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PREDICTED GAS EXCHANGE ON THE SUMMIT OF MT. EVEREST

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Abstract. The ascent of Mt. Everest (altitude 8848 m) by two climbers in May 1978 without supplementary oxygen has prompted us to make a theoretical analysis of gas exchange under these conditions of extreme hypoxia. On the basis of previous measurements made up to an altitude of 7440 m and other data, we have calculated a barometric pressure on the summit of 250 Torr, alveolar P_{CO_2} of 10 Torr, and Hb concentration of 20.5 g/100 ml. Values for cardiac output, pulmonary capillary blood volume, and diffusing capacity were based on measurements made at 5800 m. A striking result of calculations of oxygenation along the pulmonary capillary is that, even at rest, there is an alveolar-end capillary P_{O_2} of about 6 Torr caused by diffusion limitation, and this widens rapidly on mild exercise. Arterial and mixed venous P_{O_2} fall precipitously as the $\dot{V}_{O_2}$ is raised further. If we assume that the P_{O_2} in mixed venous blood cannot fall below 15 Torr, a maximal $\dot{V}_{O_2}$ of less than 700 ml/min is predicted. Arterial O_2 saturation and, to a smaller extent, the mixed venous P_{O_2} can be increased by shifting the O_2 dissociation curve to the left. This can be accomplished by fully compensating for the respiratory alkalosis at a lower altitude, and then climbing rapidly to the summit. Maximal $\dot{V}_{O_2}$ is extremely sensitive to barometric pressure, and to a lesser extent to lung diffusing capacity. The results are in general agreement with extrapolations from measurements of maximal $\dot{V}_{O_2}$ at altitudes up to 7440 m.

Alveolar- end capillary P_{O_2} differences	Maximal O_2 consumption
Alveolar gas	Mixed venous blood
Exercise	Mount Everest
High altitude	Pulmonary diffusing capacity

The ascent of Mt. Everest, altitude 8848 m, by two climbers without supplementary oxygen in May 1978 was an event of considerable physiologic interest. There is good reason to believe that the partial pressure of oxygen on the summit is near the limit of human tolerance. For example, fig. 1 shows the greatest heights attained by climbers this century. Note that although men had ascended to within 300 m of the summit of Everest as early as 1924 the mountain was not climbed until 1953,

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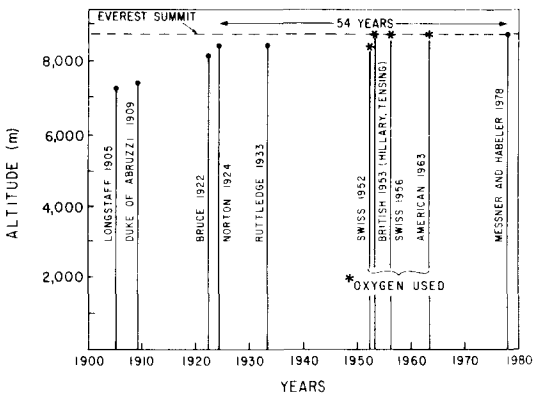

Fig. 1. Highest altitudes attained by climbers during this century. Note that as early as 1924 climbers ascended to within 300 m of the summit of Mt. Everest. However, the mountain was not climbed without supplementary oxygen until 54 years later. These data are consistent with predictions of a very low maximal oxygen uptake on the summit.

and then only with supplementary oxygen. It was not until May 1978 that climbers were successful breathing ambient air. Thus the last 300 m took 54 years!

In this paper we analyze the mechanisms of pulmonary gas exchange which is predicted at these extreme altitudes. Some data are already available up to an altitude of 7440 m, much of this information coming from the Himalayan Scientific and Mountaineering Expedition of 1960–1961. In some instances there is uncertainty about the variables because of the extent of the extrapolations which are necessary. However, the analysis identifies key measurements which would be of great interest on future physiological expeditions. Major findings are that the barometric pressure is critically important, and that diffusion limitation of oxygen transfer by the blood–gas barrier is also a key factor in the maximal work levels attained under these very hypoxic conditions.

Methods

In this section we first indicate how some of the key variables are derived, and then describe the method for calculating oxygen uptake along the pulmonary capillary.

DERIVATION OF MAIN VARIABLES

Barometric pressure. Although this is clearly of major importance there is, surprisingly, some uncertainty about it. First, no measurements on the summit have been made. Next, there is no doubt that the pressure is considerably higher than that predicted from the ICAO Standard Atmosphere (Manual of the ICAO

Standard Atmosphere, 1968) which gives a value of about 235 Torr for an altitude of 8848 m. That this is much too low is suggested by direct measurements on adjoining Mt. Makalu at altitudes of 7440 m and 7830 m where the pressures were 300 and 288 Torr respectively (Gill *et al.*, 1962). However, the ICAO Standard Atmosphere predicts pressures of about 289 and 274 Torr at the same altitudes.

The most reliable data available at the present time are from radiosonde balloons released in New Delhi which is at about the same latitude as Everest. These show that the mean barometric pressure at 8848 m in May and October (the usual months during which the summit assaults are attempted) is 249–250 Torr with a daily standard deviation of about 2 Torr (see Appendix). It should be emphasized that the 15 Torr difference between this mean value and that of 235 Torr predicted from the ICAO Standard Atmosphere is of considerable physiologic importance; for example it results in a doubling of predicted maximal oxygen uptake. Even the daily variation in barometric pressure due to variable weather conditions is physiologically significant (See below).

The reason for the discrepancy between the actual values and those predicted from the ICAO Standard Atmosphere is that the pressure at a given altitude is higher near the equator than the poles owing to the oblate spheroid shape of the atmosphere. The fact that pressures in the European Alps and Himalayas are unexpectedly high has been recognized since the observations of Zuntz *et al.* (1906) and was discussed by Pugh (1957) who predicted a pressure of 250 Torr for the summit of Mt. Everest in 1957.

Alveolar gas composition. The hyperventilation which occurs at high altitude causes striking changes in the partial pressures of alveolar gas. Figure 2 shows data collected by Gill *et al.* (1962) by the Haldane-Priestley technique (Haldane and Priestley, 1905) on the Himalayan Scientific and Mountaineering Expedition of 1960–1961. The mean values for the alveolar P_{O_2} and P_{CO_2} at an altitude of 7830 m (P_B 288 Torr) were 32.8 and 14.3 Torr respectively. Extrapolation to a barometric pressure of 250 Torr was accomplished by fitting a straight line to the plot of P_{CO_2} against barometric pressure for the 3 points shown in fig. 2. For a respiratory exchange ratio (R) of 0.8 this gives values for the alveolar P_{O_2} and P_{CO_2} of 30.5 and 10.0 Torr respectively.

In order to calculate alveolar gas partial pressures on exercise, we used data obtained at 5800 m where mixed expired gas was collected during bicycle ergometry and alveolar partial pressures were derived assuming a dead space/tidal volume ratio (West *et al.*, 1962). These studies showed that alveolar P_{CO_2} changed little with oxygen consumption up to one l/min, though alveolar P_{O_2} rose as R increased. At maximal exercise levels, alveolar P_{CO_2} fell but this was associated with R values above 1.0 and presumably represented the development of an unsteady state. In the calculations which follow we have assumed that alveolar P_{CO_2} remains constant at 10 Torr during exercise and that the alveolar P_{O_2} rises as R increases from 0.8 at rest to 1.0 on maximum steady exercise. This procedure underestimates the alveolar P_{O_2} during unsteady state bursts of high activity (see Discussion).

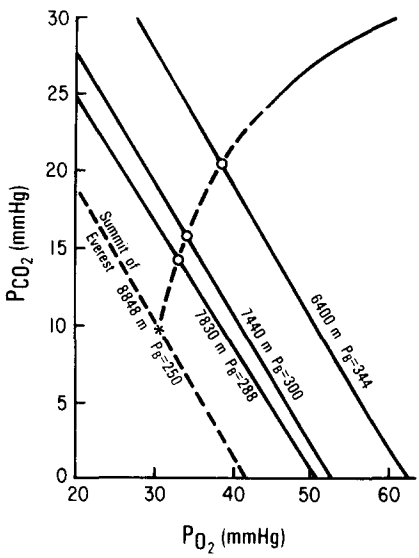

Fig. 2. Oxygen–carbon dioxide diagram showing alveolar gas composition at extreme altitudes. Extrapolation to the summit of Mt. Everest (PB 250 Torr) gives a P_{O_2} and P_{CO_2} of approximately 30 and 10 Torr respectively. (Modified from Gill *et al.*, 1962).

Cardiac output. Very few measurements have been made of cardiac output on sojourners (as opposed to permanent residents) above 4600 m because of the technical difficulties. However, Pugh (1964a) measured cardiac output by an acetylene rebreathing procedure on four members of the Himalayan Scientific and Mountaineering Expedition at sea level and 5800 m and found that cardiac output for a given work intensity was the same at the two sites. We have used this relationship between cardiac output and oxygen consumption reported by Pugh at 5800 m. However, since our maximal work levels are predicted to be so low, only the lower end of the cardiac output-O_2 uptake relationship was used. Since heart rate at high altitude is somewhat higher for a given work level at mild to moderate levels of work intensity, these data indicate that stroke volume is reduced at altitude. It should be added that some investigators have reported a reduction in cardiac output for a given work level at high altitude (Alexander *et al.*, 1967). This would adversely affect maximal oxygen uptake (see below).

Hemoglobin concentration. We have used the value of 20.5 g/100 ml which was obtained by Pugh (1964) as a mean value from 51 observations on 40 acclimatized climbers from five expeditions. Cerretelli (1976) reported an almost identical value of 20.6 g/100 ml on 10 climbers at the Mt. Everest base camp (altitude 5350 m).

Diffusing capacity of the blood-gas barrier. An extensive series of measurements of the diffusing capacity for carbon monoxide during exercise in acclimatized subjects at 5800 m showed a moderate increase in DL compared to the sea level value (West, 1962). However, by making determinations at different levels of alveolar P_{O_2} it was found that the rise in DL could be accounted for by the increased rate of

combination of carbon monoxide with hemoglobin under the hypoxic conditions and that the diffusing capacity of the blood–gas barrier was essentially unchanged by altitude at a given work level. There was a suggestion that V_c, the volume of blood in the pulmonary capillaries, was slightly reduced at altitude though there was substantial scatter in the data. A similar finding was reported by Weiskopf and Severinghaus (1972) at an altitude of 4340 m.

For the calculations of oxygenation along the pulmonary capillary we need a value of DM for oxygen. Since the relationship between DM_{O_2} and DM_{CO} is poorly understood at the present time, we used the figure of 40 ml/min/Torr for resting conditions, this being a commonly accepted value (Wagner, 1977). Additional calculations were made with values of DM_{O_2} of 20, 60, 80, and 100 ml/min/Torr.

Capillary transit time. The time spent by the red cell in the pulmonary capillary is usually assumed equal to the pulmonary capillary blood volume/cardiac output. At high altitude it appears that both these values are similar to those at sea level for a given exercise level though, as indicated above, capillary blood volume may fall slightly and this would have the effect of reducing transit time. In general, transit time decreases on exercise (Johnson *et al.*, 1960) though data are scant.

As shown later, the levels of exercise which can apparently be achieved at an altitude corresponding to the Everest summit are very low, and for these we have assumed a normal transit time of 0.75 sec which constitutes the best case. At higher exercise levels, capillary blood volume/cardiac output was varied to study its effect.

Acid–base status. It seems reasonable to assume that a subject who spends a week or more at a given altitude will have an almost fully compensated respiratory alkalosis, and three measurements of the pH of arterialized venous blood made at 5800 m are consistent with this (West *et al.*, 1962). However, climbers attempting the summit of Mt. Everest spend as little time as possible at extreme altitudes. Based on typical schedules of time spent at high camps we have assumed full compensation (that is, an arterial pH of 7.4 for the prevailing P_{CO_2}) at an altitude of 7620 m (25,000 ft.) where the alveolar P_{CO_2} is about 15 Torr (fig. 2). Additional calculations were made for a climber who was assumed to spend a sufficiently long period at 5500 m (alveolar P_{CO_2} 25 Torr) to bring his arterial pH to 7.4 before climbing so rapidly to the summit that there was a negligible change in base deficit. Such a procedure has the effect of shifting his oxygen dissociation to the left at extreme altitude as a consequence of the respiratory alkalosis. In both cases we assumed a normal P_{50} of 26.8 Torr when the pH was 7.4.

*Effect of ventilation–perfusion inequality**. All normal lungs have some ventilation–perfusion inequality both on a topographical and non-topographical basis which causes some hypoxemia. There is evidence that the topographical inequality

* An interesting feature of the analysis of ventilation–perfusion relationships under these conditions is that the ventilation–perfusion ratio line on the O_2–CO_2 diagram is virtually straight. The reason is that the slopes of the O_2 dissociation curves are nearly the same under these extraordinary conditions.

TABLE 1
Baseline values used for calculations for the summit of Mt. Everest (8848 m)

Barometric pressure	250 Torr
Inspired P_{O_2}	42.5 Torr
Alveolar P_{CO_2}	10 Torr
Alveolar P_{O_2} (rest; R = 0.8)	30.5 Torr
(exercise; R = 1.0)	32.5 Torr
Hemoglobin	20.5 g/100 ml
Cardiac output/O_2 uptake	same as sea level
D_M/O_2 uptake	same as sea level
D_M for oxygen	40 ml/min/Torr
Capillary transit time	0.75 sec
Acid-bases status (normal conditions)	pH = 7.4 for P_{CO_2} = 15 Torr
(special conditions)	pH = 7.4 for P_{CO_2} = 25 Torr
Ventilation–perfusion inequality	assumed negligible

is reduced at high altitude (Dawson, 1972) presumably as a consequence of the more uniform distribution of bloodflow resulting from the increase in pulmonary artery pressure. In any event it can be shown that the degree of ventilation–perfusion inequality normally present at sea level is responsible for a negligible degree of hypoxemia at extreme altitudes. For example if we assume a log normal distribution of ventilation–perfusion ratios with a log SD of 0.3 (Wagner *et al.*, 1974) and an inspired P_{O_2} of 42.5 Torr, the resulting alveolar-arterial P_{O_2} difference is less than 0.5 Torr. We have therefore ignored the effects of ventilation–perfusion inequality and treated the lung as if it were a homogenous single compartment.

Table 1 summarizes the baseline variables as derived above.

CALCULATION OF OXYGENATION ALONG THE PULMONARY CAPILLARY

Bohr integration. Based on the variables derived as indicated above, we have calculated the time course of oxygenation along the pulmonary capillary by the method of forward integration using the Runge-Kutta technique (Wagner and West, 1972). Changes of both P_{O_2} and P_{CO_2} in the blood were calculated at each step and thus the interdependence of these two variables was taken into account. Reaction times in blood for both oxygen and carbon dioxide were included. When the alveolar P_{O_2} was 42.5 Torr, the total transit time of 0.75 sec was divided into 15 equal time intervals; increasing the number of intervals was shown to make a negligible difference to the time course. When the alveolar P_{O_2} was higher or a longer transit time was investigated more steps were sometimes necessary. The computer program was arranged to iterate the values of the P_{O_2} and P_{CO_2} of mixed venous blood until the required oxygen uptake and carbon dioxide output were satisfied. Kelman's procedures (1966a,b, 1967) were used to describe the oxygen and carbon dioxide dissociation curves.

Conditions studied. Initially, calculations were made with the baseline values of the variables as shown in Table 1. Calculations were then made at increased barometric pressures up to 500 Torr. In addition we systematically altered the following variables above and below the baseline values to study their role in determining the P_{O_2} in arterial and mixed venous blood with a view to better understanding the factors limiting oxygen uptake: alveolar ventilation, cardiac output, hemoglobin concentration, DM_{O_2}, pulmonary capillary blood volume (and thus capillary transit time), and the P_{50} of the oxygen dissociation curve.

Results

PREDICTIONS USING THE BASELINE VALUES

Resting conditions. Figure 3A shows the calculated time course for P_{O_2} along the pulmonary capillary for a resting climber breathing air on the summit of Mt. Everest (8848 m, PB 250 Torr). A minimal oxygen uptake of 250 ml/min is assumed; R is 0.8 and carbon dioxide output is therefore 200 ml/min. Other assumptions (see Table 1 and Methods) include: cardiac output 6 l/min, capillary transit time 0.75 seconds, DM_{O_2} 40 ml/min/Torr, and a partially compensated respiratory alkalosis (pH 7.4 for P_{CO_2} 15 Torr).

It can be seen that the P_{O_2} in pulmonary capillary blood rises slowly from a value of 21 Torr in mixed venous blood to 25 Torr at the end of the capillary. Alveolar P_{O_2} is 31 Torr so that the alveolar-end capillary P_{O_2} difference is 6 Torr

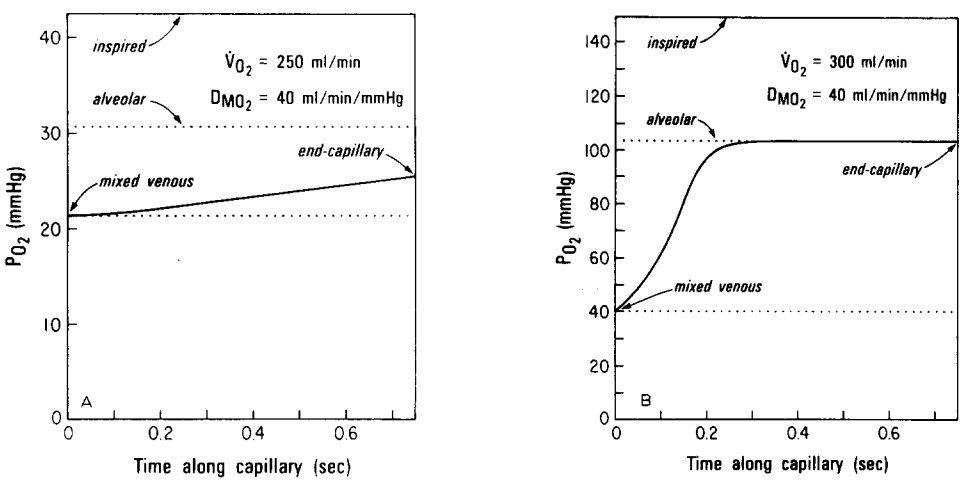

Fig. 3. A shows the calculated time course of the P_{O_2} in the pulmonary capillary of a climber at rest on the summit of Everest. Note the slow rate of rise of P_{O_2} and the marked alveolar-end capillary P_{O_2} difference. B shows the normal time course at sea level for comparison.

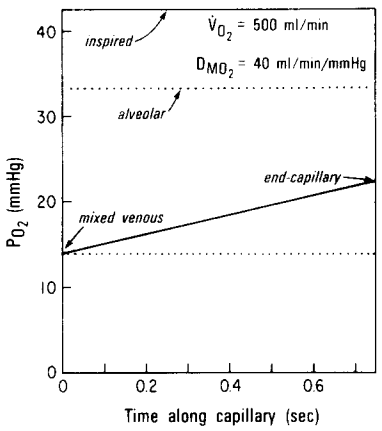

Fig. 4. Same as fig. 3 except that the oxygen consumption has been increased to 500 ml/min. Again note the large alveolar-end capillary P_{O_2} difference. The P_{O_2} in mixed venous blood is less than 14 Torr.

or 60% of the alveolar-mixed venous P_{O_2} difference! Clearly oxygen uptake is severely limited by the diffusion properties of the blood–gas barrier even under these best conditions for this altitude.

The pattern shown in fig. 3A can be contrasted with that predicted by the same computational technique for a resting subject at sea level (see fig. 3B). Under these conditions as is well-known, the capillary P_{O_2} is almost identical to the alveolar value by the time the blood has spent about one-third of its available time in the capillary.

Exercise. Figure 4 shows that the situation rapidly worsens when the climber attempts to increase his oxygen consumption. It can be seen that when $\dot{V}_{O_2}$ is 500 ml/min and R is 1.0, the alveolar P_{O_2} rises to 33 Torr. However, the P_{O_2} of mixed venous blood is only 14 Torr and the P_{O_2} increases to only 22 Torr at the end of the capillary leaving an alveolar-end capillary P_{O_2} difference of 11 Torr. Again, this is about 60% of the alveolar-mixed venous P_{O_2} difference.

Figure 5 shows some of the principal variables plotted against oxygen uptake. Note first that the alveolar P_{O_2} rises slightly because R is assumed to increase from 0.8 to 1.0. Arterial P_{O_2} falls from 25 to 20 Torr as the $\dot{V}_{O_2}$ is increased from 250 to 600 ml/min. At the same time arterial O_2 saturation falls from 57 to 42%. The P_{O_2} in mixed venous blood falls markedly from 21 to only 8 Torr at the highest work level. A solution was sought for a $\dot{V}_{O_2}$ of 700 ml/min but this failed because the P_{O_2} of mixed venous blood fell below zero. Similar results have been obtained by Dejours (1979).

Effect of increasing DM_{O_2}. The calculations shown in figs. 3–5 were made assuming a DM_{O_2} of 40 ml/min/Torr because this is a commonly accepted value for resting conditions and the work levels attained are clearly very low. However, while there is good evidence (See Methods) that DM_{CO} is the same at high altitude as at sea

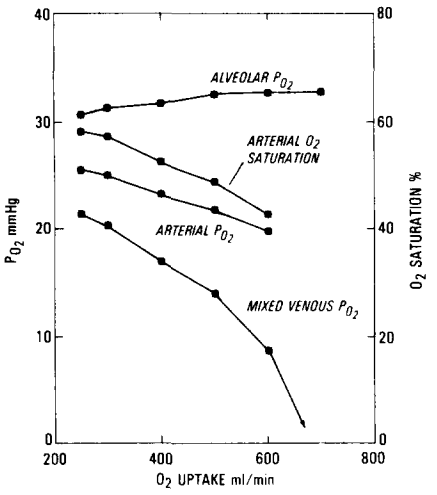

Fig. 5. Predicted effects of increasing oxygen consumption at a barometric pressure of 250 Torr. The alveolar P_{O_2} rises initially because R is assumed to increase from 0.8 to 1.0. Note the relentless fall in the P_{O_2} of arterial and, particularly, mixed venous blood.

level for a given oxygen uptake (West, 1962) there is uncertainty about the relationship between DM_{O_2} and DM_{CO}. Indeed this is probably the most unreliable variable in table 1. Accordingly we have recalculated the results shown in fig. 5 for values of DM_{O_2} of 20, 60, 80, and 100 ml/min/Torr. Figure 6 shows the results for mixed venous P_{O_2} against O_2 uptake.

It can be seen that the general pattern of a fall in P_{O_2} of mixed venous blood with increasing $\dot{V}_{O_2}$ is maintained though naturally the venous P_{O_2} is higher if DM_{O_2} is

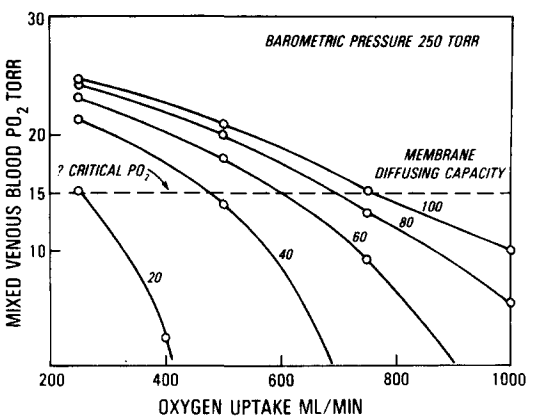

Fig. 6. Effect of increasing the membrane diffusing capacity for O_2 (DM) on the P_{O_2} in mixed venous blood. Note that if we assume that there is a minimal tolerable value for mixed venous P_{O_2} (in this case 15 Torr), this sets a limit for maximal O_2 uptake.

increased. For example, when DM_{O_2} is set at 80 ml/min/Torr, the venous P_{O_2} falls from 24 to 5 Torr as $\dot{V}_{O_2}$ is increased from 250 to 1000 ml/min.

If we take the P_{O_2} of mixed venous blood as generally indicative of tissue P_{O_2} and assume that there is a tissue P_{O_2} below which further increases in $\dot{V}_{O_2}$ are not possible, fig. 6 allows us to calculate the maximal $\dot{V}_{O_2}$. Unfortunately there are no reliable data on which to base the critical value of mixed venous P_{O_2} and indeed this may vary depending on the distribution of blood flow to peripheral tissues. However, if we choose say 15 Torr as a reasonable value, maximal $\dot{V}_{O_2}$ would be limited to about 470 ml/min/Torr for a DM_{O_2} of 40 but rise to about 690 ml/min if DM_{O_2} were as high as 80 ml/min/Torr. Clearly maximal $\dot{V}_{O_2}$ is very sensitive to DM_{O_2}. Equally clearly maximal $\dot{V}_{O_2}$ will be severely limited for any reasonable value for DM_{O_2}.

Effect of shifting the O_2 dissociation curve. Figure 7 shows the effect of shifting the O_2 dissociation curve to the left by assuming that the climber has a fully compensated respiratory alkalosis at an altitude of 5500 m (arterial P_{CO_2} 25 Torr, pH 7.4) before climbing so rapidly to the summit that his base deficit remained unchanged. The solid circles show the same data as fig. 5 and assume a fully compensated respiratory alkalosis at an altitude of 7620 m. Note that shifting the dissociation curve to the left results in a large gain in arterial O_2 saturation and in O_2 content (the latter not shown in fig. 7). There is also a moderate increase in the P_{O_2} of mixed venous blood at the highest work levels, though if we assume (see above) that this P_{O_2} cannot fall below 15 Torr, the benefit in maximal $\dot{V}_{O_2}$ is only about 15 ml/min. Interestingly the left shifted curve results in a

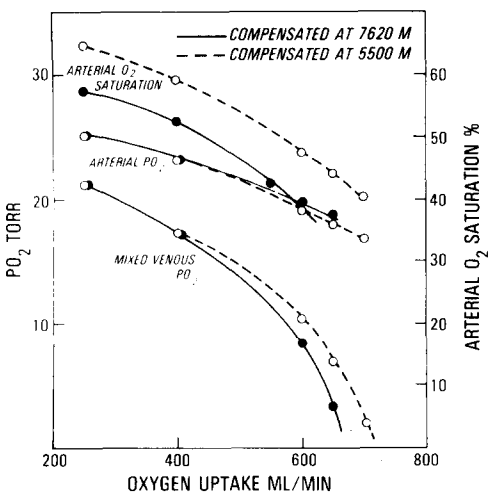

Fig. 7. Effect of shifting the oxygen dissociation curve to the left by developing a fully compensated respiratory alkalosis at an altitude of 5500 m and then climbing rapidly to the summit. This maneuver results in substantial increases in arterial oxygen saturation but only a small rise in the P_{O_2} of mixed venous blood (see text for details).

small *fall* in arterial P_{O_2} at the high work levels presumable because the O_2 dissociation curve becomes slightly steeper (See Discussion).

FACTORS LIMITING OXYGEN TRANSFER

Figure 8 shows the effects on calculated maximal $\dot{V}_{O_2}$ of altering barometric pressure, alveolar ventilation, cardiac output, hemoglobin concentration, DM_{O_2}, capillary transit time and P_{50}. In all cases one variable only was changed, all others being kept the same for the appropriate work level. Maximal $\dot{V}_{O_2}$ was assumed to occur when the P_{O_2} of mixed venous blood fell to 15 Torr.

Barometric pressure. It can be seen that maximal $\dot{V}_{O_2}$ is extremely sensitive to barometric pressure. Indeed only a 6% fall in PB from 250 to 235 Torr results in a decrease in maximal $\dot{V}_{O_2}$ of 45% (from 470 to 260 ml/min). This implies that the day-to-day variation in PB is significant. Radiosonde data indicate that a decrease of up to 4 Torr (*i.e.* twice daily SD) can be expected on occasions in May or October as a result of changes in weather (See Appendix); this will result in a fall in calculated $\dot{V}_{O_2}$ max of about 10%.

Diffusing capacity. Maximal $\dot{V}_{O_2}$ is also very sensitive to DM, though fig. 8 shows that barometric pressure is far more important. Nevertheless a 50% increase in DM beyond the assumed baseline value of 40 ml/min/Torr would be expected to increase $\dot{V}_{O_2}$ max by 28%, other things being equal.

Alveolar ventilation and cardiac output. An increase in either of these variables results in a rise in $\dot{V}_{O_2}$ max but ventilation is somewhat more effective than blood-flow. Transient burst of high ventilation would raise $\dot{V}_{O_2}$ max though strictly our analysis applies only to steady state conditions (See below).

P_{50} of O_2 dissociation curve. For fig. 8, P_{50} was altered by shifting the O_2 dissociation curve without a change in the acid base status of the blood (as occurred in the calculations shown in fig. 7). However, in both instances, a left shifted curve significantly improved $\dot{V}_{O_2}$ max.

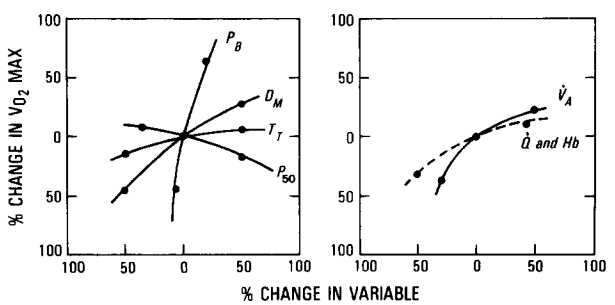

Fig. 8. Analysis of factors limiting maximal oxygen uptake at a barometric pressure of 250 Torr. Note the extreme sensitivity to barometric pressure. The membrane diffusing capacity (DM) also plays an important role. Other variables studied are capillary transit time (TT), P_{50} of the O_2 dissociation curve, a total alveolar ventilation ($\dot{V}A$) and cardiac output ($\dot{Q}$).

Capillary transit time. This was altered by changing pulmonary capillary blood volume but holding cardiac output constant. The result of reducing transit time was a fall in maximal $\dot{V}_{O_2}$ but the effect is relatively small. Note that Johnson *et al.* (1960) measured maximal reductions in transit time of only about 33% during exercise at sea level.

Discussion

DIFFUSION LIMITATION OF OXYGEN UPTAKE

One of the most striking findings of this analysis is the magnitude of the diffusion limitation of oxygen transfer as clearly shown in figs. 3A and 4. In both examples the alveolar end-capillary P_{O_2} difference is large, being about 60% of the P_{O_2} difference between alveolar gas and mixed venous blood. It is sometimes argued that the diffusion properties of the normal lung are adequate for equilibration of P_{O_2} between alveolar gas and end-capillary blood under even the most extreme conditions. However, this is clearly not the case during hypoxia of great altitudes.

These findings are consistent with previous measurements made on the Himalayan Scientific and Mountaineering Expedition of 1960–1961 at an altitude of 5800 m (PB 380 Torr). There a marked fall in arterial O_2 saturation was observed in the face of an increase in alveolar P_{O_2} during exercise with O_2 consumptions up to 2 l/min (West *et al.*, 1962). At that time diffusion limitation was deduced on the basis of the pattern of changes seen but it was not possible to analyze O_2 transfer along the capillary as done here. Other investigators (Johnson, 1967; Piiper and Scheid, 1980) have also predicted diffusion limitation during severe alveolar hypoxia.

The diffusion limitation indicated in figs. 3A and 4 is also consistent with the sensitivity of the maximal $\dot{V}_{O_2}$ to DM_{O_2} shown in fig. 8. This suggests that a climber with an unusually high diffusing capacity would have a definite advantage at extreme altitudes breathing ambient air. No information is available on Messner and Habeler, the two climbers who reached the Everest summit in May 1978 without supplementary oxygen.

The reason for the slow rate of rise of P_{O_2} along the pulmonary capillary as shown in figs. 3A and 4 is the steepness of the slope of the blood O_2 dissociation curve expressed as ΔO_2 concentration (ml/100 ml)/ΔP_{O_2}. Wagner (1977) has emphasized that diffusion limitation of a gas is likely if this slope is much higher than the solubility of the gas in the blood-gas barrier, presumably close to 0.003 ml/100 ml/Torr for O_2. The steep slope in blood can be ascribed to two factors: (1) the fact that the capillary P_{O_2} is low on the dissociation curve during the entire oxygenation process, and (2) the high hemoglobin concentration. As an illustration, the value of ΔO_2 concentration/ΔP_{O_2} for fig. 3A changes from 3.5 to 0.7 ml/100 ml/Torr from the beginning to the end of the pulmonary capillary. By contrast, at sea level in subjects with normal hemoglobin concentrations, typical

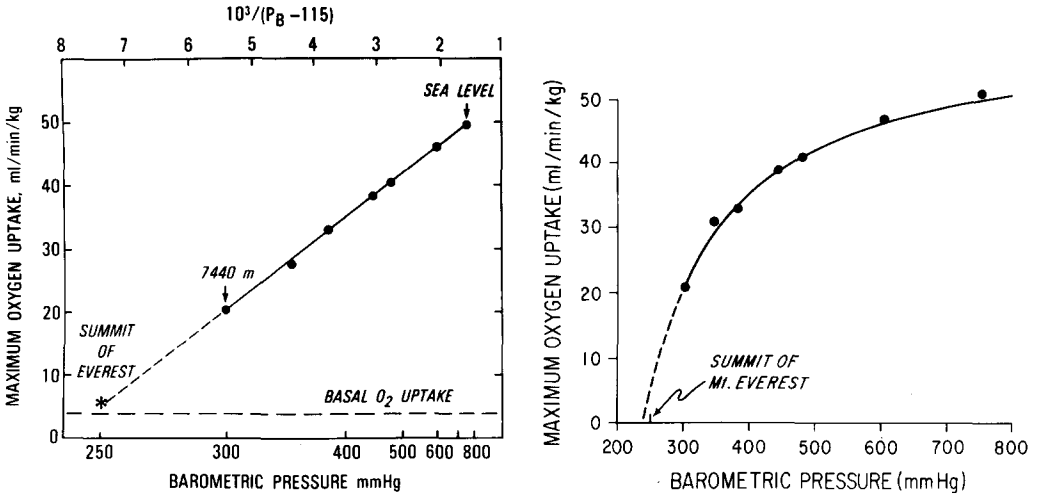

Fig. 9. Maximal oxygen consumption of acclimatized subjects plotted against barometric pressure using the data of Pugh (1964b). In A, the barometric pressure axis has been transformed to give a linear relationship. Extrapolation of the summit of Mt. Everest (PB 250 Torr) gives a maximal oxygen consumption of about 5 ml/min/kg or about 350 ml/min. Note the sensitivity of maximal oxygen consumption to barometric pressure.

values at rest at the beginning and end of the capillary respectively are 0.3 and 0.02 ml/100 ml/Torr.

SENSITIVITY OF MAXIMAL $\dot{V}_{O_2}$ TO BAROMETRIC PRESSURE

Figure 8 shows the extreme sensitivity of $\dot{V}_{O_2}$ max to PB and raises the question of whether existing data on maximal work capacity at different altitudes support this. Figures 9A and B plot measured $\dot{V}_{O_2}$ against PB over the range from 760 to 300 Torr. Most of the data were collected on the Himalayan Scientific and Mountaineering Expedition of 1960–1961 [See Pugh (1964b) for a summary]. In fig. 9A the PB axis has been transformed to allow the data points to lie on a straight line; the expression used is shown at the top of the graph. This allows a linear extrapolation of the data to PB = 250 Torr. Figure 9B shows the same data and the extrapolation on a linear scale.

It is clear that existing data strongly support two conclusions of the present theoretical analysis: (1) $\dot{V}_{O_2}$ max at PB = 250 Torr will be very low; indeed fig. 9 predicts a value of 5 ml/min/kg or about 350 ml/min in a 70 kg climber. The value predicted in fig. 6 is 470 ml/min for a DM_{O_2} of 40 ml/min/Torr; (2) the sensitivity of $\dot{V}_{O_2}$ max to PB at a PB of 250 Torr is very great.

OTHER FACTORS LIMITING OXYGEN TRANSFER

Figure 8 shows that increases in alveolar ventilation, cardiac output, hemoglobin concentration or capillary transit time, and a decrease in P_{50} would all apparently result in a higher $\dot{V}_{O_2}$ max. The question arises as to why these do not occur.

Alveolar ventilation. We have assumed that alveolar ventilation only rises enough on exercise to maintain the P_{CO_2} at the resting acclimatized value. However, measurements at maximal work levels at 5800 m show a fall in alveolar P_{CO_2} below the resting value though this is accompanied by R values above 1.0. These presumably represent unsteady state measurements (See below).

One reason why a higher ventilation does not occur may be that it would require such a high O_2 consumption by the respiratory muscles that this would steal a significant portion of the total O_2 available. For example the alveolar ventilation in fig. 4 is 43 l/min which would require a total ventilation of 54 l/min if we assume a dead space/tidal volume ratio of 0.2 (Asmussen and Nielsen, 1956). Another reason for the restricted exercise ventilations may be that the action of the respiratory muscles themselves is limited by the hypoxia. Incidentally, note that the maximal exercise ventilation falls rapidly at extreme altitudes. At an altitude of 5800 m, mean maximal exercise ventilation was about 160 l/min BTPS (Pugh, 1964b) whereas we predict a maximal steady state ventilation of less than 60 l/min on the Everest summit.

Cardiac output. Figure 8 shows that increases in cardiac output would apparently improve $\dot{V}_{O_2}$ max substantially. It clearly would be advantageous to supply the exercising muscles with greater amounts of oxygenated blood, but apparently the cardiac output at maximal exercise is near the resting level. The reason for this is unknown. Perhaps myocardial function is limited by the severe hypoxia.

There is some evidence that cardiac stroke volume becomes small at extreme altitudes. Data on heart rates at relatively low work levels (approximately 0.9 l/min $\dot{V}_{O_2}$) are available up to an altitude of 7440 m (PB 300 Torr) and if these data are extrapolated to 250 Torr, the heart rate (assuming this level of O_2 uptake could be accomplished) would be about 140/min, if the cardiac output would be less than 8 l/min implying a stroke volume of less than 60 ml.

Hemoglobin concentration. An increase would improve $\dot{V}_{O_2}$ max according to fig. 8 but in practice it is doubtful whether additional polycythemia would be advantageous. Cerretelli (1976) has suggested that the failure of $\dot{V}_{O_2}$ max to return to sea level values when acclimatized climbers are given 100% O_2 to breath (thus increasing inspired P_{O_2} above 150 Torr) may be due to impaired unloading of oxygen in peripheral capillaries. Indeed there is anecdotal evidence that reducing the hemoglobin concentration in climbers at extreme altitudes is beneficial.

Pulmonary capillary blood volume. An increase would improve $\dot{V}_{O_2}$ max by prolonging of O_2 across the blood-gas barrier. However there is apparently no way of taking advantage of this.

P_{50} of O_2 dissociation curve. Shifting the curve to the left confers a small

advantage but the only apparently feasible way of accomplishing this is to exploit the respiratory alkalosis (fig. 7).

Non-steady state exercise. The analysis presented here assumes steady state conditions where the $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ of the exercising muscles and other tissues are the same as that of the lung. It is possible that climbers at extreme altitudes can work in short non-steady state bursts. However their ability to do this is very limited. Measurements of blood lactate after severe exercise at high altitude show much lower values than at sea level (Edwards, 1936; Cerretelli, 1976) suggesting that anaerobic metabolism is greatly restricted. This is possibly because of the greatly reduced buffering capacity of the blood as a consequence of the low bicarbonate concentration. Moreover, a climber has a task which requires sustained exercise over several hours, and typically he adopts a slow measured pace with occasional pauses for rest. Norton, who climbed within 300 m of the Everest summit in 1924 without supplementary O_2 wrote this of his activity at about 8500 m: 'My ambition was to do 20 consecutive paces uphill without a pause – but I never remember achieving it – 13 was nearer the mark' (Norton, 1925). It is likely that he rested every 1–2 min (Pugh, 1964b). It seems unlikely that this intermittent type of exercise with the accumulation of small oxygen debts which are paid off every 1–2 min would substantially increase the average work level. Messner (1979) wrote this of the last stages of his climb with Habeler to the summit without supplementary oxygen. 'After every few steps, we huddle over our ice-axes, mouths agape, struggling for sufficient breath... The last 100 m of height took us more than an hour to climb'. This graphic account emphasizes that the Everest summit is clearly very near the limit of human activity without supplementary oxygen.

Appendix

Data from radiosonde balloons released twice daily at New Delhi (28-35N, 77-12E) and Gauhati (26-05N, 91-43E) were analyzed for the period 1953 to 1978. Balloon altitudes for barometric pressures of 300 and 500 m are available; the pressures at an altitude of 8848 m were obtained by interpolation. The mean pressures for May and October (the two preferred months for climbing Mt. Everest) for an altitude of 8848 m were 249.1 and 249.6 Torr respectively. The SD of the monthly mean pressures were 1.61 and 1.65 respectively, while the SD of the daily pressures were 2.00 and 2.21 Torr respectively.

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