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COMPOSITION OF ALVEOLAR AIR AND RATE OF PULMONARY VENTILATION DURING LONG EXPOSURE TO HIGH ALTITUDE

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COMPOSITION OF ALVEOLAR AIR AND RATE OF PULMONARY VENTILATION DURING LONG EXPOSURE TO HIGH ALTITUDE

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The composition of alveolar air during exposure to high altitude is of interest because it indicates more accurately the degree of hypoxia which the subject experiences than does the composition of the ambient or inspired air. For example, a subject breathing air at a simulated altitude of 16,000 feet may show an arterial oxygen saturation as low as 59% or as high as 91%, depending upon the minute volume of pulmonary ventilation (1). Likewise, during exposure to a low oxygen atmosphere, as in the anoxemia test for coronary insufficiency, the oxygen saturation of the arterial blood is dependent to an important degree upon the pulmonary ventilation. Pulmonary ventilation exerts its effect upon the oxygenation of the arterial blood primarily by altering the partial pressure of oxygen in the alveolar air.

In this paper measurements of alveolar oxygen and carbon dioxide pressures and rates of pulmonary ventilation are presented. The values were obtained during the exposure of four healthy subjects to gradually increasing simulated altitudes in a low pressure chamber during a thirty-five day period. The experimental conditions and detailed analyses of arterial blood findings have been presented elsewhere (2).

METHOD

Samples of alveolar air were obtained by the Haldane-Priestley technique from all four subjects every morning at 0630 before they

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arose from bed, care being taken that the men were as relaxed as possible. The samples were collected at the end of a rapid and forceful expiration, starting from the normal inspiratory position. They were then transferred to mercury sampling tubes and taken to sea level for analysis by the Haldane method. Above 22,000 feet, the samples were obtained periodically during a gradual ascent to 29,000 feet over an eight hour period. Though the subjects were not basal during this ascent, they were required to lie down and relax as completely as possible for ten minutes before giving the samples, which were then collected and handled exactly like the others.

Pulmonary ventilation was measured on one of the four subjects each day at 0830 (one and a half hours after breakfast). The resting subject inhaled from a large water-sealed spirometer, and inspiratory volume was measured each minute for five to ten minutes. The average of these readings was converted into expiratory minute volume by multiplying by the ratio of nitrogen concentrations in inspired and expired air. Pulmonary ventilation was thus expressed as expiratory minute volume and was corrected both for body temperature, ambient pressure, and saturation with water vapor (BTPS) and for standard temperature and pressure, dry (STPD).

Alveolar ventilation was calculated from the equation:

$$(1) \quad V_a = \frac{CO_2 \text{ output}}{\text{Alv } \% \; CO_2} \times 100.$$

Since no alveolar sample was taken at the time of the ventilatory measurements but since arterial blood was drawn and analyzed directly for $_pCO_2$ at this time (3), the alveolar $_pCO_2$ was considered equal to arterial $_pCO_2$ (4), and alveolar % CO_2 was calculated from the equation:

$$(2) \quad \text{Alv } \% \; CO_2 = \frac{\text{Arterial } {}_pCO_2}{\text{Bar. Press.} - 47}$$

Actually the arterial $_pCO_2$ corresponded closely to the alveolar $_pCO_2$ obtained earlier in the day from the Haldane-Priestley sample.

Since the Haldane-Priestley alveolar air determinations and the ventilatory measurements were not performed simultaneously, the respiratory quotients at the two times were compared to decide whether the ventilation at the two times was approxiamtely the same. The alveolar respiratory quotient, calculated from the equation:

$$(3) \quad \text{Alv. R.Q.} = \frac{\text{Alv. } _pCO_2 - \text{insp. } _pCO_2}{\text{insp. } _pO_2 - \text{alv. } _pO_2}$$

was compared to the expired air respiratory quotient, calculated in the usual way. Ferguson and Dugal (5) found that when the alveolar sample was given starting at the end of inspiration as in the present study, the alveolar respiratory quotient was a little higher than the expired air respiratory quotient. Our findings, shown in table 3 and figure 3, were the opposite, probably because the subjects were less close to a basal state at the time of the collection of expired air. It is probable, therefore, that the minute volumes of ventilation when measured, are a little higher than they would have been if they had been measured at the time of the alveolar sampling.

RESULTS

The alveolar carbon dioxide and oxygen pressures are shown in table 1. The individual values at each altitude were averaged, and these average alveolar pressures are plotted in figure 1. The smoothed curves obtained by Helmholz et al. (6) on a large number of subjects (acclimatized to 1,000 feet) are shown in broken lines, and the data reported by Schneider (7) are shown by single crosses.

In table 2 the rates of pulmonary ventilation are recorded, both under standard conditions (STPD) and under ambient conditions (BTPS). Alveolar ventilation, calculated for standard conditions, is also shown. In figure 2 these relationships are plotted.

DISCUSSION

One of the principal mechanisms by which tissue $_pO_2$ is sustained during the breathing of a low oxygen atmosphere is by the closer approach of alveolar $_pO_2$ to the $_pO_2$ of the inspired air. This is accomplished by an increase in pulmonary ventilation. At the same time alveolar $_pCO_2$ approaches more closely the $_pCO_2$ of the inspired air, i.e. it falls. If carbon dioxide production in the tissues remains constant, the lowering of alveolar $_pCO_2$ by increased ventilation causes a negative CO_2 balance until tissue $_pCO_2$ levels off at a lower value. During this transition period the CO_2 output in the expired air exceeds tissue CO_2 production, and the alveolar respiratory quotient is higher than the true metabolic respiratory quotient. When a steady state is re-established at the new level, CO_2 output in the expired air again equals CO_2 production in the tissues and the alveolar respiratory quotient equals the metabolic respiratory quotient.

The alveolar oxygen pressures found in our four subjects correspond closely to those found by Helmholz et al. in large numbers of subjects exposed to increasing altitude and also to the less numerous data of Schneider. Our data do not agree so closely with the data collected by Fitzgerald in 1913 (8) from residents at high altitudes (in the Rockies). The values for alveolar $_pCO_2$ correspond closely with those reported by other investigators for altitudes up to 18,000 feet. Above this altitude both alveolar $_pCO_2$ and alveolar $_pO_2$ values become increasingly lower in our men than in Helmholz's. This finding is strikingly similar to that which was found by the Mayo Clinic group in collaboration with the Aero Medical Laboratory at Wright Field, when men already acclimatized to 6,200 feet were taken to higher altitudes (10). The lower values for both alveolar $_pCO_2$ and alveolar $_pO_2$ for our subjects at altitudes above 18,000 feet were possible because the respiratory quotients were lower. (These relationships can be deduced from equation 3). The higher average respiratory quotient in the case of Helmholz's subjects is not surprising since the exposure of these men to high altitude was relatively brief and equilibrium conditions were not attained, whereas, due to their longer exposure, our subjects had attained equilibrium as shown by a nearly basal R. Q.

From figure 2 it is apparent that pulmonary ventilation (BTPS) increased steadily as altitude increased, though there were considerable individual differences. When pulmonary ventilation is expressed in liters per minute (STPD), however, there was little change with altitude, a finding in accord with the data of Schneider, and of Helmholz, and also with those of Barcroft (9) recalculated to standard conditions. Alveolar ventilation expressed in liters per minute (STPD) remained almost constant as altitude increased, indicating that approximately the same number of molecules of air were flushed in and out of the alveoli at all altitudes studied.

The data presented in this report thus confirm earlier indications that the acclimatized subject has a lower respiratory quotient than the unacclimatized. The amount by which ambient ventilation increases at increasing altitudes is variable but is of such an amount as to maintain on the average a constant level of ventilation when reduced to standard sea level conditions.

SUMMARY

(1) Alveolar gas pressures and resting pulmonary ventilation were repeatedly measured as four subjects were continuously exposed to increasing altitude in a low pressure chamber during a thirty-five day period.

(2) Average alveolar carbon dioxide and oxygen pressures correspond closely with the data of other observers up to 18,000 feet. Above this point the alveolar pCO_2 values of our subjects were lower. Alveolar pO_2 values were also slightly lower than those reported by Helmholz *et al*. The respiratory quotients of our partially acclimatized subjects were lower than those of the subjects of short term exposures. The values reported herein are probably more representative of the equilibrium state at any given altitude.

(3) In terms of ambient conditions, pulmonary ventilation was found to increase with increasing altitude. In terms of standard conditions, however, ventilation remained nearly constant at the altitudes studied. This indicates that roughly the same number of molecules of oxygen were taken into the lungs during inspiration at altitude as at sea level.

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TABLE ONE

Altitude in Thousand Feet	Alveolar Gas Pressures mm. Hg — McNutt PO2	McNutt PCO2	Morris PO2	Morris PCO2	Hertel PO2	Hertel PCO2	Wilkins PO2	Wilkins PCO2	Average All Subjs PO2	Average All Subjs PCO2	Alv. R.Q.
2	87	42	99	33	94	35	98	33	94.5	36	.84
4	84	43	-	-	97	31	95	34	88.5	36.5	.96
8	58	40	74	31	64	34	71	32	67	34	.83
9	54	40	65	32	65	33	70	30	63.5	34	.84
10	51	36	51	33	56	31	62	30	55	34	.75
11	48	38	59	30	58	32	63	29	57	32	.82
12	46	36	50	32	55	32	59	28	52.5	32	.82
13	42	36	49	31	50	32	61	26	50.5	31	.84
14	40	34	41	32	52	29	49	29	45.5	31	.84
15	36	34	40	31	50	28	50	26	44	30	.83
15.5	38	32	38	31	48	27	-	-	41	30	.81
16	36	32	-	-	43	28	47	26	42	29	.85
16.5	33	32	39	28	40	27	49	24	40	28	.80
17	35	30	37	28	44	24	44	26	40	27	.82
17.5	33	29	35	27	40	25	43	25	38	26.5	.80
18	32	29	35	26	36	26	41	25	36	26.5	.78
18	33	30	33	28	38	25	39	24	36	27	.79
18.5	32	28	38	25	42	22	46	21	37.5	24	.80
19	31	28	31	26	38	22	42	22	35.5	24.5	.79
19	33	26	34	25	39	22	43	20	37	24	.81
19.5	31	28	31	27	36	23	43	22	35	24.5	.82
20	30	28	-	-	34	23	38	22	34	24	.83
20.5	29	26	33	24	35	22	37	23	33.5	24	.84
21	28	25	31	24	34	20	-	-	31	23	.78
21.5	28	24	32	22	33	21	36	21	32	22	.81
22	21	22	31	22	33	20	36	19	30	21	.76
20	32	25	34	24	36	22	43	19	36	22.5	.83
20	32	26	35	24	38	22	43	19	37	23	.87
21	32	23	33	22	36	19	43	17	36	20	.82
23	30	21	30	20	34	16	38	16	33	18	.84
24	28	20	31	18	-	-	35	16	31	18	.82
25	26	19	30	17	30	15	32	16	29.5	17	.86
26.1	26	17	26	16	30	14	31	14	28	15	.79
27.4	24	16	25	14	-	-	-	-	24.5	15	.77
28.15	23	15	24	13	-	-	-	-	23.5	14	.76
29.03	23	13	21	14	-	-	-	-	22.5	13.5	.79
29.03	24	13	22	14	-	-	-	-			
20	33	24	34	24	37	19	42	18			
S.L.	110	30	128	22	117	28	135	20			
8/2	115	29	124	25	120	27	135	22			
8/4	114	29	-	-	-	-	-	-			
8/5	108	36	128	25	-	-	-	-			
8/7	109	34	-	-	-	-	-	-			
8/8	114	36	-	-	-	-	-	-			

TABLE TWO

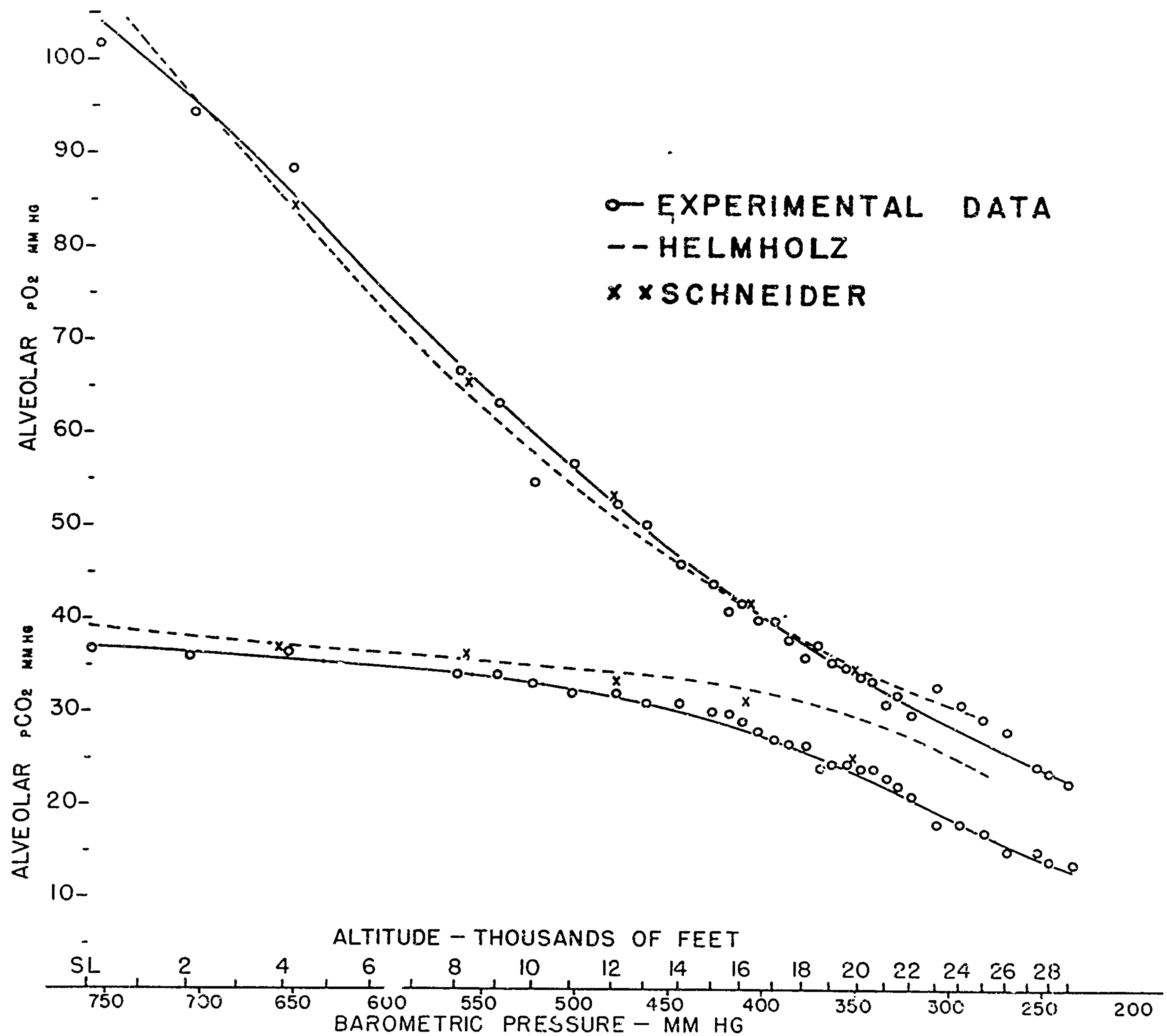
Respiratory Rate and Volume at Increasing Altitude, Measured Under Resting Conditions.

Altitude Thousand Feet	Subject	Resp. Rate per Minute	Resp. Min. Vol. L/Min. S.T.P.D.	Resp. Min. Vol. L/Min. B.T.P.S.	Alv. Vent. L/Min. S.T.P.D.
9	MC	12.8	4.91	8.55	3.21
10	MO	7.7	4.18	7.58	4.14
11	HE	12.2	4.85	9.18	3.46
12	WI	13.0	5.36	10.6	3.80
14	MC	13.5	4.56	9.87	2.84
15	MO	13.0	5.18	11.7	4.05
15.5	HE	8.4	4.80	11.10	3.93
16	WI	17.7	4.02	9.50	2.85
17	MC	11.6	4.47	11.1	4.00
17.5	MO	10.5	3.86	9.8	3.24
18	HE	11.0	4.4	11.45	3.82
18	WI	16.0	4.54	11.78	3.49
18.5	MC	15.0	5.12	13.58	4.03
19	MO	9.2	4.66	12.68	3.44
19.5	HE	7.0	4.82	13.42	3.75
20	WI	16.0	3.57	10.2	2.24
21	MC	13.3	3.60	10.78	2.68
21	MO	10.0	4.34	12.98	3.80
22	HE	24.0	6.01	18.94	3.62
20	WI	15.2	3.62	10.35	2.41
20	MC	10.8	4.70	13.44	3.80
21	MO	10.0	4.34	12.98	3.80
20	HE	18	8.08	23.1	5.40

TABLE THREE

Relationship of Alveolar Respiratory Quotient (under basal conditions) to Expired Air Respiratory Quotient (Under resting conditions).

Date	Altitude	BP-47 21	Alv PO_2	Alv PCO_2	Alv R.Q.	Expir. R.Q.	Subject
5	9	104	54	40	.80	833	MC
6	10	100	51	33	.67	834	MO
7	11	96	58	32	.84	828	HE
8	12	92	59	28	.85	898	WI
10	14	84	40	34	.77	774	MC
11	15	80	40	31	.78	813	MO
12	15.5	79	48	27	.87	896	HE
13	16	77	47	26	.87	804	WI
15	17	73	35	30	.79	805	MC
16	17.5	71	35	27	.75	798	MO
17	18	70	36	26	.77	831	HE
18	18	70	39	24	.77	798	WI
19	18.5	68	32	28	.78	810	MC
21	19	67	31	26	.72	868	MO
22	19.5	65	36	23	.79	798	HE
23	20	63	38	22	.88	796	WI
25	21	61	28	25	.76	832	MC
26	21.5	59	32	22	.82	879	MO
27	22	58	33	20	.80	850	HE
28	20	63	43	19	.95	856	WI
29	20	63	32	26	.84	881	MC
30	21	61	33	22	.79	827	MO
31	20	63					HE
1	20	63	42	18	.85		WI



EXPERIMENTAL DATA
HELMHOLZ
SCHNEIDER
ALVEOLAR pO2 MM HG
ALVEOLAR pCO2 MM HG
100
90
80
70
60
50
40
30
20
10
ALTITUDE – THOUSANDS OF FEET
SL 2 4 6 8 10 12 14 16 18 20 22 24 26 28
750 700 650 600 550 500 450 400 350 300 250 200
BAROMETRIC PRESSURE – MM HG

FIGURE 1

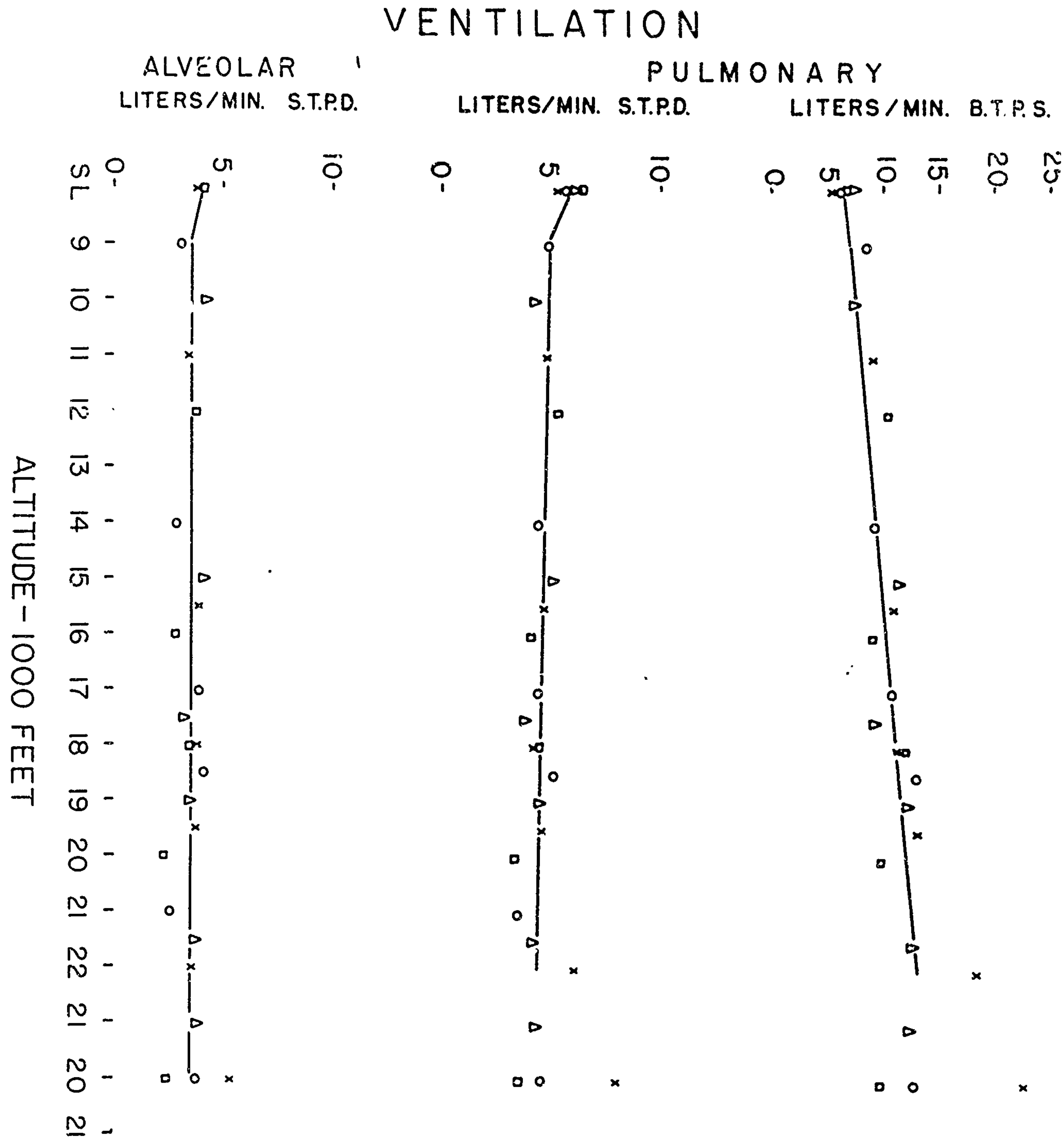

VENTILATION
ALVEOLAR
LITERS/MIN. S.T.P.D.
PULMONARY
LITERS/MIN. S.T.P.D.
LITERS/MIN. B.T.P.S.
ALTITUDE-1000 FEET

FIGURE 2

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