PULMONARY VENTILATION OF MAN AT ALTITUDE

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Although the physiological changes associated with acclimatisation to high altitude have been studied quite extensively, most of these studies refer to the resting condition. Relatively little work appears to have been done on exercise in acclimatised subjects, although high altitude life usually involves a great deal of exercise. Zuntz et al. (1906) first recorded such a study in the beginning of this century at heights varying between sea level and 14,000 feet. In 1913 Douglas et al. made further studies on Pike's Peak (14,000 feet), and confirmed that although ventilation (BTPS= body temperature pressure saturated) increased for a given rate of work oxygen consumption remained the same as at sea level. In 1935 an International Physiological expedition was taken to Andes to cover more grounds. Christensen (1937) studying muscular exercise at altitude (17,600-feet) confirmed the earlier findings that the metabolic rate is independent of altitude. He also showed that the relation between work rate and mass of inspired air at altitude was similar to that at sea level. Mathews (1954) asserted this contention in his claim that all observations at altitude fall on the same curve when reduced to sea level pressure. However, these observations were only few, and the subjects of these experiments were only partially acclimatised or acutely exposed to low pressure. While confirming this claim of Christensen, Pugh (1957-58) observed that the resting ventilation (STPD=standard temperature pressure dry) remained unaltered, and the relation of mass of respired air to work rates was virtually independent of altitude although set at a lower level. This altitude work of Pugh on exercise was limited within the range of 200 to 600 kg.-m/min. and performed on subjects who were acclimatised at altitude for a few weeks only. From this investigation the nature of ventilation at higher work rate could not be predicted reliably. The present investigation covered higher levels of exercise performed by several subjects acclimatising for 5 to 7 months at altitude between 15,000 and 19,000 feet including 12 to 16 weeks at 19,000 feet. The influence of breathing sea level oxygen on ventilation and performance of the acclimatising subjects, which presents an analysis with respect to blood pH, has also been worked out.

METHODS

Exercise was performed on a calibrated bicycle ergometer, and respiratory measurements were made following the usual techniques. Briefly, the subject was either seated at rest or pedalling bicycle at 300, 600, 900 or 12,00 kg-m/min. He breathed through a low resistance check-valve box having small dead space. After

a suitable warming up period of 5 to 10 minutes, expired air was collected over a timed period. Exercise at 900 kg-m min. was limited to 5 minutes, and in some subjects work rate at 1200 kg-m/min. was limited to shorter period. The expired air was analysed by Haldane's apparatus as modified by Lloyd (1958), and its volumes were measured in a dry gas meter and corrected to BTPS and STPD. Blood gas measurements were made as described in Cunningham, et al. (1963).

RESULTS

Measurements were made on six male adult subjects. The results were very similar, and the data obtained on a single subject are given unless otherwise mentioned. The relationship between work rate and oxygen consumption at sea level and at altitude is shown in Fig· 1A. It can be seen that, within the range of work,

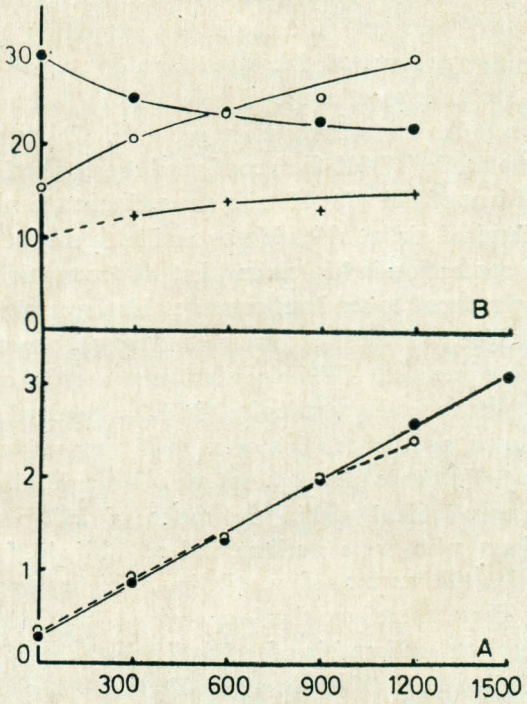

Fig. 1. Relation of oxygen consumption and work rate at sea level (●) and at 19,000 feet after 3 to 4 months acclimatization (O) is shown in the bottom half, A. In the upper half, B, ventilatory equivalent for oxygen is shown : sea level (●); 19,000 feet (O); 19,000 feet with sea level inspired oxygen (+).

efficiency remained unaltered at altitude. However, maximum rate of oxygen consumption decreased at altitude. This was 2.44 l/min. as against 3.10 l/min. at sea level in this particular subject. The acclimatised subject at altitude was able to

maintain his maximum efficiency only for a shorter period. Sea level oxygen supplement, however, improved the performance and lowered VBTPS.

In Fig. 2A VBTPS is plotted against work rate. This confirms the claim of earlier workers (Christensen, 1937; West, 1962) that VBTPS in the acclimatised

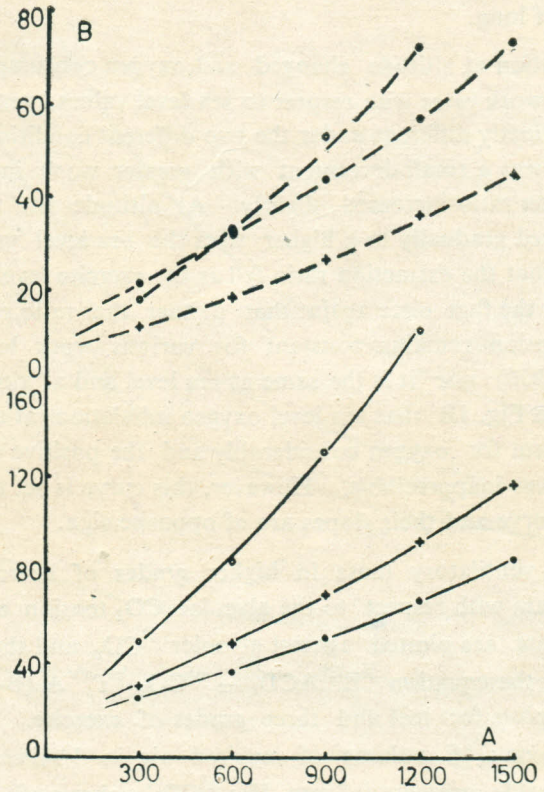

Fig. 2. Relation of ventilation and work rate at sea level (●) and at 19,000 feet amlient inspired oxygen (O) and with sea level inspired oxygen (+) after 3 to 4 months acclimatization. Bottom half, ventilation at body temperature pressure saturated; upper half, ventilation at standard temperature presure dry.

subjects is vastly increased and that sea level oxygen breathing lowers this. This latter, however, is maintained at a higher than the sea level values.

The ventilation data expressed as STPD are given in Fig. 2B. These plots bear out one conclusion that VSTPD in acclimatised subjects is lower in light work rate. Increase of these values with the increasing work rate is, however, more than the sea level values so that VSTPD line of the altitude acclimatised subjects crosses over the sea level line at work rate around 600 kg-m/min. This is a new observation and is not in conformity with what is often claimed (Mathews, 1954; Pugh,

1957-58). Sea level oxygen inhalation at altitude lowered VSTPD in the acclimatised subject. This lowering was, however, not appreciable at rest and in light work but was increasingly apparent at higher work rate. Higher oxygen inhalation did not produce any further appreciable drop in ventilation within the limits of work rate. This is also borne out from inspection of West's (1962) data in connection with the diffusing capacity of lung.

Since ventilation at altitude changed and oxygen consumption remained unchanged at various work rates with respect to sea level values, ventilatory equivalent for oxygen was distinctly different under the two different conditions. This is shown in Fig. 1B. There was a small decrement with greater work intensity at sea level i.e. oxygen extraction ratio increased slightly. At altitude the resting values were smaller but increased gradually to a higher than the sea level values at high work rates. This means that the extraction ratio fell as the exercise level was raised. This analysis brings out the fact once again that neither the ratio of ventilatory mass to oxygen consumption remains constant for various work levels as is so often stated (Gordins, 1950) nor it is the same at sea level and at altitude (Pugh, 1958). It can be seen from Fig. 1B that sea level oxygen inhalation at altitude diminished ventilatory equivalent for oxygen considerably and the positive change with higher grades of exercise was inappreciable. However, this curve is set at a far lower level than the sea level curve and their slopes are of opposite sign.

Increase in ventilatory mass in higher grades of exercise warranted an analysis of these data with respect to the alveolar CO_2 tension and metabolic rate. In Fig. 3 ^{V}BTPS data are plotted against alveoler $^{P}CO_2$, and the metabolic hyperbolae according to the equation $^{V}E.^{P}ACO_2 = {}^{V}CO_2\ {}^{V}T/{}^{V}A$ (B-47) are also constructed in these plots for rest and three grades of exercise. The symbols have conventional meaning : ^{V}E volume of expired air in 1/min. (BTPS); $^{P}ACO_2$, alveolar carbon dioxide pressure in mm. Hg; $^{V}CO_2$ volume of carbon dioxide in 1/min. (STPD); $^{V}T/^{V}A$ was assumed to lie within 1.1 and 1.25; B barometric pressure in mm. Hg. Sea level $^{P}ACO_2$ has been assumed to be 40 mm. Hg. and it can be seen that these $^{P}ACO_2$—^{V}BTPS points fall very closely on the respective metabolic hyperbolae. It is interesting to note that the fall in $^{P}ACO_2$ in exercise at altitude is proportional to ^{V}BTPS, and a straight line can be drawn through all these V-$^{P}ACO_2$ points. These points also fall closely on the respective metabolic hyperbolae which show that the data are self consistent. According to the metabolic hyperbolae the observed fall in $^{P}ACO_2$ was expected to achieve the high ventilation rate. Lactic acid produced during exercise could have been entirely responsible for this lowering of $^{P}ACO_2$ and maintenance of high ventilation, but this did not appear to be so as measurement of blood bicarbonate showed. Lowering of $^{P}ACO_2$ without corresponding lowering of total CO_2 resulted in an increase in blood pH in

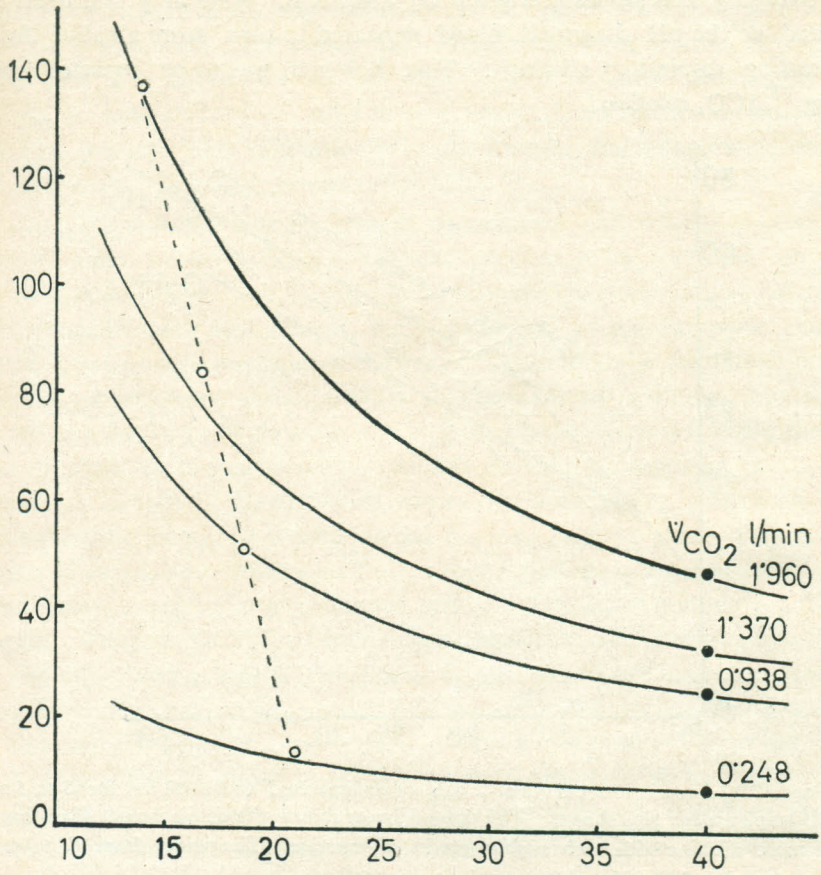

Fig. 3. Relation of ventilation and alveolar carbondioxide presure at sea level (●) and at 19,000 ft. (O) after 3 to 4 months acclimatisation. Isopleths for different metabolic rates corresponding to rest and work rates of 300, 600 and 900 kgm./min. respectively are shown. Any point on a given isopleth describes the relation between corbondioxide pressure and ventilation for that metabolic rate. Vertical displacement from the resting alveolar point is the pathway for hypermetabolic states. Altitude points are displaced to the left.

exercise at altitude as shown in Fig. 4. The carbon dioxide dissociation curves and pH diagonals for the blood of acclimatised subjects is shown here. The curve for oxygenated blood was directly determined by tonometry; that for reduced blood was obtained by applying linear correction to the data obtained from the partially unsaturated blood. The pH diagonals are the extrapolation of the nomogram of Dill, Talbott and Consolazio (1937) for miners at 19,100 feet. $^{P}ACO_2$ total $C0_2$ points are marked for resting (R) and exercising subjects. The dotted arrow shows the direction of change of these points with higher grades of exercise. The dissociation curves are for resting subject; in exercise they are expected to shift downwards

without changing their slopes at a given O_2 saturation. Assuming that these do not change and so the pH diagonals blood appeared to turn more alkaline from the already resting respiratory alkalosis. This, however, was to be expected from the foregoing $^{VP}ACO_2$ relation.

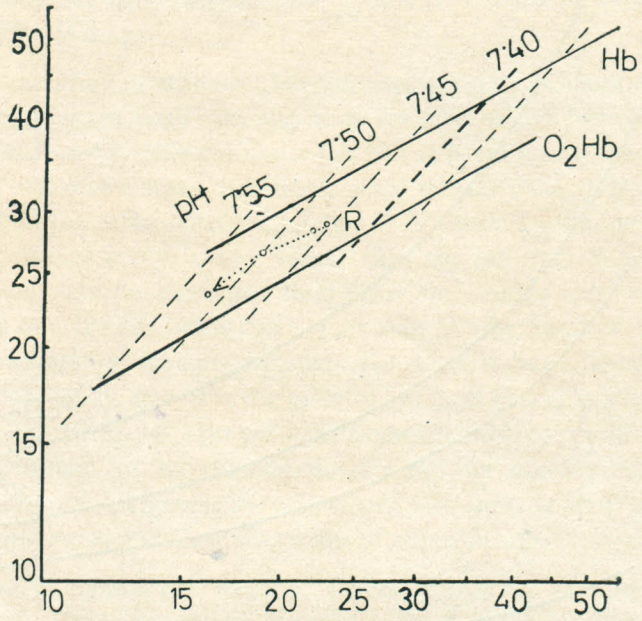

Fig. 4. Blood CO_2 dissociation curves of a subject acclimatised to 19,000 feet for 3 to 4 months. pH isopleths are also shown. The dotted arrow shows the displacement of resting pH R to more alkaline side with higher grades of exercise. The prints from R towards left correspond to 300, 600 and 900 kgm/min. respectively.

DISCUSSION

The data presented here shows convincingly that pulmonary ventilation in altitude-sojourners after 3 to 4 months acclimatisation increase in such a way that the ventilatory mass is smaller at rest and in mild exercise but higher at high levels of exercise on bicycle ergometer. There is an isoventilatory mass point at around 600 kg-m/min. This demonstration is new, and is not in conformity with the claims of Chritensen (1937) and Mathews (1954) and with the tacit assumptions so often made on the same lines (Dejours et al. 1963). The present work, however, confirms that the relation between work rate and oxygen consumption in the altitude sojourners is independent of altitude. This appears to mean that respiratory adaptation keeps the overall metabolic cost unchanged in the newcomers. From these results a change in ventilatory equivalent for oxygen in acclimatised subjects was obvious. However, meaning of this change in terms of adaptation is not so clear. Since pulmonary ventilation is not the same at sea level and at altitude when

expressed in the same units, it is apparent that only the physical characteristics of atmosphere at altitude is not responsible for the change in ventilation in acclimatisation. This is true even after taking into consideration the relative importance of viscosity and density of air at low and high flow rates respectively. This conclusion is indicated by the well known observations that acute exposure does not produce the same high ventilation of acclimatisation and a fixed hyperventilation persists for several days after return to sea level.

The difference between the present observation and others' observation on ventilatory mass in acclimatising subjects may only be apparent, and which could be attributed to the experimental conditions like degree of acclimatisation, range of work rate studied, etc. Inspection of old literature also shows that there is not enough justification for generalisation that the ventilatory mass for a wide range of oxygen consumption is independent of altitude. For example, Schneider and Clarke's (1926) work to which frequent reference is made shows that ventilatory mass is inversely related to the altitude of exposure in their acute experiments. In spite of the decreased respiratory work due to reduced air density, the corresponding change in ventilation did not take place at once. Changes in the regulation of ventilation seem to take place over a period—a rapid change in a few days and a slow change over a prolonged period. This latter period is not known for certain. Despite the claims for complete respiratory acclimatisation within days (Rhan and Olis 1949) or weeks (Douglas et al. 1913) there are indications that acclimatising newcomers probably hyperventilate more than the altitude residents (Chiodi, 1957 : also our unpublished observations). This also appears to bear out from the fact that alveolar Pco_2 is higher in altitude residents (Hurtado & Aste Salazer, 1948). Assuming that racial difference is not the determining factor, it appears that in the initial phase of respiratory acclimatisation the resting ventilation gradually increases before settling to a steady state smaller value. However, the data are inadequate to make such prediction. Milledge (1963) and Kellogg (1963) reported an increased $C0_2$ response in resting altitude sojourners. Extension of this work to the altitude residents should be an advancement.

Greatly diminished ventilation in acclimatised subjects on sea level inspired PO_2 particularly in exercise unequivocally proves that hypoxic drive from the peripheral chemoreceptors continues to play its normal important role in the regulation of ventilation. This depressing effect of oxygen on ventilation would be further enhanced if the concomitant increase in $C0_2$ acidity complex due to $PAC0_2$. H^+ and HbO_2 is taken into account,—thus narrowing down further the difference in VBTPS (on sea level $P0_2$) before and after acclimatisation. It may be recalled here that at sea level at rest extra oxygen does not show a steady effect and acute hypoxia does not produce hyperpnoea until the alveolar PO_2 falls below something like 60 mm. Hg. In exercise, however, as the balance of evidence shows (Astrand, 1954; Dejaurs etal 1963) subjects respond readily to similar degree of acute hypoxia. In

contrast, subjects acclimatised to altitude respond to similar oxygen lack or excess much more readily and vigorously both at rest and in exercise. It appears, therefore, that acclimatised subjects' response with respect to oxygen is changed although adequate supporting quantitative data are not at hand.

Hyperpnoea of muscular exercise is not well understood. Much less is known about this in acclimatised subjects. Exercise at altitude results in a fall of arterial oxygen saturation (west et al., 1962) (as well as PO_2) along the steeper part of 0_2 dissociation curve of blood from an already low saturation. This acute hypoxia superimposed on chronic hypoxia along with the afferent stimuli from the muscles seems to become dominant in causing exercise hyperpnoea which although keep up PAO_2 incidentally depresses arterial PCO_2 and H^+ concentration. (In passing it should be mentioned that respiratory alkalosis produced in this way increases affinity between haemoglobin and oxygen which means that more oxygen is taken up in the lungs by blood at a given pressure but this oxygen is retained in the blood passing through the tissues. This would lower the tissue PO_2 and the advantage gained in the lungs would be lost completely in the tissues and the purpose would be defeated) Thus the place of $C0_2$-acidity complex in exercise hyperpnoea at altitude is not obvious. Kellogg's (1963) observation that altitude sojourners are more responsive to CO_2 at a higher blood pH and Kao's (1963) demonstration that exercise hyperpnoea is due predominantly to neurogenic stimuli from muscles may fit in with the observations presented here but much work would be needed before differences are resolved and a reasonably unified picture emerges.

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