Diffusing capacity of the lung for carbon monoxide at high altitude[1]

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WEST, J. B. *Diffusing capacity of the lung for carbon monoxide at high altitude.* J. Appl. Physiol. 17(3): 421–426. 1962.— Diffusing capacity of the lung for carbon monoxide (DL) was measured in London (PB approx. 750 mm Hg), at 15,300 ft (4,700 m; PB approx. 440 mm Hg), and at 19,000 ft (5,800 m; PB approx. 380 mm Hg) on seven members of the Himalayan Scientific and Mountaineering Expedition, 1960–61. At each altitude DL was measured at two work levels (300 and 900 kg-m/min) and at three different inspired oxygen tensions in order to separate membrane and blood components of the diffusing barrier. A steady state method was used with mixed expired gas analysis; dead space-to-tidal volume ratio was assumed but calculated DL was insensitive to this. There was no consistent change in DL at 15,300 ft (subjects breathing ambient air) compared with sea level, but DL was significantly increased after 7–10 weeks at 19,000 ft (mean changes of 15 and 19% for work levels of 300 and 900 kg-m/min, respectively). However, this small change in DL can be wholly accounted for by the increased rate of reaction of carbon monoxide with hemoglobin due to hypoxia and by the increased blood hemoglobin concentration.

IT IS WELL KNOWN that the diffusion limitations of the lung become particularly important when the inspired oxygen tension is reduced, and it therefore is perhaps surprising that so few attempts have been made to measure the diffusing capacity of the lung at altitude. During an expedition to the Andes in 1922, Barcroft and his colleagues (1) compared the diffusing capacities for carbon monoxide of five members of the party at sea level and at 14,000 ft, using the single-breath method of Krogh and Krogh (2), and found no consistent change. More recently, Velasquez (3) measured the diffusing capacities of native residents in Morococha, Peru, at 14,900 ft, using the two-level oxygen method of Lilienthal et al. (4); he concluded that the diffusing capacities were higher than would be expected for subjects of the same age, height, and weight using the normal data of Cohn et al. (5). The present paper reports findings of the 1960–61 Himalayan Scientific and Mountaineering Expedition, a party of which wintered at 19,000 ft (5,800 m). The diffusing capacity of the lung during exercise was measured in London (PB approx. 750 mm Hg), at 15,300 ft (4,700 m; PB approx. 440 mm Hg), and at 19,000 ft (PB approx. 380 mm Hg) on a group of seven subjects by a steady state carbon monoxide method. At each altitude the carbon monoxide was given in three different inspired oxygen tensions in order to separate the membrane and blood components of the diffusing barrier (6).

METHODS

The method used was very simple and was a modification of the steady state method of Bates et al. (7) suggested by Dr. R. A. B. Holland. It depends on the fact that a reasonably accurate measurement of diffusing capacity can be obtained from normal subjects during exercise by sampling only the inspired and the mixed expired gas, because under these conditions the calculated diffusing capacity is insensitive to changes in the dead space-to-tidal volume ratio. Thus the only measurements necessary are the ratio of the mixed expired to inspired carbon monoxide concentrations, the minute volume, and the barometric pressure, so that the method is ideally suited to field work.

The technique was as follows. The subject pedaled a stationary bicycle and breathed through a low-resistance valve with low dead space. The inspiratory Douglas bag was filled with a carbon monoxide mixture of approximately 0.05% concentration. This was done by injecting 100 ml of pure carbon monoxide from a syringe into the bag and diluting to 200 liters with the appropriate gas mixture. The pure carbon monoxide was carried in a small compressed gas cylinder. Note that in this method it is not necessary for the concentration of the inspired mixture to be known but only the ratio of the expired to inspired gas concentrations. At each altitude, three different oxygen mixtures were used to dilute the carbon monoxide; the

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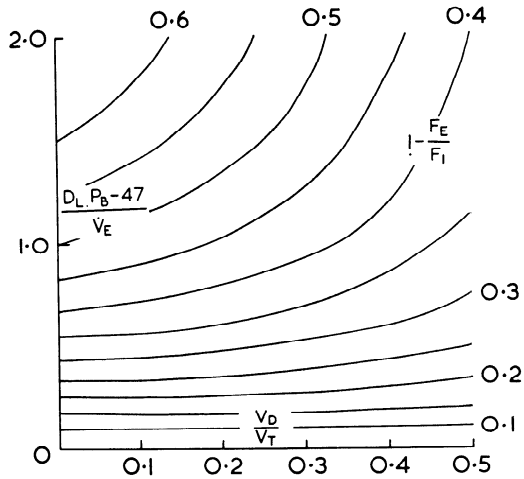

FIG. 1. Chart showing theoretical relations between diffusing capacity, barometric pressure, minute volume, dead space-to-tidal volume ratio, and extraction ratio for carbon monoxide. It can be seen that when V_D/V_T and $1 - F_E/F_I$ are small, the calculated D_L is insensitive to changes in V_D/V_T.

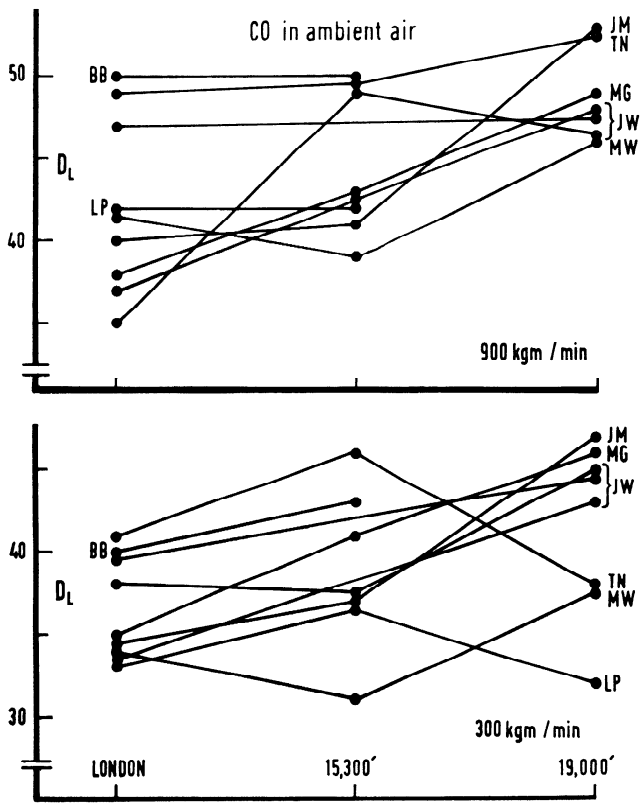

FIG. 2. Diffusing capacities (in ml/min/mm Hg) at London, 15,300 ft, and 19,000 ft for subjects breathing ambient air and exercising at 300 and 900 kg-m/min.

compositions of these are given in Table 1 with the alveolar oxygen tensions estimated from data obtained in a companion study (manuscript in preparation). The oxygen-air mixtures at altitude were chosen so that the diffusing capacities could be compared at approximately the same alveolar oxygen tension as existed when the subject breathed air in London.

The exercise in London was at three work levels (300, 900, and 1,500 kg-m/min) but only the first two levels were studied at altitude. After a preliminary warm-up period, the subject was switched to a bag containing the appropriate oxygen mixture which he breathed for 3 min. He was then switched to another inspiratory bag containing the carbon monoxide mixture at the same oxygen partial pressure. The expired gas was allowed to go to waste for ½ min while equilibration within the lung occurred (8), and the gas was then collected for a further timed ½ min except at the 300 kg-m/min exercise level, where the collection was for ¾ min because of the smaller volume. The gas was analyzed with an infrared carbon monoxide meter (Infra Red Development Co.) which was run in London from the main supply and at altitude from a transistorized inverter fed by a bank of Ni-Fe cells. The stability of the meter was generally good, and a two-way tap allowed the inspiratory and expiratory mixtures to be compared without delay. The gas was pumped into the carbon monoxide meter through a soda-asbestos tube to remove carbon dioxide and a magnesium perchlorate tube to remove water vapor. In order to determine the initial alveolar level of carbon monoxide, the subject rebreathed into a small bag for about five breaths. The level was rarely more than 0.001 % and was subtracted from the expired gas concentration. Only two subjects smoked, one (*BB*) six cigarettes a day and the other (*LP*) an occasional pipe. The volume of the gas expired was measured by passing it through a dry gas meter containing a thermometer, and the volume was converted to STPD. The experiments were done in a laboratory in London, in the open air in mild weather at 15,300 ft, and in a warm tent or hut at 19,000 ft.

The basic expression from which the diffusing capacity of the lung (D_L) was calculated is:

$$\frac{D_L \cdot (P_B - 47)}{\dot{V}_E} = \frac{\left(1 - \frac{F_E}{F_I}\right)\left(1 - \frac{V_D}{V_T}\right)}{\left(\frac{F_E}{F_I} - \frac{V_D}{V_T}\right)}$$

thus

$$D_L = \frac{\dot{V}_E \left(1 - \frac{F_E}{F_I}\right)\left(1 - \frac{V_D}{V_T}\right)}{(P_B - 47)\left(\frac{F_E}{F_I} - \frac{V_D}{V_T}\right)}$$

where P_B is the barometric pressure, $\dot{V}_E$ is the minute volume, V_D/V_T is the dead space-to-tidal volume ratio, and F_E and F_I are the fractional concentrations of carbon monoxide in the expired and inspired gas, respectively. The derivation of this is given in the appendix.

In practice, the extraction ratio $\left(1 - \frac{F_E}{F_I}\right)$ was first calculated and the factor $\frac{D_L \cdot P_B}{\dot{V}_E}$ was then read off a chart for an assumed dead space-to-tidal volume ratio.

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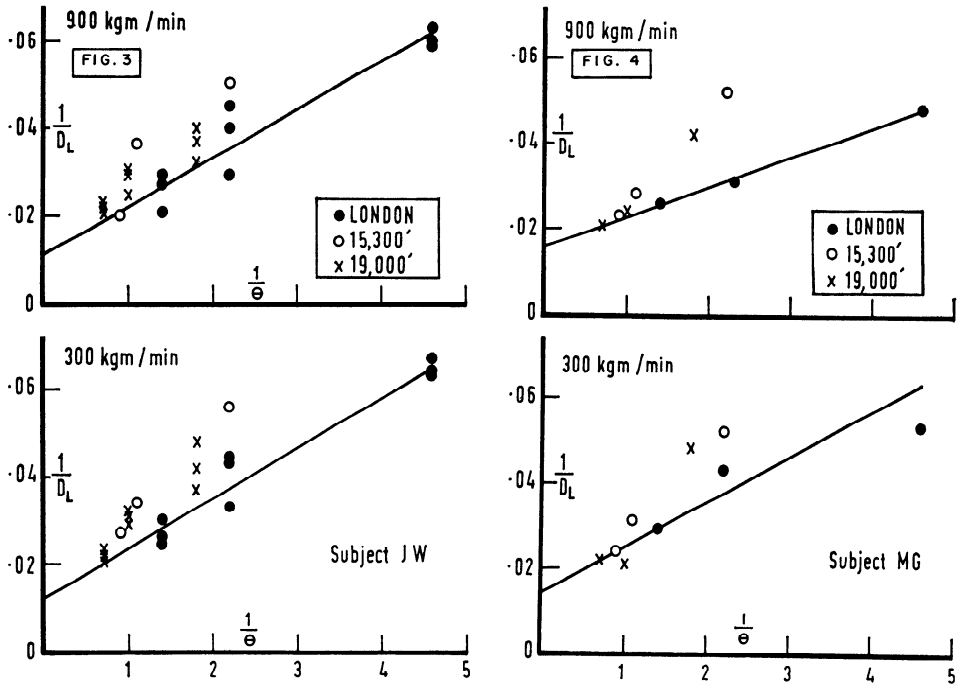

FIG. 3. Inverse of diffusing capacity (min mm Hg/ml) plotted against inverse of θ (min mm Hg) for 3 inspired oxygen mixtures at 3 altitudes. θ has been corrected for increased blood hemoglobin concentration at altitude. A line of visual best fit has been drawn through the London points where D_M = 83 and 88 ml/min/mm Hg and V_c = 86 and 91 ml at 300 and 900 kg-m/min, respectively.

FIG. 4. Same as Fig. 3 but for *subject MG*. D_M = 71 and 65 ml/min/mm Hg and V_c = 91 and 140 ml at 300 and 900 kg-m/min, respectively.

The chart (reproduced in Fig. 1) is useful in that it shows how insensitive D_L is to error in the assumed V_D/V_T. It can be seen that when $\left(1 - \frac{F_E}{F_I}\right)$ is less than about 0.4 (as is the case in the majority of the results) and V_D/V_T is not greater than 0.2 (as is usually the case during exercise), variations in V_D/V_T do not cause large changes in D_L. For example, varying V_D/V_T from 0.1 to 0.2 causes less then a 10% change in D_L. In the present study V_D/V_T was taken as 0.2 for the 300 kg-m/min exercise (V_T from about 1–2 liters BTPS) and 0.1 for the 900 and 1,500 kg-m/min work levels (V_T from about 2–4 liters BTPS) (9).

Comparison of diffusing capacity at different altitudes is complicated by the fact that changes in the alveolar oxygen tension alone will cause changes in D_L because of the varying affinity of carbon monoxide for hemoglobin (10). However, Roughton and Forster (6) have shown that if D_L is measured at different alveolar oxygen tensions, the diffusing barrier can be separated into two components. The first is the membrane component D_M; the second is the blood component, which can be written $\theta \cdot V_c$, where θ is the rate of reaction of carbon monoxide with hemoglobin, which varies with the prevailing oxygen tension, and V_c is the pulmonary capillary blood volume undergoing gas exchange. The values of $1/\theta$ in Table 1 are taken from Roughton and Forster (6), the two lowest figures being derived by extrapolation. The above factors are related by the expression

$$\frac{1}{D_L} = \frac{1}{D_M} + \frac{1}{\theta \cdot V_c}$$

and thus a convenient way of displaying variations in D_L with alveolar oxygen tension is to plot $1/D_L$ against

TABLE 1. *Inspired O_2 tensions (warmed, wet gas), estimated alveolar O_2 tensions, and $1/\theta$ (for blood of O_2 capacity 20 vol %) for three inspired gas mixtures*

Altitude	P_B, mm Hg	O_2, %	$P_{I_{O_2}}$ mm Hg	$P_{A_{O_2}}$, mm Hg	$\frac{1}{\theta}$ min mm Hg
London	750	21	147	110	1.4
	750	43	303	260	2.2
	750	100	703	660	4.6
15,300 ft	440	21	82	60	1.1
	440	38	150	120	1.4
	440	100	393	360	2.8
19,000 ft	380	21	70	50	1.0
	380	45	150	120	1.4
	380	100	333	300	2.5

$1/\theta$. The result is then a straight line whose y axis intercept is $1/D_M$ and whose slope is $1/V_c$. A λ of 2.5 has been assumed (6). To take into account the increased blood hemoglobin concentration at altitude, $1/\theta$ must be multiplied by oxygen capacity at sea level/oxygen capacity at altitude, and these corrected values have been used in Figs. 3 and 4. Oxygen capacities, measured by Haldane's volumetric method by Dr. S. Lahiri, rose to about 27 vol % at altitude. The above procedure has been followed in the RESULTS section so that the components of the diffusing capacities at different altitudes may be readily compared.

The subjects were members of the expedition; their physical characteristics are shown in Table 2. The weights are approximate because they varied considerably during the expedition. The subjects had been at altitude for different periods when their diffusing capacities were measured. The values at 15,300 ft were obtained after *MW* and *JW* had been at that altitude for 2 weeks, *LP* for 5 weeks, and the other four subjects had been at or above that height for 10–12 weeks. The

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measurements at 19,000 ft were made after all subjects had been at that height for 7–10 weeks.

It might be thought that observations made at these high altitudes were unreliable because of the anoxia. There is, however, a lot of evidence that this was not so. Previous expeditions have reported that simple routine measurements can be made accurately although they may take more time, and the repeatability of the measurements at 19,000 ft on *JW* was as good as that of the measurements done in London. The conditions for working in the hut at 19,000 ft were excellent, with a comfortable temperature, reliable equipment, and good lighting, and there was more than enough time during the winter months. All the calculations made at altitude were checked in London, and the number of errors was no more than expected in a similar series done at sea level. Tests of special senses and simple performance tests such as card sorting (to be reported elsewhere) generally showed no impairment.

TABLE 2. *Age, height, and weight of subjects studied*

Subject	Age, years	Height, cm	Weight, lb
BB	29	170	154
MG	23	180	154
JM	30	175	140
TN	31	179	143
LP	50	183	166
MW	35	178	156
JW	32	183	153

RESULTS

The results at the three altitudes are summarized in Tables 3, 4, and 5. It can be seen that minute volume usually fell as the alveolar oxygen tension was raised, particularly at the high exercise levels and especially at high altitude. At a given work level and alveolar oxygen tension, the STPD minute volume generally fell as the altitude increased, an observation at variance with Christensen's report (11). A companion study (to be published) confirmed previous findings that for a given work level, the oxygen consumption was independent of altitude.

The extraction ratios fell both as the exercise level was raised and as the inspired oxygen tension was increased at a given altitude. The diffusing capacity increased with exercise but fell as the alveolar oxygen tension was raised. Figure 2 shows the diffusing capacities for all subjects breathing ambient air at the three altitudes. It can be seen that an altitude of 15,300 ft, there was no consistent change in D_L. At an altitude of 19,000 ft, both the 300 and 900 kg-m/min work levels gave values of D_L that were generally above the London values. The mean changes in D_L were 15 and 19%, respectively. The differences are significant ($P < 0.02$ and $P < 0.001$, respectively) on paired t tests.

As explained under METHODS, by plotting $1/D_L$ against $1/\theta$ the two components of the diffusion barrier can be separated, and the inevitable effect of the hypoxia of

TABLE 3. *Diffusing capacity in London*

Subj.	Work Level, kg-m/min	CO in Ambient Air; P_{IO_2} = 147 mm Hg (Approx.)				CO in O_2 Mixture; P_{IO_2} = 303 mm Hg (Approx.)				CO in O_2; P_{IO_2} = 703 mm Hg (Approx.)			
		P_B	$\dot{V}_E$, liters/min STPD	$1 - \frac{F_E}{F_I}$	D_L	P_B	$\dot{V}_E$, liters/min STPD	$1 - \frac{F_E}{F_I}$	D_L	P_B	$\dot{V}_E$, liters/min STPD	$1 - \frac{F_E}{F_I}$	D_L
BB	300	748	29.0	.43	40					748	18.6	.38	20
	900	748	37.6	.45	50					748	42.7	.27	25
	1,500	748	89.2	.27	52					748	69.1	.19	23
MG	300	750	27.6	.41	35	750	26.6	.34	23	750	25.5	.31	19
	900	750	40.6	.38	38	750	42.5	.32	31	750	37.8	.27	21
	1,500	750	69.0	.31	50	750	67.4	.25	35	750	71.3	.19	26
JM	300	753	23.9	.45	35					744	22.4	.42	28
	900	753	40.1	.39	40					744	39.0	.33	28
	1,500	753	67.9	.33	50					744	50.2	.29	31
TN	300	750	19.2	.52	41	748	15.9	.45	23	750	19.7	.39	21
	900	750	40.9	.43	49	748	35.9	.36	32	750	39.6	.29	25
	1,500	750	74.3	.30	49	748	70.5	.28	43	750	66.0	.26	35
LP	300	746	19.1	.47	33	750	18.0	.41	22	746	24.6	.31	17
	900	746	37.3	.42	42	750	39.5	.30	26	746	35.2	.23	16
	1,500	746	71.3	.32	52	750	64.0	.24	31	746	63.4	.17	21
MW	300	750	19.3	.48	34	750	15.6	.45	23	740	22.2	.35	19
	900	750	45.5	.37	42	750	35.6	.33	27	740	35.5	.26	18
	1,500	750	84.5	.27	49	750	63.5	.24	31	740	54.0	.23	25
JW	300	749	24.2	.46	38	743	18.5	.42	23	743	17.6	.34	16
	900	749	40.5	.36	35	743	39.6	.28	22	743	38.7	.23	17
	1,500	749	82.8	.27	48	743	76.5	.21	30	743	65.2	.17	20
	300	753	18.9	.49	33	749	24.2	.41	30	750	21.2	.32	16
	900	753	40.7	.37	37	749	42.6	.34	35	750	39.8	.23	17
	1,500	753	77.1	.26	42	749	74.5	.22	31	750	67.3	.17	21
	300	740	19.3	.51	40	750	23.2	.37	23	753	18.7	.33	15
	900	740	39.4	.38	47	750	40.3	.29	25	753	39.8	.22	16
	1,500	740	71.6	.28	44	750	67.2	.20	25	753	64.4	.17	19

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altitude on the blood component can be extracted. Thus the membrane barrier can be validly compared at different altitudes. Figure 3 shows this analysis on *subject JW* at two exercise levels. It can be seen that the London measurements lie approximately on a straight line whose y axis intercept gives $1/D_M$ and whose slope gives $1/V_c$. The measurements made at altitude lie on or above this line, indicating that for a given value of $1/\theta$, D_L is equal to or less than the London values. Thus the small increases in D_L at 19,000 ft seen in Fig. 2 can be wholly accounted for by the increased rate of reaction of the carbon monoxide with hemoglobin due to hypoxia and by the increased blood hemoglobin concentration. Three complete sets of measurements were made on this subject in London and at 19,000 ft, so that the repeatability of the method can be judged.

Figure 4 shows the same analysis on *subject MG*; the other subjects showed similar patterns.

DISCUSSION

Various possible errors in the method require examination. Before the inspired and expired gas mixtures were pumped into the analyzer, they were passed through tubes to absorb water vapor and carbon dioxide. The measurement of the fractional concentration of carbon monoxide in dry gas is valid, but the removal of carbon dioxide from the expired gas will reduce its volume by about 5% and therefore raise the apparent carbon monoxide concentration by the same amount. Thus the extraction ratio will fall by 5%, and reference to Fig. 1 shows that this will reduce the D_L by 7–10%, depending on which part of the graph is being used. In general, this is a systematic error which will not affect the comparison of diffusing capacity at different altitudes and its magnitude is tolerable. The decision to absorb carbon dioxide was made because infrared carbon monoxide meters may become sensitive to this gas, and it was

TABLE 4. *Diffusing capacity at 15,300 ft*

Subj.	Work Level, kg-m/min	CO in Ambient Air; P_{IO_2} = 82 mm Hg (Approx.)				CO in O_2 Mixture; P_{IO_2} = 150 mm Hg (Approx.)				CO in O_2 P_{IO_2} = 393 mm Hg (Approx.)			
		P_B	$\dot{V}_E$, liters/min STPD	$1 - \frac{F_E}{F_I}$	D_L	P_B	$\dot{V}_E$, liters/min STPD	$1 - \frac{F_E}{F_I}$	D_L	P_B	$\dot{V}_E$, liters/min STPD	$1 - \frac{F_E}{F_I}$	D_L
BB	300	438	34.7	.30	43	435	30.6	.31	39	437	31.4	.18	20
	900	438	47.4	.29	50	435	37.0	.29	40	437	35.1	.17	20
MG	300	438	20.0	.40	41	437	17.3	.38	32	437	17.5	.28	19
	900	438	53.4	.23	43	437	30.3	.30	35	437	28.2	.21	19
JM	300	438	23.2	.35	37	438	17.2	.42	39	438	14.3	.35	22
	900	438	45.9	.25	41	438	32.1	.28	33	438	34.2	.20	22
TN	300	440	18.4	.44	46	440	15.1	.43	36	440	18.8	.27	19
	900	440	35.8	.34	50	440	30.0	.33	39	440	30.3	.22	22
LP	300	440	17.1	.41	37	440	17.2	.32	24	440	14.3	.29	17
	900	440	47.6	.25	43	440	29.3	.28	30	440	28.0	.18	17
MW	300	442	19.1	.36	31	442	14.4	.36	24	440	13.9	.33	19
	900	442	47.4	.24	39	442	29.6	.25	27	440	29.0	.22	21
JW	300	442	22.2	.37	37	435	16.7	.37	29	442	17.6	.27	18
	900	442	49.8	.28	50	435	27.4	.28	28	442	30.0	.21	20

TABLE 5. *Diffusing capacity at 19,000 ft*

Subj.	Work Level, kg-m/min	CO in Ambient Air P_{IO_2} = 70 mm Hg (Approx.)				CO in O_2 Mixture; P_{IO_2} = 150 mm Hg (Approx.)				CO in O_2; P_{IO_2} = 333 mm Hg (Approx.)			
		P_B	$\dot{V}_E$, liters/min STPD	$1 - \frac{F_E}{F_I}$	D_L	P_B	$\dot{V}_E$, liters/min STPD	$1 - \frac{F_E}{F_I}$	D_L	P_B	$\dot{V}_E$, liters/min STPD	$1 - \frac{F_E}{F_I}$	D_L
MG	300	380	17.4	.42	46	380	14.7	.46	48	380	13.2	.32	21
	900	380	52.1	.23	49	380	26.9	.33	42	380	26.3	.23	24
JM	300	380	15.2	.45	47	380	12.1	.45	38	380	14.6	.29	19
	900	380	47.4	.26	53	380	27.4	.32	41	380	28.5	.22	25
TN	300	378	13.5	.43	38	379	13.8	.41	35	378	13.5	.35	25
	900	378	56.5	.23	53	379	30.6	.30	41	378	24.4	.26	27
LP	300	381	18.2	.34	32	380	12.5	.34	22	378	16.2	.27	19
MW	300	379	19.2	.36	38	379	13.4	.38	29	380	13.2	.32	21
	900	379	56.4	.21	46	379	26.0	.31	37	380	26.3	.23	24
JW	300	380	17.0	.42	45	380	13.7	.41	34	380	13.7	.34	24
	900	380	43.4	.25	46	380	30.0	.30	41	380	25.0	.26	27
	300	379	16.9	.41	43	383	13.0	.41	32	380	15.2	.34	27
	900	379	51.8	.23	48	383	27.5	.29	34	380	26.7	.23	25
	300	381	17.8	.41	45	380	14.2	.38	31	380	14.4	.30	21
	900	381	52.1	.23	48	380	25.8	.29	33	380	29.7	.25	31

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thought that the simplicity of the technique used justified the small error incurred.

The estimation of alveolar oxygen tension which is necessary in order to assign a value for θ is only approximate. It was done on the basis of a related study (manuscript in preparation) in which the oxygen and carbon dioxide concentrations of mixed expired gas were measured at the same work levels with the subjects breathing ambient air. The estimations assume that the oxygen consumption is unchanged when an enriched oxygen mixture is inspired, and they are probably correct to 15 mm Hg. This error will produce a negligible change in θ in view of the other uncertainties in its measurement (6).

The inaccuracies introduced by assuming a dead space-to-tidal volume ratio have already been examined.

The results show that, for a given work level, the diffusing capacity for carbon monoxide remains the same, or increases slightly, when normal subjects spend several months at altitude. The small increase which occurs is wholly explained by the more rapid reaction of carbon monoxide with hemoglobin caused by the anoxia and by the raised blood hemoglobin concentration.

A feature of the results, as shown in Figs. 3 and 4, is that the altitude points lie generally above the line drawn through the London values. This means that, for the same alveolar oxygen tension, D_L is lower at altitude than at sea level. Two possible reasons are evident. The values of $1/\theta$ for the altitude points have been reduced by about 25% because of the increased hemoglobin concentration, and the result of this correction is to move the points to the left The assumption here is that changes in the arm venous hematocrit reflect changes in the pulmonary capillary hematocrit, which may not be true. If the hematocrit correction is reduced, the altitude points move to the right and lie close to the line drawn through the London points.

Assuming that the hematocrit correction is valid, another possibility exists. The disposition of the altitude points is such that their line of best fit would be steeper than the London line but would intercept the y axis at about the same place. This suggests that the fall in D_L is not caused by a reduced membrane-diffusing capacity but by a decreased pulmonary capillary blood volume. Although at first this sounds unlikely, it may be that the pulmonary vascular bed is reduced. There is good evidence that pulmonary vascular resistance increases at altitude (12), and a companion study showed that the cardiac output during work at altitude may be lower than at sea level.

Comparison of the results with those of previous workers who have measured the diffusing capacity at altitude is difficult. The figures of Barcroft and his colleagues (1) agree well with those reported here, but the measurements of Velasquez were made using oxygen and the validity of this method has recently been challenged (13, 14).

The author thanks all members of the expedition, whose cooperation made this study possible.

APPENDIX

The diffusing capacity of the lung is

$$D_L = \frac{\dot{V}_{CO}}{P_{A_{CO}}}$$

Omitting the subscript CO,

$$D_L = \frac{\dot{V}_E(F_I - F_E)}{P_A} \qquad (1)$$

if R = 1. A small error is introduced if R $\neq$ 1. Now

$$F_A(V_T - V_D) + F_I \cdot V_D = F_E \cdot V_T \text{ (Bohr equation)}$$

Therefore

$$P_A = \frac{F_E - F_I \cdot \frac{V_D}{V_T}}{1 - \frac{V_D}{V_T}} \cdot (P_B - 47)$$

Substituting in *equation 1* gives:

$$D_L = \frac{\dot{V}_E}{P_B - 47} \cdot \frac{1 - \frac{F_E}{F_I}}{\frac{F_E}{F_I} - \frac{V_D}{V_T}} \cdot \left(1 - \frac{V_D}{V_T}\right)$$

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