HUMAN ACCLIMATIZATION TO ALTITUDE

J. R. BROTHERHOOD, MB, BS

Laboratory for Field Physiology,
National Institute for Medical Research,
Hampstead, London

The decision to hold the 1968 Olympic Games at Mexico City — an altitude of 2,200 m (7,450 ft) — necessitated physiological research into the effect of this moderate altitude on muscular exercise and athletic performance. Pugh (1967) showed that a period of acclimatization of at least four weeks enabled lowland athletes to improve their performances at altitude. Since 1968 training at altitude has been increasingly used by sportsmen in an attempt to improve their performances at sea level.

The difficulties experienced by men at high altitude are due to oxygen lack. Nonetheless mountaineers have shown that after suitable acclimatization men can live and work at heights that would be lethal on rapid ascent, such as in an aeroplane, without oxygen.

altitude the partial pressure of oxygen in the atmosphere and the lungs is reduced and the haemoglobin incompletely saturated. Less oxygen is conveyed to the tissues and the maximum working capacity reduced.

During acclimatization to altitude three main physiological changes minimize the effects of a reduced atmospheric oxygen tension:

1. An enlargement of the oxygen-carrying capacity of the blood by an increase in the haemoglobin concentration.
2. Increased breathing to raise the oxygen tension in the lung alveoli.
3. Changes at cellular level in the tissues, enabling oxygen to be utilized at lowered pressures.

Fig. 1. Diagram of the oxygen transport system at sea level and at altitude, before and after acclimatization. Although the working capacity improves with acclimatization, it does not regain sea level maximum. R.B.C. = red blood cells. Hb = haemoglobin. pCO_2 = partial pressure of carbon dioxide.

Figure 1 illustrates the oxygen transport system of the body. The degree to which the haemoglobin in the red blood cells is saturated with oxygen depends on the partial pressure of oxygen in the depths of the lungs (the alveolar oxygen tension). At sea level the oxygen tension is sufficient to ensure that the haemoglobin is fully saturated during its passage through the lungs. At high

The blood haemoglobin concentration

The haemoglobin concentration in people acclimatized to or resident at altitude is inversely proportional to the prevailing barometric pressure (Fig. 2). Thus at sea level and a barometric pressure of about 760 mm Hg, the average haemoglobin level in males is 14.5 g per 100

Fig. 2. Relation between haemoglobin concentration and barometric pressure in native residents and acclimatized visitors at various altitudes. , mean values for residents at Denver (5,000 ft – 1,500 m), Mexico City (7,500 ft – 2,200 m), Oroya (12,000 ft – 3,600 m), Morococha (14,900 ft – 4,600 m), and 'Quilcha' (17,500 ft – 5,300 m), published by various authors. values from 5 Himalayan expeditions (Pugh, 1964; 1965). (By courtesy of the Academic Press.)

ml, but at Mexico City, 580 mm Hg, it is 17.5 g per 100 ml. This increase in haemoglobin concentration is due to an increase in the number of red blood cells per cubic millimetre of blood (the red cell count) and not to increased filling of the red cells with haemoglobin. The increase in the red cell count is brought about in two ways: by a reduction in the plasma volume (the liquid portion of the blood), and by an increase in the rate of formation of red cells in the bone marrow. The first is a rapid change which accounts for the immediate increase in haemoglobin concentration observed during the first 48 hours at altitude. The second is a slow change taking four to six weeks for completion. In persons who stay at altitude many months the reduction in plasma volume slowly passes off and is replaced by an increase which, with the increase in red cells, results in a true increase in blood volume. Eventually the total amount of haemoglobin per kilogramme of body weight may be double the sea-level value although the haemoglobin concentration has only increased by a third (Pugh, 1965; Reynafarje, 1964). Balke et al (1966) have claimed that the blood volume increases also in athletes within 10 days of arrival at altitude. If this were true, it would provide a convincing reason for increased performance after returning to sea level, since Ekblom et al (1972)

have shown that the aerobic capacity of trained men can be artificially increased by blood transfusion. Unfortunately Balke's results have not been confirmed.

Another way of increasing the oxygen transport to the tissues is by raising the output of the heart. This response is a first-line defence against acute exposure to altitude which passes off as other adaptive mechanisms develop. It explains the rapid, forceful pulse beats in the head which many people experience during their first few nights after ascending from sea level to altitudes of 2,500 m (8,200 ft) and above.

Increased breathing

The second important change is an increase in breathing or lung ventilation. This reduces the difference

Fig. 3. Mexico City results. Time course of respiratory changes at three levels of O_2 intake. The value of each level of O_2 intake is given in l/min by the number to the right of each time course. The O_2 intakes covered a range from light to sub-maximal work for each subject. The party arrived in Mexico City at 01.00 hr on 7 November (Pugh, 1967). (By courtesy of the Editor, the Journal of Physiology.)

in oxygen tension between the atmospheric air and the alveoli and is an important means of compensating for the reduced atmospheric oxygen tension. This response does not occur immediately, but develops over a few days as shown in Fig. 3 (Pugh, 1967). Unfortunately there are also disadvantages to an increase in ventilation; it results in a reduction in the partial pressure of carbon dioxide in the blood which renders the blood too alkaline. This is corrected by the kidneys with an increase in bicarbonate (alkali) excretion in the urine, but takes several weeks to complete.

Cellular changes

About 30 years ago physiologists began to realize that the oxygen tension in the blood of acclimatized individuals was very similar to that of persons acutely exposed to the same degree of oxygen lack in decompression chambers. However, because of the greater tolerance of the acclimatized, it was inferred that there must be changes at tissue level, improving cellular function at lowered oxygen tensions. Changes in the tissues have subsequently been identified in both man and animals. There is an increase in the myoglobin content of the muscles, myoglobin being a respiratory pigment similar to haemoglobin which acts as a temporary oxygen store in the muscles. Changes in the characters of the mitochondria and an increase in their numbers have also been demonstrated in muscle cell, as have increases in certain oxidative enzymes (Tappan and Renafarje, 1957; Tappan et al, 1957; Reynafarje, 1962).

The major physiological changes brought about by acclimatization to altitude in man are summarized in Figure 1. The individual variations in response to altitude can be considerable, and this was well demonstrated in Pugh's (1967) study in Mexico City. These changes are lost in time on return to sea level, but the process of acclimatization appears to take place more rapidly on successive visits to altitude.

When the results of the running events in the Mexico City Olympic Games are compared with contemporary sea level standards they show a remarkably uniform reduction in performance of about 6% in the endurance events (i.e. those events requiring concurrent oxygen intake), but no change, and even some improvement, in events shorter than 1,500 m (Fig. 4). (The improvement in the sprint events is probably explained by the reduced

Olympic games 1968, winner's times compared with world record times at sea level.

Fig. 4. Results of the running events in the 1968 Olympic Games at Mexico City, 2,200 m (7,450 ft). (Drawn from Pugh, 1969).

air density). Athletes native to high altitude dominated the endurance events. The advantage that these athletes have competing at high altitude has been attributed to the fact that persons born, or at least reared, at altitude, and whose occupation involves heavy labour, have larger hearts and lungs in relation to their body size. The reason why they are not equally superior at sea level is not easy to explain. One possibility may be that lung ventilation during severe exercise may not, as has been proposed, be a limiting factor at sea level.

Conclusions

It is, therefore, by no means certain that the changes brought about by acclimatization to high altitude can be of benefit to athletes competing at sea level. Whether athletes can improve their performance at sea level by training at altitude, how this may be brought about physiologically, and how long it lasts, are the questions we are here to discuss.

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DISCUSSION

DR CRAIG SHARP (University of Birmingham): You said that the reduction in the alkali reserve took place over several weeks. Surely the reserve shows an exponential fall-off and the main bulk of the bicarbonate is excreted between the third and the tenth day?

DR BROTHERHOOD: I do not know the details of this, relative to the time factor. It certainly does not occur immediately, but is a fairly slow process.

DR CRAIG SHARP: In fact, we found that people coming from Nairobi (which is 5,453 ft — 1,660 m — above sea level) excreted very little bicarbonate in the first two or three days.

DR BROTHERHOOD: Of course, this is related to the increase in ventilation. As I pointed out, this increase does not occur for the first three or four days. It takes about seven days to develop and it is not until it has happened that the pH of the blood rises, requiring excretion of alkali. I should imagine that is the explanation.

DR CRAIG SHARP: With regard to muscle cell changes, is the increase in myoglobin, in the number and size of the mitochondria, and in the cytochrome enzymes greater at altitude than in the same athlete training maximally at sea level?

DR BROTHERHOOD: I should like to leave that to be thought about during the day's proceedings.

CHAIRMAN: There are no muscle biopsy experiments in comparable groups which would give the answer?

DR BROTHERHOOD: Most of the work has been on animals, though the myoglobin has been measured in natives living at altitude. The whole question is one which, if it cannot be answered today, should be investigated.

CHAIRMAN: I presume that nobody here can give the answer?

Do you believe that the fatigue experienced by athletes attempting to train during their first few days at altitude can be explained by the changes in circulating blood volume and by the other aspects of adjustment which you mentioned?

DR BROTHERHOOD: Again, I do not feel qualified to answer that question. I suspect that a number of processes result in fatigue. Perhaps the most obvious is that an athlete attempting to train at his sea level performance will, in fact, be working at a far higher rate and much nearer to his maximum oxygen intake. This in itself is more fatiguing. There may be other changes too, such as increased use of muscle glycogen, that may account for this fatigue. However, I do not know the details.