ORIGINAL ARTICLE

Exercise at Altitude

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This article is an updated and revised version of that published by T. Reilly
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Abstract

Altitude poses physiological challenges to the sports participant in excess of those encountered at sea level. The main problem is hypoxia and the reduction in oxygen transport capacity, which is linked to the fall in alveolar oxygen tension. Training at altitude is imperative as preparation for competing there in aerobic events. The acute adaptations on exposure to moderate altitudes may be beneficial for subsequent performance at sea level, and this has led to the use of altitude training camps, though their advantages have not been conclusively demonstrated. The benefits of altitude training depend on a variety of factors, including individual characteristics and environmental training variables.

Key Words

Exercise, altitude, adaptation, benefits.

Introduction

Many sports participants now engage in exercise at altitude. These range from mountaineers scaling high peaks to recreational skiers on activity holidays. Additionally, sport competitions are occasionally held at altitude. These have included the Olympic Games in Mexico City and subsequently the World Cup soccer tournaments in 1970 and 1986. The forthcoming World Cup tournament in South Africa in 2010 will also include a number of venues that are at moderate altitude (around 1500m). Rugby Union teams preparing for the World Cup in South Africa in 1995 had to consider the prospects of playing matches at altitude, and cyclists attempting to qualify for the 1996 Olympic Games in Atlanta had to do so at altitude in Columbia.

Dwellers at sea-level are generally disadvantaged when competing at altitude. Some individuals are more affected than others and need to place greater attention on their preparation for such conditions. The physiological adaptations that occur as a result of a period of exposure to altitude may benefit subsequent performance at sea level. This idea has prompted the use of training camps based at altitude and also hypobaric huts where the percent of oxygen in the air can be manipulated to stimulate altitude. Nevertheless, there is not a consensus among sports scientists as to whether there is a net benefit of training at altitude for sea-level performance.

The main physiological challenge caused by exercise at altitude is hypoxia.[1] The air is less dense as ambient pressure decreases and, therefore, less oxygen is inspired. The decrease in alveolar oxygen tension results in a lowered oxygen delivery by the red blood cells to the active tissues. Consequently, performances that rely on aerobic metabolism are adversely affected. The body does demonstrate some adaptive responses which compensate for the relative lack of oxygen in the air. These responses begin immediately on exposure to hypobaric conditions but, for some people, the full response is not manifested until weeks or months at altitude. Even with complete adaptation, the sea-level visitor to altitude is never as completely adapted as the individual born and bred there. This is apparent in the case of endurance sports in particular.

The highest permanent human settlement is in the Andes and it seems that above an altitude of about 5,000m acclimatization is replaced by a steady deterioration. For mountaineers, their sojourns above this level need to be restricted to avoid inevitable high altitude deterioration. This includes loss of muscle strength and muscle atrophy as well as the varieties of mountain sickness described elsewhere.[2] The focus in this review is on moderate altitudes, below about 3,000m, where many sports competitions are still held and many “altitude training” camps are based. Further recent reviews include those by Mazzeo[3] and Reilly and Waterhouse.[4]

Effects of High Altitude on Exercise Performance

The maximal aerobic power (VO_2max) is reduced by about 15% at an altitude of 2.3km, and it is estimated that VO_2max declines by about 1-2% for every 100m above 1.5km. After three to four weeks at altitude, a portion of this impairment is recovered but the VO_2max remains below sea-level values. For example, the 15% initial drop in VO_2 at an altitude of 2.3km is reversed to a reduction by 9% of the sea-level value within four weeks. These average values mask a wide variation between individuals. There is also a reduction in the maximal heart rate that is reached at altitude.

The fall in maximal aerobic power as a consequence of the reduction in ambient air pressure means that a fixed exercise challenge imposes a greater physiological stress on the athlete. Consequently, higher blood lactate values are observed compared with the same work-rate at sea-level and the increase corresponds to the decline in VO_2max. This has implications for games players since longer periods than normal are required to clear the lactate that is produced and accumulates in the bloodstream. Alongside the increased relative physiological stress is a rise in the perceived exertion, as a consequence of which, the training intensity that can be tolerated is lower than at sea-level. It has been considered that decreased cerebral oxygenation is an important component of the fall in reduced exercise capacity at altitude.[5]

Aerobically trained individuals generally have an immediate decrease in VO_2 at an inspired partial oxygen tension (PO_2) of about 130mmHg, corresponding to an altitude of 600-900m above sea level. In contrast, sedentary individuals are unaffected up to at least 1,200 m.[6] Above this altitude, the oxygen-haemoglobin (O_2-Hb) saturation curve starts to decline steeply and this affects the oxygen transport system by reducing the saturation of haemoglobin leaving the lungs. The decline in VO_2max is mirrored by a decrease in distance-running performance. The experimental work undertaken at Mexico City in the year prior to the 1968 Olympics demonstrated a deterioration in the time to run three miles. Sea-level performance (13min 46s) deteriorated at altitude by 62s but improved over four weeks at altitude, by 19s on average.[7]

By contrast, the reduction in air density at altitude means that performance may be improved in events where air resistance is a limiting factor. This applies to throwing events, jumping and sprinting. It is notable that world records at the Mexico City Olympics were set in track events at all distances up to 800m. The contribution of the reduced air density (and wind assistance) to the world record of Bob Beamon in the long jump was calculated to be 0.31m.[8] In contrast, medal winners at all track distances from 1,500m upwards (who had either lived or trained at altitude prior to the games) returned performances that were below those attained that year at sea-level.

Altitude can present difficulties to games players when completing important elements of technical performance. The decreasing air density associated with increasing altitude results in changes in the aerodynamics of ball flight. These alterations include a reduction in the lateral deflection or "curve" of the ball and increased flight as the ball travels more easily through the thinner air.[9] This can cause difficulty for all outfield positions when shooting, chasing the ball, controlling long passes and clearing the ball using long kicks. The goalkeeper in soccer may also be more easily deceived by shots at goal owing to the faster flight of the ball and its altered trajectory. These changes in ball flight may become especially important when a team prepares for competition at one altitude but contests a competitive game at a very different height without a suitable time period to re-adjust to the new flight characteristics.[10]

Team sport athletes may also face relatively unique physiological challenges when competing at altitude. The physical performance of invasive team sports such as soccer, rugby and hockey require athletes to complete an intermittent exercise pattern. As a consequence, the activities completed range from those that are performed at a low-sub-maximal intensity and stress predominantly the aerobic energy systems (e.g. walking, jogging) to those completed maximally using anaerobic metabolism (e.g. sprinting). There is little literature that has specifically attempted to evaluate the impact of altitude on intermittent exercise patterns. Levine et al,[9] recently recommended that team sport players, more specifically footballers, would have to adjust their pacing strategies at altitude in response to the observed declines in VO_2max to prevent excessive fatigue during games. It was suggested that impairments in maximal exercise performance would be less pronounced at least in part to the improvements associated with discrete sprinting bouts via the reduced air resistance at altitude. These interpretations would seem to indicate that some concessions in game tactics would need to be made to compensate for these reductions in performance, particularly for individuals that are more vulnerable to altitude deterioration. The evidence for the recommendations presented by Levine et al,[9] are, however, predominantly based on research studies that have examined the impact of increasing altitude on maximal and sub-maximal exercise performance completed as distinct bouts of activity. This approach is limited as the physiological and metabolic responses associated with intermittent exercise are not the same as those observed with exercise bouts performed at similar intensities completed as isolated exercise sessions. Such observations do not invalidate these recommendations but merely illustrate the need for more sport-specific research.

Acute Adaptations to High Altitude

The reduction in oxygen PO_2 in the inspired air at altitude is the source of the unique stress on sports performers. The immediate physiological adjustment to altitude exposure is an increase in minute ventilation to boost the PO_2 in the pulmonary alveoli. This helps to offset the fall in oxygen saturation that follows the reduction in alveolar PO_2.

The drop in oxygen saturation may not lead to a decline in the oxygen transport system until an altitude of 1,200m, although this is subject to individual differences (in particular, the level of aerobic fitness). This is because of the sigmoid shape of the O_2-Hb saturation curve. Oxygen desaturation at high exercise intensities may occur at lower altitudes in well-trained endurance athletes, who may, therefore, experience greater deterioration in their aerobic performance when exercising at altitude than their untrained counterparts.

The respiratory compensation response to hypoxia (hyperventilation) leads to a rise in blood pH as a result of increased loss of CO_2. As CO_2 in solution is a weak acid, the blood is more alkaline than normal and there is an excess of bicarbonate ions (Henderson-Hasselbach equation). The kidneys respond by excreting bicarbonate over the course of several days (metabolic compensation), which helps to restore blood pH towards normal. The alkaline reserve is temporarily decreased by this process and so the blood has a poorer capability for buffering additional acids that may be released. For example, lactic acid generated by exercise at altitude will not be buffered as easily as normal. High-intensity performance declines earlier than at sea-level as a result, and the intensity or aerobic training needs to be lowered for training sessions to be sustained.

The low oxygen tension (partial pressure) does not significantly affect the uptake of oxygen by the red blood cells until it reaches a critical point when it declines below the plateau portion of the O_2-Hb saturation curve and encroaches upon the falling portion. However, with adaptation to altitude, this critical oxygen pressure falls. This fall is due to increased production of 2,3-bisphosphoglycerate (BPG) by the red blood cells; it is beneficial in that it aids the unloading of oxygen from the red cells at the tissues.

The oxygen-carrying capacity of the blood is enhanced by an increase in the number of red blood cells. Within a few days of reaching an altitude location, a rise in haemoglobin concentration is apparent, but this initial increase is a result of haemoconcentration owing to the drop in plasma volume. This fall in blood volume arises from increased water loss due to hyperventilation and decreased water intake due to loss of appetite. Nevertheless, there is a gradual true increase in haemoglobin which is mediated by stimulation of the bone marrow to release slightly immature red blood cells (reticulocytes) and also to promote the early stages of erythropoiesis.[11]

The bone marrow increases its iron uptake to form haemoglobin after about 48 hours at altitude; it is important that the body's iron stores are adequate to cope with this increased demand and it might mean supplementation of iron intake prior to and during the stay at altitude. If the individual remains at high altitude, it takes two to three weeks to secure a true increase in total body haemoglobin, and the red cell count continues to increase for one year or more but does not attain the values observed in high-altitude natives. As the haemoglobin concentration increases, there is an associated rise in the haematocrit.

On first exposure to altitude there is an increase in heart rate response to sub-maximal exercise. Later, successful adaptation to altitude results in a reduction in the heart rate response to a near-normal level.

Metabolic Adaptations

Saltin's group[12] has provided evidence that anaerobic capacity may be positively affected by short stays at altitude. Changes include alterations in lactate dehydrogenase isoform pattern and in muscle buffer capacity. Such changes persist for two weeks on return to sea-level. Changes in muscle buffer capacity were correlated with improved performance time in cross-country skiers following a period of altitude training. Saltin[2] considered that improved performances in activities taxing aerobic and anaerobic systems may be attributable to an improved anaerobic capacity. Other work supports the view that the uptake of oxygen by muscles and their mechanical efficiency are comparatively little affected by altitude.[13]

Adaptations to altitude may occur at any of the steps in the oxygen cascade between the lungs and the muscle cells. Ventilatory and circulatory adaptations are complemented by increased peripheral uptake of oxygen by the active muscles. This could be due to increased mitochondrial activities, capillarization and tissue myoglobin as well as increased concentrations of 2,3-BPG.[10] Additionally, substrate utilization is enhanced by mobilization of free fatty acids and increased use of blood glucose, thereby saving muscle glycogen.[14]

The success of East African middle-distance and long-distance runners in major competitions has led to the belief that their excellent performances are linked to their living in natural highlands. Whilst the Kenyan runners tend to have VO_2max values of 82 $mlkg^{-1}.min^{-1}$, and a blunted ammonia response to exercise compared to Europeans,[15] the difference between East African and European teenagers was found to be small. This led to the conclusion that the success of the Kenyan athletes was attributable more to strenuous training and to the large pool of well-conditioned youngsters in the country than to chronic exposure to hypoxia.

Altitude Training Camps

The use of altitude training camps for enhancement of sea-level performances received renewed interest in the 1990s amongst British coaches, the outcome being a symposium convened by the British Olympic Association.[16] This was an attempt to coordinate the experiences of the various sports and provided an opportunity to consider the relevance of altitude training for games players. The exact value of intermittent high-altitude acclimatization (using altitude training camps) continues to be a source of debate.[17]

Middle-distance and long-distance runners from the UK had used a range of altitude locations from Albuquerque (1,500m) to Mexico City (2,300m). The difference in these two exposures was reflected in a significant increase in haemoglobin concentration at Mexico and no change after Albuquerque. It seems that an altitude in excess of 2,000m, when the reduction in ambient pressure takes the oxygen-saturation curve of haemoglobin into its region of steep decline, is needed to induce an appreciable adaptive effect. There have also been investigations of how short a time of high-altitude acclimatization is effective.[18]

The most comprehensive monitoring of athletes was of the rowers. Particular attention was given to reducing the training load on early exposure in order to avoid acute mountain sickness. Later, individuals were carefully programmed with increased training loads whilst metabolic responses were regularly recorded.[19] The programme took into account the competitive schedule following return to sea-level. There is not a consensus on the optimal timing of this return to sea-level before participation in major competition.

A study of Swedish skiers was carried out for a similar three week period at 1.9km with a subsequent long-term follow-up. Ingier & Myhre[20] reported that a strict liquid-intake regimen was effective in reducing the fall in plasma volume associated with dehydration at altitude. The blood lactate response to a sub-maximal exercise test was lowered on immediate return to sea level. This decrease was correlated with the improvement in haemoglobin concentration and haematocrit that had occurred at altitude. It seems that those that benefit most from altitude training are those individuals with the greatest room for elevating oxygen-carrying capacity.

The level of altitude seemingly influences the stimulatory effect of erythropoietin. At about 1,900m the rise in serum erythropoietin is approximately 30% higher than at sea level after two to three days, but at 4,500m this increase is about 300%. Serum erythropoietin concentrations decrease after approximately one week at altitude and this may be associated with increased oxygenation of the tissues owing to the production of 2,3-BPG. The average true rise in haemoglobin approximates to 1% each week, at least at altitudes between 1.8km and 3km.[11]

It is estimated that optimal haematological adaptations to altitude take around 80 days to accrue. This may be accelerated by periodic visits to higher altitude (up to 3km) but not training there. The inability to tolerate high training loads at altitude may lead to a drop in aerobic fitness which offsets the positive effects of the altitude sojourn. The answer may be a combination of living at altitude for a sustained period but frequently returning to near sea level (locally if possible) for strenuous exercise training. The best combination seems to be to live at about 2.8km but train at below 2km.[10]

Upon return to sea-level, it will take a few days for the acid-base status to be re-established. Hypoxia no longer stimulates erythropoiesis and the elevated red cell count slowly falls. The decreased affinity of red blood cells for oxygen, which facilitated its unloading to the active tissues by means of the activity of

2,3-BPG, is soon lost on return to sea level. Any exploitation of the haematological adaptation must be carefully timed to occur before the red blood cell count returns to normal; this may take up to six weeks. Otherwise, repeated sojourns to altitude are needed to maintain the benefits.

A study of Canadian swimmers at an altitude of 1.85km provided a chance of monitoring the changes in haemoglobin and erythropoietin during the stay at the training camp and for six months afterwards. The increases in erythropoietin differed between endurance swimmers and sprint specialists. The results did not clarify how specific training determines the erythropoietin response to altitude exposure, and further research is required.[21]

Altitude training to enhance subsequent performance capability at sea-level is widely used by sea-level natives in a range of sports. Such a manoeuvre is legal and has spawned the development of training camps based at altitude resorts to enhance preparation for sea-level performance. Hypoxic huts and hypobaric chambers provide opportunities for athletes to spend time in hypoxic conditions in attempts to induce the physiological adjustments associated with altitude exposure. The hypoxic stimulus is accentuated by sleeping in the hut as the alveolar PO_2 drops during sleep. Portable altitude simulators in which the inspired oxygen tension is reduced have been designed for use as a back-pack whilst training. They are effective in altering the ventilatory response to exercise but may not induce any further adaptive benefit.[22]

Overview

The benefits of the haematological adaptation to altitude will depend on a host of factors. These include the nature of the sport, the training and nutritional status of the athlete, the duration of the sojourn, the frequency of visits to altitude and the timing of the return to sea-level. The opportunity to take advantage of altitude training depends either on an accident of birth[23,24] or the financial support available to the sea-level dweller. Even then, exposure to altitude demands careful attention to physiological detail so that adverse effects (such as acute mountain sickness) are avoided and the training stimulus carefully matched to the prevailing capability of the individual.

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