but equally deep breathing (forced breathing).

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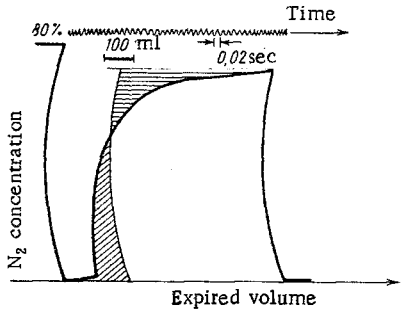

Fig. 1

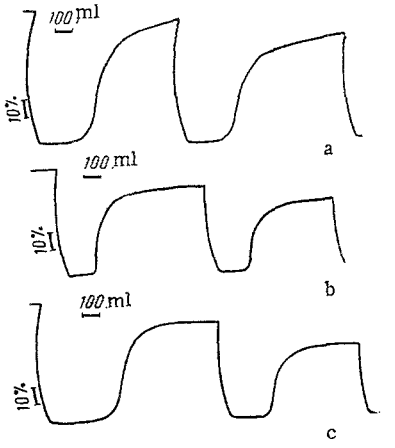

Fig. 2

Fig. 1. Nitrogen concentration in the expired gas during respiration. Planimetric determination of size of respiratory dead space (explanation in text).

Fig. 2. Nitrogen concentration curves for one of the subjects: a) forced breathing; b) quiet breathing; c) ordinary inspiration, holding the breath for 2 sec, forced expiration (explanation in text).

TABLE 1. Comparison of Results in Pairs Obtained during Slow, Deep Breathing and during Fast, Deep Breathing

Subject	Respiratory vol. (ml)	Respiration rate (min)	DS	ΔDS
			ml	
G	2400	7	160	210
	2400	25	370	
	1450	8	145	135
	1450	30	280	
	1300	8	140	135
	1300	32	275	
S	2300	7	240	160
	2300	25	400	
	1300	8	200	140
	1300	32	340	
	1900	8	225	165
	1900	30	390	
	1450	8	210	150
	1450	30	360	

Note: In each pair the results of forced breathing are given on the lower line.

EXPERIMENTAL RESULTS AND DISCUSSION

The nitrogen concentration curves obtained during slow, deep breathing showed a gradual rise to the alveolar plateau (Fig. 2b). During forced breathing there was a substantial increase in the steepness of the alveolar plateau (Fig. 2a). This was connected with an increase in the DS.

Pairs of results obtained during breathing under different conditions for two subjects are given for comparison in Table 1. To rule out any dependence of the size of DS on the respiratory volume, it was the same in each pair of results compared. As Table 1 shows, the respiratory DS increased significantly during forced breathing – by 135-210 ml compared with slow, deep breathing. Similar results were obtained with all the other subjects.

The mean results for all the experiments are summarized in Table 2. With an increase in the minute volume of respiration (from 7 to 18 liters/min for the first type and to 55-75 liters/min for the second type) of respiration DS increased in all subjects on the average by 100-150 ml. The increase in DS with forced breathing can be explained on the basis of an increased contribution of mechanical mixing and a decrease in the contribution of diffusion to the mixing of the gases in the lungs. The time for diffusion during forced breathing was not enough to ensure even mixing of the inspired air with that remaining in the lungs after expiration to the extent that it took place during quiet breathing. At inspiration inhomogeneity of the alveolar air was therefore found: a marked increase in the steepness of the alveolar plateau. Under these circumstances the respiratory DS was increased because of a shift of the boundary between DS and the alveolar space in the distal direction along the bronchial tree.

The gradual slope of the alveolar plateau observed in the healthy subjects during quiet breathing can be explained by three factors: 1) the continuous gas exchange in the lungs, 2) regional inhomogeneity, caused by the uneven distribution of the inspired gas, and 3) stratified inhomogeneity.

The effect of the first factor is explained on the grounds that the respiratory quotient was less than unity and decreased in the course of expiration; the alveolar nitrogen concentration must increase because

TABLE 2. Averaged Results of Analysis of Nitrogen Concentration Curves for Six Subjects during Breathing under Two Different Conditions

Subject	Type of breathing	No. of meas.	DS	ΔDS
			ml	
G.	Slow, deep	15	155	145
	Forced	15	300	
M.A.	Slow, deep	10	160	
	Forced	10	290	130
P.	Slow, deep	5	150	100
	Forced	5	250	
M.B.	Slow, deep	5	260	110
	Forced	5	370	
S.	Slow, deep	6	210	150
	Forced	6	360	
B.	Slow, deep	5	190	120
	Forced	5	310	

Note. DS for all subjects is statistically significant ($P < 0.05$).

of the decrease in the volume within which it is distributed. Quantitative analysis of this factor [6] showed, however, that its contribution to the gradient of the alveolar plateau was unimportant.

The contribution of regional inhomogeneity to the slope of the alveolar plateau implies the existence of well and poorly ventilated regions simultaneously in the lungs and a temporary shift in the emptying of these regions (the poorly ventilated regions must be emptied by the others). The theory of consecutive evacuation has been criticized [6]. The consecutive evacuation is very small as the sole explanation of the alveolar slope. It has accordingly been concluded that during quiet breathing stratified inhomogeneity makes an important contribution to the slope of the alveolar plateau, although this slope itself is very small in healthy subjects [3].

A considerable slope of the alveolar plateau was found during forced breathing. The question arises whether the increase in the alveolar slope is the result of the greater importance of consecutive evacuation of the well and badly ventilated segments of the lungs during forced breathing. The following experiments were carried out to test this hypothesis. The subject inhaled pure oxygen, held his breath for 2 sec, and then gave a very quick forced expiration. Holding the breath promotes the development of diffusion. The slope of the alveolar plateau in this case could have been attributed entirely to consecutive evacuation (regional inhomogeneity). However, the experiments showed that the slope of the alveolar plateau was virtually absent under these circumstances (Fig. 2c). Consequently, the alveolar slope during forced breathing (without breath holding) is explained by the inadequacy of the diffusion process and not by delayed exhalation from the poorly ventilated parts of the lungs.

In healthy subjects the alveolar slope, by whatever factors it is produced, is ill-defined during quiet breathing, and consequently these factors themselves must be unimportant under these conditions. During forced breathing however, the conditions favor an increase in stratified inhomogeneity, and this is expressed as a slope of the alveolar plateau. The inadequacy of the diffusion processes in this case is the cause of the increased size of the respiratory DS. The results of this investigation and their analysis provide an explanation for the well-known phenomenon of the sharp increase in DS during intensive muscular activity [2], during which the minute volume of respiration rises sharply, with the result that the mixing of the gases by diffusion is reduced.

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