Journal of Sports Sciences, 2004, **22**, 928–945

Taylor & Francis
healthsciences

Altitude and endurance training

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Accepted 29 January 2004

The benefits of living and training at altitude (HiHi) for an improved altitude performance of athletes are clear, but controlled studies for an improved sea-level performance are controversial. The reasons for not having a positive effect of HiHi include: (1) the acclimatization effect may have been insufficient for elite athletes to stimulate an increase in red cell mass/haemoglobin mass because of too low an altitude (< 2000–2200 m) and/or too short an altitude training period (< 3–4 weeks); (2) the training effect at altitude may have been compromised due to insufficient training stimuli for enhancing the function of the neuromuscular and cardiovascular systems; and (3) enhanced stress with possible overtraining symptoms and an increased frequency of infections. Moreover, the effects of hypoxia in the brain may influence both training intensity and physiological responses during training at altitude. Thus, interrupting hypoxic exposure by training in normoxia may be a key factor in avoiding or minimizing the noxious effects that are known to occur in chronic hypoxia. When comparing HiHi and HiLo (living high and training low), it is obvious that both can induce a positive acclimatization effect and increase the oxygen transport capacity of blood, at least in 'responders', if certain prerequisites are met. The minimum dose to attain a haematological acclimatization effect is > 12 h a day for at least 3 weeks at an altitude or simulated altitude of 2100–2500 m. Exposure to hypoxia appears to have some positive transfer effects on subsequent training in normoxia during and after HiLo. The increased oxygen transport capacity of blood allows training at higher intensity during and after HiLo in subsequent normoxia, thereby increasing the potential to improve some neuromuscular and cardiovascular determinants of endurance performance. The effects of hypoxic training and intermittent short-term severe hypoxia at rest are not yet clear and they require further study.

Keywords: athletes, cardiovascular function, erythropoietin, hypoxic training, intermittent hypoxia, maximal oxygen uptake, red cell mass.

Introduction

In the last 20–30 years, the maximal oxygen uptake ($\dot{V}O_{2max}$) of athletes has increased, and the world records in distance running have improved. One of the factors influencing the increase in $\dot{V}O_{2max}$ and the improvement of world records is training at altitude, since athletes living in mountainous regions have won many Olympic and World Championship medals in distance running during the last decades. However, the scientific literature on sea-level dwellers training at altitude is equivocal, with most controlled studies failing to observe a positive effect on sea-level performance. This has encouraged the search for alternative strategies to use hypoxia as an additional stimulus for athletes. During the last 10 years, the number of techniques and methods designed to simulate altitude hypoxia and altitude training has increased markedly. Altitude houses and tents, as well as special breathing apparatus, have been developed to provide inspired hypoxia at rest and during exercise and the term 'intermittent hypoxic training' (IHT) has been coined. Intermittent hypoxic training refers to the discontinuous use of normobaric or hypobaric hypoxia, in an attempt to harness the benefits of, and to avoid the problems related to, natural altitude exposure and training. In general, intermittent hypoxic training can be divided into two different strategies: (1) providing hypoxia at rest, with the primary goal of stimulating altitude acclimatization; or (2) providing hypoxia during exercise, with the primary goal of enhancing the training stimulus (Levine, 2002).

In this review, issues relating to altitude, hypoxia and endurance training are evaluated in relation to compe-

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Journal of Sports Sciences ISSN 0264-0414 print/ISSN 1466-447X online
DOI: 10.1080/02640410400005933

titive sports. This review tries to establish the effects (positive or negative) of altitude training (living high and training high – HiHi) on athletes from sea level. In addition, the benefits and problems of the different IHT approaches – that is, living high and training low (HiLo), short-term intermittent exposure to severe hypoxia at rest (short-term IHR), and living low and training in hypoxia (hypoxic training, HT) – are discussed, with special reference to sea-level performance. If studies on elite or well-trained athletes were not available, data on physically active or untrained individuals have been utilized.

Endurance performance and training response at sea level and at altitude

The stimuli that induce the training effect in endurance athletes can be divided into mechanical, neuromuscular and chemical stimuli (e.g. force, tension, neural activity, hormones, oxygen tension; see, for example, Rusko 2003). At altitude, exposure to hypoxia is known to influence all functional systems of the body, including the central nervous system, respiratory system, cardiovascular system and muscles. At the tissue level, hypoxia promotes rapid oxygen sensing and consequent cellular functions. The current model is based on the hypoxia-inducible factor 1 (HIF-1) that consists of α and β subunits. In normoxia, HIF-α is rapidly degraded. In hypoxia, the newly formed HIF-α is stabilized and translocated into the nucleus and dimerized with HIF-β subunits, which are present independently of the partial pressure of oxygen (PO_2) to form HIF-1. The HIF-1 binds to hypoxia-responsive elements of HIF-1 target genes and stimulates the corresponding protein synthesis (e.g. erythropoietin – erythropoiesis; vascular endothelial growth factor – angiogenesis; nitric oxide synthetase – vasodilation; glycolytic enzymes – anaerobic metabolism; tyroxine hydroxylase – catecholamine synthesis) (Jelkmann and Hellewig-Bürgel, 2001; Lahiri *et al.*, 2002). Consequently, living and training in hypoxia may have an influence on almost all organs and tissues in the body. However, the main effects of different altitude training approaches can be observed in those organs and tissues that influence aerobic and anaerobic endurance performance.

In endurance athletes, the capacity of the muscles to receive and consume oxygen exceeds the capacity of the cardiovascular system to transport oxygen (Wagner, 2000). The main aim of altitude training is to increase the total volume of red blood cells and haemoglobin mass to improve the limiting link (i.e. oxygen delivery) by increasing the arterial blood oxygen-carrying capacity, and thus increase $\dot{V}O_{2max}$ and improve performance both at sea level and at altitude. Altitude training may also induce some negative effects on performance determinants (Rusko, 1996; Bailey and Davies, 1997; Hahn and Gore, 2001), thus masking and preventing the use of the benefits from increased red blood cells. One possible reason for the absence of a positive altitude training effect is that even moderate hypoxia during exercise may substantially compromise training pace and decrease mechanical and neuromuscular stimuli, leading to gradual weakening of some specific determinants of endurance performance. Therefore, although $\dot{V}O_{2max}$ and oxygen transport have a crucial role to play in most endurance sports, attention should be paid to other factors, including neuromuscular and anaerobic characteristics ('muscle power factors'), that influence endurance performance and the training response to altitude training.

Several studies have shown that in normoxia, neuromuscular and anaerobic characteristics can differentiate homogeneous groups of runners according to their distance running performance (Bulbulian *et al.*, 1986; Rusko and Nummela, 1996; Paavolainen *et al.*, 1999a,b). Some 'taper' studies have reported an improvement in endurance performance with reduced training without a change in $\dot{V}O_{2max}$ (Shepley *et al.*, 1992; Houmard *et al.*, 1994). Runners also attain higher $\dot{V}O_{2max}$ during uphill running than during horizontal running, and the closer horizontal running $\dot{V}O_{2max}$ is to uphill running $\dot{V}O_{2max}$ is related to better running performance (Paavolainen *et al.*, 2000). Furthermore, pre-activation of the muscles before ground contact during running, which is known to be pre-programmed in the higher centres of the central nervous system, is higher and contact time is shorter in high calibre runners than in low calibre runners with similar $\dot{V}O_{2max}$ (Paavolainen *et al.*, 1999b). Strength training has also been shown to improve the performance of endurance athletes without changes in $\dot{V}O_{2max}$ (Johnston *et al.*, 1997; Paavolainen *et al.*, 1999c).

The limiting factors of endurance performance and the role of the delivered oxygen have also been studied during exercise at different altitudes or at different oxygen fractions of inspired air (F_iO_2). The effects of acute and chronic hypoxia and hyperoxia on exercise performance have recently been reviewed by Noakes *et al.* (2001). In both hypoxia and hyperoxia, the change in $\dot{V}O_{2max}$ exceeds the change in exercise performance, suggesting that some factors influence exercise performance irrespective of changes in $\dot{V}O_{2max}$ (Table 1).

Although exercise performance and $\dot{V}O_{2max}$ do not change equally with changes in F_iO_2, there is a strong positive correlation between changes in maximal workload and maximal cardiac output both in hypoxia and hyperoxia (Peltonen *et al.*, 2001). Interestingly, the maximal cardiac output of elite athletes seems to be

Table 1. Maximal power output and $\dot{V}O_{2max}$ in acute hypoxia and hyperoxia compared with normoxia indicating smaller changes in power than in $\dot{V}O_{2max}$

	Power		$\dot{V}O_{2max}$	
Study	Hyperoxia	Hypoxia	Hyperoxia	Hypoxia
Peltonen *et al.* (1995, 1997)	+2.3%*	−5.3%*	+11.2%*	−15.5%*
Peltonen *et al.* (2001a)	+5.5%	−2.8%*	+15.2%*	−20.9%*
Peltonen *et al.* (2001b)	+3.0%	−3.9%*	+10.1%*	−7.6%*
Mean	+3.6%	−7.3%	+12.2%	−14.7%

* Significantly different from normoxia, $P < 0.05$.

reduced in acute hypoxia when compared with normoxia even though the need for increased cardiac output is high, as shown by the increased cardiac output during submaximal exercise in hypoxia (Peltonen *et al.*, 2001) and maximal sympathetic activation (Lundby *et al.*, 2001a).

Endurance performance in normoxia and hypoxia has also been shown to depend on the function of the neuromuscular system and not only on energy supply and energy depletion (Kayser *et al.*, 1994; Peltonen *et al.*, 1995, 1997; Paavolainen *et al.*, 1999b; Kay *et al.*, 2001; Carter *et al.*, 2003; for further references, see Noakes, 2000; Noakes *et al.*, 2001). During maximal exercise in hypoxia, both muscular electrical activity and maximal cardiac output are attenuated (Kayser *et al.*, 1994; Peltonen *et al.*, 1997) in comparison with normoxia and hyperoxia, suggesting that the central nervous system plays a role in limiting exercise performance. Therefore, the reduced maximal cardiac output and $\dot{V}O_{2max}$ in hypoxia might be the result rather than the cause of reduced skeletal muscle recruitment, supporting the existence of a controlled link (or 'central governor') between cardiac function and muscular performance (Peltonen *et al.*, 2001; see also Noakes *et al.*, 2001). It is unclear whether the suggested 'central governor' is responsible for these responses or if they simply indicate that hypoxic neuronal and cerebral depression and dysfunction is not a regulated process. There is increasing evidence of reduced output of the central nervous system induced by fatiguing muscle contractions (Gandevia, 2001; Di Lazzaro *et al.*, 2003).

In conclusion, exercise performance and $\dot{V}O_{2max}$, as well as the training response at sea level and at altitude, may not be dependent only on oxygen delivery and utilization, but also on other factors linked to the ability of the central nervous system to recruit the muscles. According to the central governor hypothesis, the central nervous system decides how much the muscles are recruited and allowed to produce force and power and thereby regulates, for example, the pumping function of the heart. Potentially, both feedback (e.g. chemoreceptors, baroreceptors, proprioceptors) and feedforward mechanisms could affect central nervous system function. With optimal training, the continued increased recruitment of the muscles results in a new higher-level maximal cardiac output, $\dot{V}O_{2max}$ and exercise performance (see Rusko 2003).

Exercise in hypoxia / at altitude

Arterial haemoglobin oxygen saturation (S_aO_2%) decreases at altitude and some elite endurance athletes are known to develop exercise-induced arterial hypoxaemia during maximal exercise even at sea level (Dempsey *et al.*, 1984; Dempsey and Wagner, 1999). The additional small decrease in S_aO_2% even at low altitudes decreases $\dot{V}O_{2max}$ in elite athletes at ~600 m ($\dot{V}O_{2max}$ ~5.5 $l \cdot min^{-1}$ and ~77 $ml \cdot kg^{-1} \cdot min^{-1}$; Gore *et al.*, 1996), in well-trained athletes at ~900 m ($\dot{V}O_{2max}$ ~5.0 $l \cdot min^{-1}$, ~72 $ml \cdot kg^{-1} \cdot min^{-1}$; Terrados *et al.*, 1985), in recreational athletes at 1200 m ($\dot{V}O_{2max}$ ~4.4 $l \cdot min^{-1}$, ~60 $ml \cdot kg^{-1} \cdot min^{-1}$; Squires and Buskirk, 1982) and in elite female athletes at ~600 m (~3.6 $l \cdot min^{-1}$, ~61 $ml \cdot kg^{-1} \cdot min^{-1}$; Gore *et al.*, 1997). The decrease in $\dot{V}O_{2max}$ is greater the higher the altitude and each 1% decrement in S_aO_2% below the 95% level approximates to a 1–2% decrement in $\dot{V}O_{2max}$ (Dempsey and Wagner, 1999). Consequently, athletes are obliged to train at a lower $\dot{V}O_{2max}$ and at lower maximal sustained and interval training velocities in hypoxia than in normoxia (Gore *et al.*, 1996, 1997; Brosnan *et al.*, 2000). In hypoxia, the S_aO_2% of elite athletes also decreases during submaximal (60–85% $\dot{V}O_{2max}$) exercise (Gore *et al.*, 1995; Peltonen *et al.*, 1999, 2001). Consequently, athletes are obliged to train at lower submaximal training velocities in hypoxia (Levine and Stray-Gundersen, 1997; Hahn *et al.*, 2001) that may further decrease the physical and neural stimuli to muscles compared with training in normoxia. As an indication of decreased neuromuscular training stimuli, integrated electromyogram (iEMG) activity is

reduced in comparison with normoxia at peak exercise during chronic (Kayser *et al.*, 1994) and acute (Peltonen *et al.*, 1997) hypoxia. However, iEMG activity increases with oxygen administration at altitude (Kayser *et al.*, 1994).

Sustained hypoxia leads to a well-known reduction in maximal cardiac output (for references, see Hahn and Gore, 2001) and, contrary to previous findings, maximal cardiac output may decrease during acute hypoxia, at least in elite endurance athletes (Peltonen *et al.*, 2001). There is also increasing evidence that maximal cardiac output and maximal heart rate (HR_{max}) are both decreased during maximal exercise in hypoxia (Peltonen *et al.*, 2001; for further references, see Hahn and Gore, 2001). The lowest altitude for decreased HR_{max} seems to be close to 3100 m, above which HR_{max} is lower the higher the altitude (Lundby *et al.*, 2001b). The decrease in HR_{max} is linearly related to the decrease in S_aO_2% (Benoit *et al.*, 2003) and, therefore, elite athletes with greater decreases in S_aO_2% at altitude may have decreased HR_{max} even at altitudes <3100 m. Similar to iEMG activity, HR_{max} increases with oxygen administration towards sea-level values in both acute (Lundby *et al.*, 2001b) and chronic hypoxia (Kayser *et al.*, 1994; Boushel *et al.*, 2001), and maximal cardiac output is higher in acute hyperoxia than hypoxia (Peltonen *et al.*, 2001) or after oxygen administration in chronic hypoxia (Boushel *et al.*, 2001).

Hypoxia during exercise shifts the ventilation, heart rate and blood lactate concentration versus velocity curves to the left compared with sea-level values (Fig. 1). In addition, the blood lactate concentration versus heart rate curve shifts to the left, especially at high heart rates and, consequently, training heart rates may be slightly decreased during training in hypoxia (Levine and Stray-Gundersen, 1997; Peltonen *et al.*, 1999, 2001; Hahn *et al.*, 2001). Similarly, submaximal $\dot{V}O_2$ at a given heart rate is much lower in hypoxia (Peltonen *et al.*, 2001; Fig. 1), and because the plasma volume is decreased and heart rate is increased during submaximal exercise, the stroke volume and cardiac output may also be decreased during endurance training at altitude (Wolfel *et al.*, 1991; Peltonen *et al.*, 2001) despite the fact that the cardiac output versus $\dot{V}O_2$ curve shifts to the left (Peltonen *et al.*, 2001; Fig. 1).

In summary, there are many possible reasons for the absence of a positive altitude training effect and one of them is that even moderate hypoxia during training may substantially compromise training pace and decrease mechanical and neuromuscular stimuli for attaining a

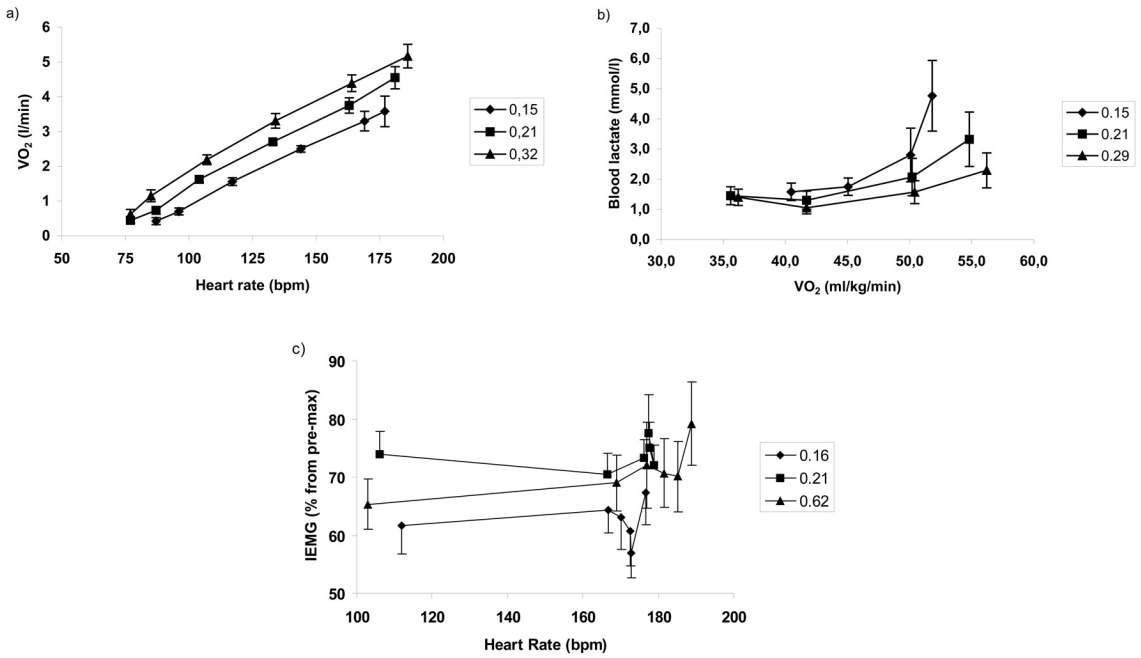

Fig. 1. Changes in (a) $\dot{V}O_2$ versus heart rate curves during incremental exercise to exhaustion (modified from Peltonen *et al.*, 2001), in (b) blood lactate concentration versus $\dot{V}O_2$ curves during incremental submaximal exercise (modified from Peltonen *et al.*, 1999), and in (c) iEMG activity versus heart rate curves during a maximal 2500 m rowing time-trial (modified from Peltonen *et al.*, 1997; data points indicate values recorded at the start and at 500 m intervals during the time-trial) in acute hypoxia, normoxia and hyperoxia. In hypoxia, $\dot{V}O_2$ at the same submaximal heart rate and blood lactate concentration is lower, and the recruitment of muscles during sustained exercise is less, than in normoxia or hyperoxia. For further explanation, see text. ◆, 0.15; ■, 0.21; ▲, 0.32 oxygen fraction in inspired air.

training effect. In addition, recent findings suggest that training stimuli for the cardiovascular system and oxygen consumption may also be decreased during training in hypoxia, leading to a gradual weakening of some specific determinants of endurance performance.

Comparison of HiHi and HiLo in inducing the acclimatization effect

The effects of acclimatization have been studied in natural environments during continuous altitude exposure and training, when travelling back and forth between higher and lower altitudes, and in artificial environments using normobaric or hypobaric hypoxia at sea level. Natural locations to carry out HiLo are few but they allow prolonged daily exposure (>20 h daily) to hypoxia. One possibility of applying HiLo is to increase the oxygen concentration of inspired air during training at natural altitude (Chick *et al.*, 1993). Another approach is the so-called 'altitude house', in which a normobaric hypoxic living atmosphere is created at sea level by decreasing the oxygen concentration of a house, flat or tent to 15–16% oxygen, corresponding to an altitude of $\sim$2500 m and a partial pressure of inspired oxygen of 110–120 mmHg (Rusko *et al.*, 1995a; Rusko, 1996). An altitude house allows individuals to remain in normobaric hypoxia for 12–20 h without limiting normal living or training schedules at sea level. In contrast, when using hypobaric chambers, the daily exposure time to hypoxia is usually only a few hours and the pressure difference limits transitions between hypoxia and normoxia. A recent review summarized different techniques to modify the partial pressure of inspired oxygen (Wilber, 2001).

Irrespective of the approach, a reduced partial pressure of inspired oxygen results in an immediate reduction in the partial pressure of oxygen in arterial blood (P_aO_2) as well as S_aO_2% if the drop in P_aO_2 is great enough. After the immediate initial drop during the first minutes in hypoxia, a slight increase in S_aO_2% using pulse oximetry (S_pO_2%) has been observed during a night in hypoxia; however, during consecutive nights in hypoxia, nocturnal S_pO_2% seems to level off and to remain at a decreased level (Hahn *et al.*, 2001).

The decreased S_aO_2% induces an increase in the renal release of erythropoietin within a few hours. Irrespective of the method of introducing the hypoxia, the increase in erythropoietin concentration in blood is higher the greater the hypoxia and the greater the decrease in S_aO_2% (e.g. Eckhardt *et al.*, 1989; Berglund, 1992; Piehl-Aulin *et al.*, 1998). The threshold altitude for stimulating sustained erythropoietin release is 2100–2500 m (Ri-Li *et al.*, 2002). Interestingly, morning erythropoietin concentration remains at a higher level after 2–5 days during HiLo than during HiHi (Fig. 2). However, during daytime hours in normoxia during HiLo, the erythropoietin concentration decreases significantly compared with early morning values (Rusko *et al.*, 1995a; Stray-Gundersen *et al.*, 2000) due to the short half-time of erythropoietin elimination (Berglund, 1992; Jensen *et al.*, 1995).

To understand the transient nature of the increase in erythropoietin concentration and the differences between HiHi and HiLo exposures, it should be borne in mind that serum erythropoietin concentration reflects a balance between erythropoietin production by the kidney and erythropoietin consumption by the bone marrow. On arrival at altitude, erythropoietin production exceeds consumption, and serum erythropoietin concentration rises. However, increased erythroid activity leads to greater erythropoietin consumption, resulting in a fall in erythropoietin concentration. A new dynamic equilibrium at mildly increased serum erythropoietin concentration is then established, manifest by an elevated rate of erythropoietin turnover. Measurements of serum erythropoietin concentration alone will not reflect this sustained increase in erythropoietin production, which maintains the enhanced level of erythropoiesis (Grover and Bärtsch, 2001, pp. 501–502).

To obtain an acclimatization effect from hypoxia exposure, the increase in erythropoietin production should lead to an increase in the oxygen transport capacity of blood as measured by the total volume of red blood cells and/or haemoglobin mass. Previous studies of untrained participants indicate that total red cell volume is increased in altitude dwellers compared with people living at sea level and the critical partial pressure of oxygen in arterial blood that leads to increased total red cell volume is around 65 mmHg, corresponding to an altitude between 2000 and 2600 m (Reynafarje *et al.*, 1959; Weil *et al.*, 1968; Fiori *et al.*, 2000; Böning *et al.*,

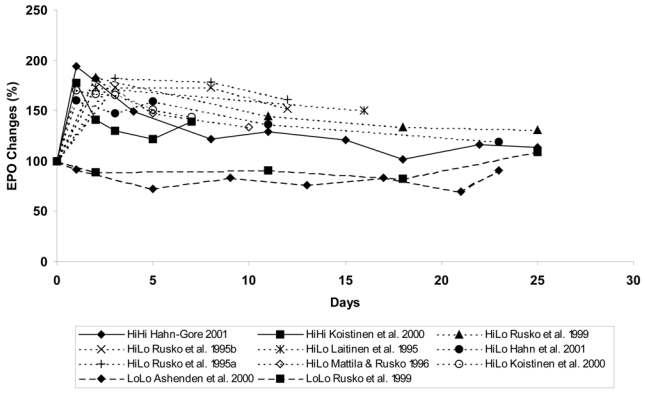

Fig. 2. Percentage changes in serum erythropoietin (EPO) concentration during HiHi, HiLo and LoLo. Mean values from different studies suggest that during HiLo, erythropoietin is higher than during HiHi after 2–4 days.

2001; Schmidt *et al.*, 2002). At higher altitudes, total red cell volume is greater the higher the altitude of residence. In sea-level dwellers, acclimatization for 3–4 weeks increases significantly the total red cell volume of untrained individuals even without training at altitude (e.g. Reynafarje *et al.*, 1959; Wolfel *et al.*, 1991; Heinicke *et al.*, 2003). It is difficult to apply these studies to endurance athletes who have a 20–25% greater total red cell volume/haemoglobin mass and blood volume than untrained individuals even without training at altitude (Remes, 1979; Böning *et al.*, 2001; Schmidt *et al.*, 2002); however, cross-sectional studies indicate a cumulative effect from altitude exposure and from training at altitude (Schmidt *et al.*, 2002).

Many longitudinal studies also indicate that HiHi for 4 weeks increases significantly the total red cell volume/haemoglobin mass of athletes at altitudes $\geqslant$2500 m (Stray-Gundersen *et al.*, 1992, 1993, 1995; Levine and Stray-Gundersen, 1997). We found a 6% increase in red cell volume in 14 elite distance runners after 4 weeks of altitude training at $\sim$2200 m using a reliable method (isotope dilution method, technetium-labelled red blood cells) for measuring total red cell volume (Rusko and Tikkanen, 1996). It has been calculated that the increase in haemoglobin mass during altitude training is quite small and slow ($\sim$1% per week; Berglund 1992) and total red cell volume may continue to increase for 6–8 months during altitude exposure (Reynafarje *et al.*, 1959). Some studies have failed to show an increased total red cell volume/haemoglobin mass in athletes after HiHi. Gore *et al.* (1998) found haemoglobin mass to be unchanged after training for 31 days at 2690 m, although all of their participants had clinical symptoms (see next section). In another study, training for 1 month at $\sim$1900 m increased the blood volume (+7%) and haemoglobin mass (+3%) of elite cross-country skiers, but the changes were non-significant (Svedenhag *et al.*, 1997).

Some studies have indicated that HiLo (living high at $\sim$2500 m and training low at $\sim$1300 m) for 4 weeks increases total red cell volume/haemoglobin mass by $\sim$5% (Levine *et al.*, 1991; Levine and Stray-Gundersen, 1997; Wehrlin *et al.*, 2003). Similarly, HiLo studies using an altitude house at sea level (Laitinen *et al.*, 1995; Rusko *et al.*, 1999) have shown a significant $\sim$5% increase in total red cell volume (technetium-labelled red blood cells) or haemoglobin mass (CO-rebreathing method) of elite endurance athletes while training for 3–4 weeks. In one study, the 3.5% increase in haemoglobin mass after 4 weeks of HiLo using an altitude house was not statistically significant (Piehl-Aulin, 1999). In some HiLo studies, increased morning erythropoietin concentrations have been observed but haemoglobin mass was not increased (Ashenden *et al.*, 1999a,b; Hahn *et al.*, 2001; Dehnert *et al.*, 2002).

The above results suggest that HiHi and HiLo may induce the acclimatization effect and increase total red cell volume/haemoglobin mass if certain prerequisites are fulfilled (Fig. 3). In the HiHi studies with increased total red cell volume, the athletes stayed 24 h a day for 4 weeks at altitudes of approximately 2500 m. In the HiLo studies at natural altitude, the daily exposure time to the living altitude of 2500 m has been 18–20 h and the total duration $3\frac{1}{2}$ –4 weeks (Levine and Stray Gundersen, 1997; Wehrlin *et al.*, 2003). In the Nordic HiLo studies using an altitude house at sea level, the normobaric hypoxia has corresponded with altitudes of approximately 2500 m, the daily exposure to hypoxia has been 12–18 h and the HiLo period 3–4 weeks (Laitinen *et al.*, 1995; Piehl-Aulin, 1999; Rusko *et al.*, 1999). In addition, in the Finnish studies (Laitinen *et al.*, 1995; Rusko *et al.*, 1999), the athletes have spent their daytime hours in hypoxia in an altitude house, between the training sessions at sea level, and they have also performed a few low-intensity training exercises per week in hypoxia, which might have influenced their erythropoietin and total red cell volume responses. The failure of short exposure periods and short daily exposure times to raise total red cell volume/haemoglobin mass (Ashenden *et al.*, 1999a,b; Hahn *et al.*, 2001; Dehnert *et al.*, 2002) suggests that the minimum time to attain an acclimatization effect is $>12\ \mathrm{h \cdot day^{-1}}$ at an altitude $>$2000 m for at least 3 weeks (Fig. 3). Individual differences observed in total red cell volume/haemoglobin mass may be due to participants with iron deficient before the HiHi or HiLo period being unable to increase their red cell volume (Hannon *et al.*, 1969; Stray-Gundersen *et al.*, 1992).

Clinical problems related to altitude training

During altitude training, several clinical problems may develop, such as acute mountain sickness, high-altitude

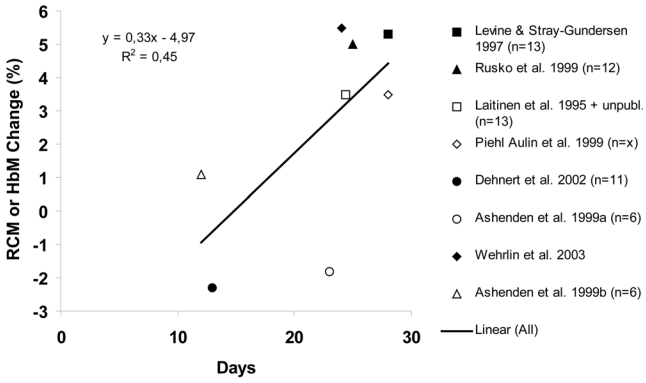

Fig. 3. Percentage changes (%) in the mean total red cell volume (RCM) or haemoglobin (HbM) mass during HiLo in relation to the number of days of the HiLo period.

cerebral oedema or high-altitude pulmonary oedema. The frequency and severity of these problems depend on altitude, rate of ascent and degree of individual susceptibility. Acute mountain sickness symptoms appear to be more severe the higher the altitude above 2500 m (Bärtsch and Roach, 2001; Schneider *et al.*, 2002) and symptoms may also occur during HiLo periods in an altitude house (H.K. Rusko, unpublished data). Although not all individuals ascending to altitude suffer from these symptoms, hypoxia may still cause other detrimental effects while in hypoxia and some symptoms may persist for some time after return to sea level. On the other hand, pre-acclimatization even at lower altitudes may diminish the symptoms (Bärtsch and Roach, 2001). HiLo has also been successful for pre-acclimatization to HiHi, for example for increasing resting ventilation and the partial pressure of oxygen in arterial blood and reducing end-tidal carbon dioxide and the severity of acute mountain sickness (Beidleman *et al.*, 2003).

The global cerebral metabolic rate for oxygen and brain oxygen delivery seem to be maintained during acute hypoxia in individuals at rest without acute mountain sickness through compensatory mechanisms that include increased cerebral blood flow and increased haemoglobin concentration (Roach and Hackett, 2001). In contrast, recent studies indicate that during exercise in acute hypoxia (after 4 days at 3450 m), brain oxygen saturation measured with near-infrared spectroscopy may fall by 5–25%, with the greatest reduction at $>85\%$ of maximal heart rate (Bradwell *et al.*, 1999). It appears, therefore, that if hypoxia is severe enough, humans will experience substantial systemic and cerebral oxygen desaturation during exercise at altitude, and those with the most severe cerebral desaturation will develop the most severe acute mountain sickness and high-altitude cerebral oedema (Roach and Hackett, 2001). Future studies on athletes exhibiting arterial hypoxaemia during maximal exercise at sea level are warranted at altitudes that are mainly used for athletic training.

Although the greatest effects of hypoxia on brain function are reported to occur at high altitudes, even modest levels of hypoxia ($\geqslant$1500 m) can impair brain function. Symptoms such as visual perturbation and slowed performance, particularly on more complex tests of cognitive and motor function, have been reported (Hornbein, 2001). During sustained hypoxia and with increasing altitude, remarkable perturbations on neuropsychometric tests have been reported, together with changes in behaviour, mood and even neurological function (Hornbein, 2001). Similarly, cerebral desaturation may potentially affect several systems critical to exercise performance. During acclimatization to chronic hypoxia, an increase in the cerebral microvasculature that has been observed in animal studies (Harik *et al.*, 1996) may potentially improve brain tissue oxygenation both at altitude and at least transiently after return to sea level, thereby reducing the limiting effect of the central nervous system to exercise performance.

Another mechanism related to altitude exposure is the hypoxic ventilatory response. The fall in arterial haemoglobin oxygen saturation that occurs with exercise in hypoxia is inversely related to the hypoxic ventilatory response and sojourners with a high response may perform better at high altitude (Ward *et al.*, 1999, pp. 69–97; Schoene, 2001). However, the increasing hypocapnia resulting from hyperventilation is considered to have the potential to decrease cerebral circulation (Bradwell *et al.*, 1999; Hornbein, 2001). The result may be that, while exercising at altitude, the muscles are receiving more oxygen but the brain is receiving less, which may lead to negative after-effects on return to sea level (Hornbein, 2001). It is also known that endurance athletes have a blunted chemosensitivity for the control of ventilation compared with non-athletes and experienced climbers (Schoene, 1982). Interestingly, endurance athletes may experience changes to the respiratory control system and potentiate their hypoxic ventilatory response during the HiLo period (Mattila and Rusko, 1996; Townsend *et al.*, 2002). This is possibly due to increased sympathetic activation and/or a change in the partial pressure of carbon dioxide (PCO_2) set point of the respiratory control mechanism (Townsend *et al.*, 2002), or, as recently hypothesized, may indicate a primary long-term respiratory control effect of PO_2 (Robbins, 2001).

One factor that could result in problems during altitude training and decrease sea level $\dot{V}O_{2max}$ after altitude training is hypoxia-induced stress and the consequent overtraining symptoms (Rusko, 1996; Gore *et al.*, 1998). Sympathetic activation is increased at altitude, which, together with increased glycolytic metabolism during exercise, increases the overall stress of training. A significant increase in resting serum cortisol (Vasankari *et al.*, 1993; Wilber *et al.*, 2000) and decrease in serum testosterone concentrations (Gore *et al.*, 1998) have been found after altitude training in elite endurance athletes, which may also depress erythropoiesis in the bone marrow, especially in the early phase of altitude training (see Berglund, 1992). Hypoxia also decreases immunoreactivity, specifically by suppressing T-cell mediated immunity (Meehan *et al.*, 2001), and a 50–100% increase in the frequency of upper respiratory tract and gastrointestinal tract infections during or immediately after altitude sojourns has been observed (Bailey *et al.*, 1998; Gore *et al.*, 1998). The possibility of oxidative damage mediated by free radicals also increases at altitude (Vasankari *et al.*, 1997).

Altitude acclimatization and endurance performance

Several studies have shown that HiHi may improve $\dot{V}O_{2max}$ and performance at moderate altitude (>1500 m). During acclimatization, $\dot{V}O_{2max}$ and performance at altitude start to increase slowly, but $\dot{V}O_{2max}$ does not attain its sea-level value after 4 weeks of HiHi (Saltin, 1967; Faulkner *et al.*, 1968; Adams *et al.*, 1975; for further references, see Hahn and Gore, 2001). As shown earlier in this review, the $\dot{V}O_{2max}$ of endurance athletes is decreased at low altitudes, suggesting that acclimatization might be beneficial for race performances held at those low altitudes. However, there are no studies indicating that HiHi or HiLo could improve performance or $\dot{V}O_{2max}$ at low altitudes (500–1500 m).

The scientific literature on HiHi for improved sea-level performance is equivocal. Although some studies have shown improvements (e.g. Daniels and Oldridge, 1970; Mellerowicz *et al.*, 1970), most controlled studies on elite athletes have failed to observe a positive effect on sea-level $\dot{V}O_{2max}$, lactate threshold, running economy or performance after 2–4 weeks of HiHi compared with similar training at sea level, and in all studies considerable individual variation in response to altitude training has been observed (Svedenhag *et al.*, 1991; Jensen *et al.*, 1993; Rusko *et al.*, 1996; Levine and Stray-Gundersen, 1997; Bailey *et al.*, 1998). Animal experiments also indicate that, despite the same absolute training intensity in hypoxia as in normoxia, HiHi for 10 weeks did not confer significant advantages over living and training in normoxia: $\dot{V}O_{2max}$ and maximal cardiac output in normoxia increased similarly with both training regimens (Henderson *et al.*, 2001).

During HiLo, it is possible to attain the benefits of both altitude acclimatization and normoxic training stimuli (Levine and Stray-Gundersen, 1997). Several studies have shown that HiLo can increase sea-level $\dot{V}O_{2max}$ and improve sea-level endurance performance (Levine *et al.*, 1991; Mattila and Rusko, 1996; Levine and Stray-Gundersen, 1997; Chapman *et al.*, 1998; Piehl-Aulin, 1999; Rusko *et al.*, 1999; Stray-Gundersen *et al.*, 2001; Roberts *et al.*, 2003; Wehrlin *et al.*, 2003). In a well-controlled study, Levine and Stray-Gundersen (1997) showed that, after 4 weeks of lead-in training at sea level, both HiLo and HiHi increased sea-level $\dot{V}O_{2max}$ in direct proportion to the increase in red cell volume. In addition, HiLo improved the ventilatory threshold and the velocity at $\dot{V}O_{2max}$ at sea level and consequently sea-level 5000 m track running perfor-

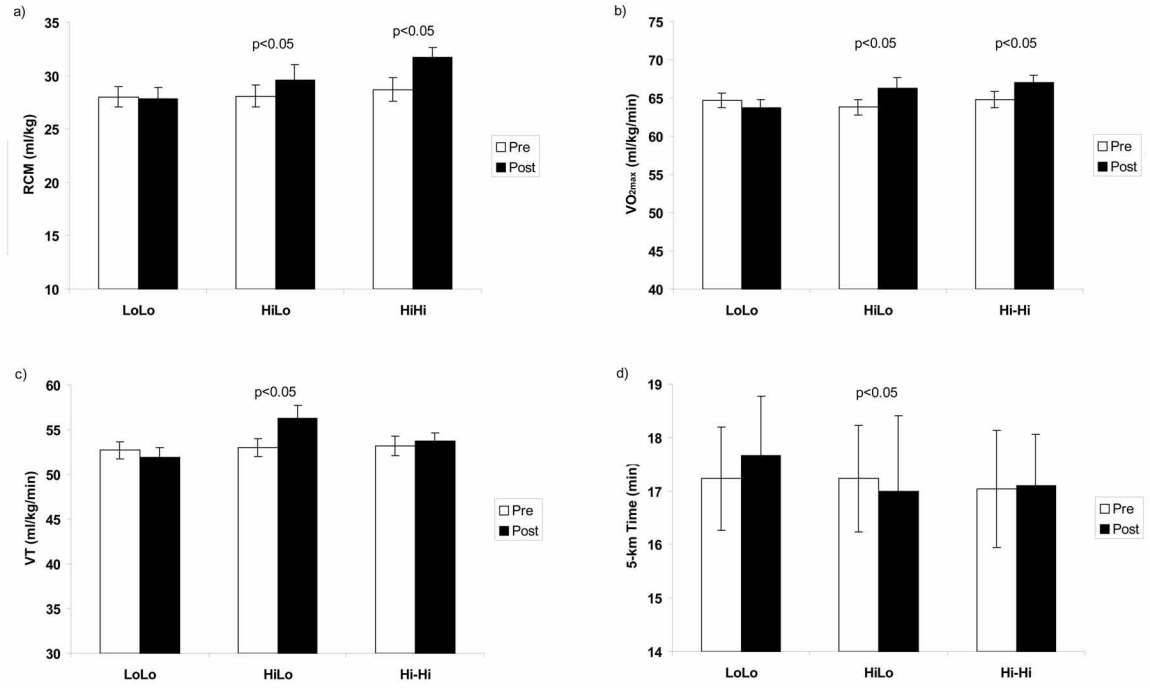

Fig. 4. Comparison of changes in (a) total red cell volume (RCM), (b) maximal oxygen uptake ($\dot{V}O_{2max}$), (c) ventilatory threshold (VT) and (d) 5000 m time-trial performance after sea-level training (LoLo), after living high and training low (HiLo) and after altitude training (HiHi). The results indicate that both HiHi and HiLo increase total red cell volume and $\dot{V}O_{2max}$, but only HiLo improves the ventilatory threshold and 5000 m time. □, pre-training; ■, post-training. Modified from Levine and Stray-Gundersen (1997).

mance, which were not improved by HiHi or LoLo (Fig. 4). The importance of maintaining a high training velocity, cardiac output and oxygen flush primarily during interval training was confirmed in another study in which elite athletes performed all the high-intensity training exercises at low altitude (1250 m), while all base and recovery training was carried out at the living altitude of 2500 m (HiHiLo; Stray-Gundersen *et al.*, 2001). HiHiLo induced almost identical improvements in performance compared with the HiLo athletes, who did all their training exercises at low altitude: after 4 weeks of HiHiLo, the improvement in sea-level $\dot{V}O_{2max}$ was 3% and it was accompanied by a 1.1% (5.8 s) significant improvement in sea-level 3000 m running performance (Stray-Gundersen *et al.*, 2001). In the study of Wehrlin *et al.* (2003), elite endurance athletes lived at ~2500 m for 24 days, performed base training twice a week at ~1800 m and interval training twice a week at ~1000 m; this HiHiLo schedule resulted in significant improvements of $\dot{V}O_{2max}$ of 4.5% and 5000 m running time of 18 s.

The effects of HiLo and HiHiLo are similarly individual as those of HiHi. The responders (greater than mean improvement in sea-level running performance) had a more marked erythropoietin response at altitude than non-responders, and responders also showed significant increases in total red cell volume and $\dot{V}O_{2max}$ that were not observed in non-responders (Chapman *et al.*, 1998). In addition, the responders were better able to maintain normal training velocities and oxygen flux than the non-responders.

HiLo studies of elite endurance athletes using an altitude house at sea level have also found a significant increase in $\dot{V}O_{2max}$ after 25–28 days. Rusko *et al.* (1999) showed a significant increase (~5%) in maximal treadmill performance after 25 days of HiLo and Piehl-Aulin (1999) a significant increase (~3%) after 21–28 days of HiLo. An approximately 4% improvement in cycling performance has also been reported in elite cyclists after 11 days of HiLo in an altitude house, corresponding to an altitude of 2500–3000 m (Mattila and Rusko, 1996). In contrast, no significant changes in sea-level $\dot{V}O_{2max}$ or performance have been observed in some other HiLo studies (Ashenden *et al.*, 1999a,b, 2000; Hahn *et al.*, 2001; Dehnert *et al.*, 2002). As noted earlier, a plausible explanation for the contradictory findings is the low total duration of exposure to hypoxia and the lack of an increase in total red cell volume/haemoglobin mass (Figs. 3 and 5). The studies that have found a significant increase in sea-level $\dot{V}O_{2max}$ and performance after HiLo have also reported a significant or almost significant increase in total red cell volume/haemoglobin mass (Levine and Stray-Gundersen, 1997; Piehl-Aulin, 1999; Rusko *et al.*, 1999; Wehrlin *et al.*, 2003), and the changes in $\dot{V}O_{2max}$ and total red cell volume/haemoglobin mass have correlated with each other (Levine and Stray-Gundersen, 1997; Wehrlin *et al.*, 2003).

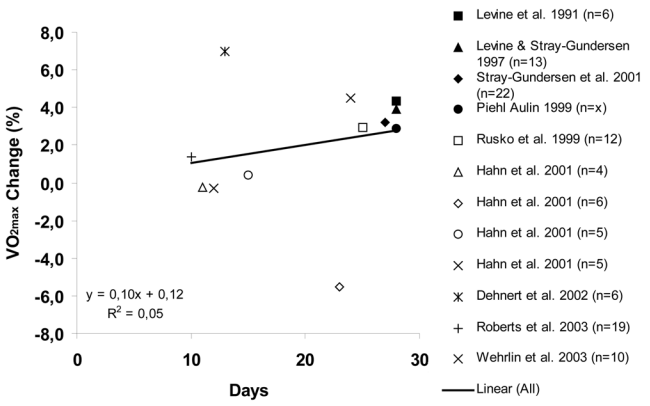

Fig. 5. Percentage changes (%) in mean maximal oxygen uptake ($\dot{V}O_{2max}$) during HiLo in relation to the number of days of the HiLo period.

In another HiLo study, athletes who had lived and trained for one year at altitude improved their endurance performance significantly after a concomitant 6-week HiLo training period while breathing 70% oxygen during four weekly training sessions at altitude that allowed increased training intensities (Chick *et al.*, 1993). Similarly, breathing hyperoxic gas during three high-intensity sessions per week for 3 weeks at an altitude of 1840 m allowed a higher absolute training intensity (Wilber *et al.*, 2003) and led to an improved maximal lactate steady state and time to complete a 120 kJ performance test (Morris *et al.*, 2000). An animal experiment also found improved running performance, decreased heart rate during constant velocity running and increased left ventricular mass and triceps surae mass in a HiLo than a LoLo group (Miyazaki and Sakai, 2000).

Piehl Aulin (1999) observed significant improvement in sea level $\dot{V}O_{2max}$ during HiLo (day 21), as well as immediately after and 1 week after the 28-day HiLo period. Levine and Stray-Gundersen (1997) found significant improvements in both sea-level $\dot{V}O_{2max}$ and performance 3, 7, 14 and 21 days after HiLo. In contrast, Rusko *et al.* (1999) reported improvements in $\dot{V}O_{2max}$, maximal treadmill performance and cycling performance (Mattila and Rusko, 1996) 1 week after the HiLo period but not immediately (a few hours) after the last night in hypoxia (Rusko *et al.*, 1999). In several Australian studies, post-tests were performed 'within 36 hours' after the HiLo period and no significant changes were observed (Ashenden *et al.*, 1999a,b, 2000; Hahn *et al.*, 2001).

Improved sea-level endurance performance could also be due to increased aerobic capacity of the muscles or improved economy after HiHi and HiLo. High-altitude dwellers have a greater muscle myoglobin

concentration and greater muscle respiratory capacity than sea-level residents (Reynafarje, 1962). However, in elite athletes, neither HiHi nor HiLo has been shown to increase the oxidative or glycolytic capacity of the muscles (Rahkila and Rusko, 1982; Saltin *et al.*, 1995a,b; Stray-Gundersen *et al.*, 1999). The results of studies on the effect of altitude training on economy are contradictory (Svedenhag *et al.*, 1991; Saltin *et al.*, 1995a; Levine and Stray-Gundersen, 1997; Green *et al.*, 2000; Gore *et al.*, 2001).

Altitude acclimatization and anaerobic performance

Owing to decreased air resistance, new world records were recorded in all sprinting events at the Mexico City Olympic Games in 1968. Karvonen *et al.* (1990) have shown that maximal sprinting speeds increased during 2 weeks of altitude training at 1860 m, probably because of the decreased air resistance during sprint training. Gale and Nagle (1971) have shown that in rats sprint training at ~2300 m altitude for 5 weeks at the same velocity as in normoxia increased phosphocreatine stores in gastrocnemius-plantaris muscle.

During exposure to altitude, supramaximal performances requiring glycolytic energy production should be decreased because of bicarbonate loss and a decrease in plasma volume (Hahn and Gore, 2001). Indeed, during supramaximal 10 × 6-s bouts of interval exercise, the ability to maintain high power output during the last bout was impaired, $\dot{V}O_{2max}$ was lower and lactate accumulation was greater in hypoxia (~3000 m) than in normoxia (Balsom *et al.*, 1994). Acute severe hypoxia, however, did not impair performance on a single 30–45 s Wingate test even though $\dot{V}O_{2max}$ was reduced, muscle lactate increased and glycogen decreased following performance in hypoxia compared with normoxia (McLellan *et al.*, 1990). Sodium bicarbonate ingestion or infusion has been shown to increase the blood-buffering capacity at altitude, decrease arterial desaturation and improve performance and interval training at altitude (Hausswirth *et al.*, 1995; Nielsen *et al.*, 2002), indicating that the potential for training and glycolytic energy production is decreased at altitude without compensatory increases in buffer capacity. Other measures to improve race performance and training intensity at altitude could be caffeine ingestion (Berglund and Hemmingsson, 1982) and a diet high in carbohydrate (Hansen *et al.*, 1972).

Chronic HiHi for 3–4 weeks has been shown not to improve supramaximal anaerobic performance capacity at sea level (Rusko *et al.*, 1996; Levine and Stray-Gundersen, 1997; Bailey *et al.*, 1998). However, altitude training above 2000 m for 2 weeks has been shown to increase running time to exhaustion (range 240–380 s) during sea-level $\dot{V}O_{2max}$ measurement without an increase in $\dot{V}O_{2max}$, and to increase the maximal accumulated oxygen deficit and muscle buffer capacity after return to sea level (Mizuno *et al.*, 1990; Svedenhag *et al.*, 1991; Saltin *et al.*, 1995b). Martino *et al.* (1996) have also shown that anaerobic performance at sea level may be improved after sprint swimming training at altitude.

HiLo training for 2 weeks with 14–18 h daily exposure to normobaric hypoxia in an altitude house (15.8% O_2 in inspired air, ~2500 m) and normal sprint training at sea level has also been shown to improve sea-level 400 m race time of elite sprinters as well as decrease their blood lactate concentration during submaximal sprinting on a treadmill (Nummela and Rusko, 2000). Gore *et al.* (2001) have shown that 23 days of HiLo in an altitude house, corresponding to an altitude of 3000 m, increased muscle buffer capacity. In a recent Australian study, none of the HiLo durations of 5, 10 or 15 days, 8–10 h per night, induced significant changes in $\dot{V}O_{2max}$, maximal accumulated oxygen deficit or maximal mean power output in 4 min ($MMPO_{4min}$), but using the pooled data from all three experimental periods, maximal accumulated oxygen deficit and $MMPO_{4min}$ increased significantly (Roberts *et al.*, 2003). Although Levine and Stray-Gundersen (1997) did not observe an improvement in maximal accumulated oxygen deficit and Stray-Gundersen *et al.* (1999) found a decreased muscle buffer capacity after 4 weeks of HiLo in athletes training for aerobic endurance, it would appear that HiHi and HiLo with sprint-type training may improve subsequent anaerobic performance at sea level.

Effects of hypoxic training

Studies in which hypoxia was experienced only during the training sessions have shown no acclimatization effects (e.g. Roskam *et al.*, 1969; Terrados *et al.*, 1988; Geiser *et al.*, 2001; Hendriksen and Meeuwsen, 2003), even though erythropoietin is increased after exercise in hypoxia (Schmidt *et al.*, 1991).

Hypoxic training has been shown to increase $\dot{V}O_{2max}$ and submaximal and maximal performance at sea level but the effects have been similar to those of normoxic training (Roskam *et al.*, 1969; Davies and Sargeant, 1974; Terrados *et al.*, 1988; Burtscher *et al.*, 1996). In a recent crossover study design, moderate-intensity hypoxic training (60–70% $\dot{V}O_{2max}$) for 10 days increased normoxic maximal aerobic and anaerobic power output 2–9 days after the hypoxic training had ended. However, the increase in maximal aerobic power output was not significantly greater than after normoxic control

training, and $\dot{V}O_{2max}$ did not change significantly (Hendriksen and Meeuwsen, 2003), even though some significant changes were found during the first half of the crossover study (Meeuwsen *et al.*, 2001). Similarly, in trained athletes, hypoxic training for 6 weeks, three times per week, did not lead to improved performance in either normoxic or hypoxic conditions (Ventura *et al.*, 2003). According to Geiser *et al.* (2001), there were no differences between the effects of hypoxic and normoxic training in untrained individuals when $\dot{V}O_{2max}$ was measured in normoxia, but hypoxic training increased $\dot{V}O_{2max}$ measured in hypoxia more than normoxic training, and the high-intensity training in hypoxia was the most effective stimulus for increasing muscle oxidative capacity. Terrados *et al.* (1988) have also shown that hypoxic training increased the work capacity of athletes in hypoxia more than normoxic training at sea level; the increase was related to a decreased exercise blood lactate concentration, increased capillarization and decreased glycolytic capacity. Indeed, when the absolute training intensity in hypoxia is equal to that in normoxia (e.g. single leg exercises in hypoxia and normoxia), improved sea-level performance and increased myoglobin and oxidative capacity in human muscles have been observed (Terrados *et al.*, 1990; Melissa *et al.*, 1997; Hoppeler and Vogt, 2001).

The above findings suggest that hypoxic training induces similar changes for improved sea-level performance as training in normoxia, but hypoxic training may be more beneficial than sea-level training for an improved performance at altitude.

Short-term intermittent hypoxia at rest

Short-term intermittent hypoxia at rest (IHR) was originally developed in the former Soviet Union and consists of breathing hypoxic air (9–11%) through a mask or mouthpiece for repeated periods of 5–7 min, interrupted by equal periods of recovery in normoxia, totalling 1–3 h for one or two sessions a day (Bernardi, 2001; Serebrovskaya, 2002). As an indication that short-term intermittent hypoxia at rest could improve altitude acclimatization, Tkatchouk *et al.* (1999) reported an increased partial pressure of oxygen in arterial blood (from 54 ± 1 to 62 ± 2 mmHg), $P(a\text{-}v)O_2$ (from 22 ± 3 to 31 ± 1 mmHg) and arterial haemoglobin oxygen saturation (from 87 to 91%) during an acute ascent to 3000 m in an altitude chamber in comparison with pre-IHR values. According to Serebrovskaya (2002), who reviewed the studies conducted in the former Soviet Union and the Commonwealth of Independent States, intermittent hypoxia at rest 'induces increased ventilatory sensitivity to hypoxia as well as other hypoxia-related physiological changes, such as increased hematopoiesis, alveolar ventilation and lung diffusion capacity, and alterations in the autonomic nervous system'. Positive effects from short-term intermittent hypoxia at rest for an improved sea-level performance have been reported in competitive swimmers versus a control group (Bulgakova *et al.*, 1999).

There are also studies conducted in the West claiming positive acclimatization effects of short-term intermittent hypoxia at rest and suggesting that exposure of 3–5 h daily for 2–4 weeks to severe short-term IHR might increase performance, haemoglobin concentration, haematocrit and reticulocytes (Hellemans, 1999; Rodríguez *et al.*, 1999, 2003; Casas *et al.*, 2000). These results need to be confirmed because of the lack of control groups, because total red cell volume/haemoglobin mass has not been measured and because training in hypoxia has been included in some studies. Similarly, 5 days after a double-blind controlled study of 4 weeks of a IHR-breathing programme (5 sessions per week, 9–11% O_2), the experimental group ($n = 14$) of sports students showed a reduced heart rate, minute ventilation and double product (heart rate $\times$ systolic blood pressure) at a constant 150 W cycling workload in comparison with the placebo group ($n = 14$) (Burtscher *et al.*, 1999). In contrast, in an Australian study (Clark *et al.*, 1999), eight elite rowers were pair-matched for $\dot{V}O_{2max}$ and performance. The treatment group inhaled 12.2% O_2 and the control group 20.9% O_2 in a 5 min treatment / 5 min recovery ratio for a total of 90 min per day for 14 days. During intermittent hypoxia at rest, there was a decrease in arterial haemoglobin oxygen saturation using pulse oximetry ($P < 0.05$) and an increase in heart rate ($P = 0.06$) in the experimental group compared with the control group. However, there was no change in resting values for total red cell volume, haemoglobin concentration, haematocrit and reticulocytes between pre- and post-experimental values for either group. During the rowing ergometer test, there were no differences in heart rate, submaximal $\dot{V}O_2$, $\dot{V}O_{2max}$, exercise capacity, lactate concentration and respiratory exchange ratio.

The above results suggest that short-term intermittent hypoxia at rest does not result in a haematological acclimatization effect and it is doubtful that it can enhance the training stimuli for improving sea-level performance without exercising in hypoxia. However, it may improve adaptation to subsequent exposure and training at altitude.

Carryover effects from 'living high' to subsequent 'training low'

Some effects of living high continue to influence the subsequent training in normoxia – decreased plasma

volume, increased haemoglobin concentration and increased total red cell volume/haemoglobin mass (Levine and Stray-Gundersen, 1997); increased sympathetic and parasympathetic activation (Boushel *et al*., 2001); and increased hypoxic ventilatory response and ventilatory response to exercise during and after HiLo (Mattila and Rusko, 1996; Ward *et al*., 1999, pp. 69–97; Townsend *et al*., 2002). An enhancement of the hypoxic ventilatory response is potentially a positive adaptation for sea-level training because an increase in ventilation raises alveolar oxygen pressure and improves arterial oxygenation. Consequently, arterial haemoglobin oxygen saturation using pulse oximetry and arterial oxygen content are increased in normoxia during HiLo and after HiHi and HiLo, and arterial haemoglobin oxygen saturation using pulse oximetry during exercise in normoxia may increase over the pre-sea-level values (H.K. Rusko, unpublished). Increased 2,3DPG induced by living in hypoxia could also increase oxygen extraction during subsequent training in normoxia (Mairbäurl, 1994). Thus, the potential for an increased training intensity during subsequent training in normoxia is increased during and after HiLo. Indeed, a decreased blood lactate concentration during submaximal exercise has been observed on return to sea level one day after an altitude training camp compared with pre-altitude training, and the decrease in blood lactate concentration was greater the greater the increase in haemoglobin concentration and hematocrit (Ingjer and Myhre, 1992).

Conclusions

The benefits of living and training at altitude (HiHi) for an improved altitude performance of athletes are clear but controlled studies for an improved sea-level performance are controversial. The reasons for the absence of a positive effect from HiHi are as follows: (1) the acclimatization effect may have been insufficient for elite athletes to stimulate an increase in total red cell volume/haemoglobin mass, due to insufficient altitude ($<$2000–2200 m) and/or an inadequate period of time spent at altitude ($<$3–4 weeks); (2) the training effect at altitude may have been compromised due to insufficient training stimuli for enhancing the function of the neuromuscular and cardiovascular systems; and (3) enhanced stress with possible overtraining symptoms and an increased frequency of infections. When comparing HiHi and HiLo, it is clear that both induce a positive acclimatization effect and increase the oxygen transport capacity of blood, at least in 'responders', if certain prerequisites are met. The minimum time to attain an acclimatization effect appears to be $>$12 h a day for at least 3 weeks at an altitude or simulated altitude of 2100–2500 m. The exposure to hypoxia seems to have some positive transfer effects on subsequent training in normoxia during and after HiLo. The increased oxygen transport capacity of blood allows training at higher intensities after HiHi and during and after HiLo in subsequent normoxia, thereby increasing the training stimuli and improving some neuromuscular and cardiovascular determinants of endurance performance. The effects of hypoxia in the brain may influence both training intensity and physiological responses during training in hypoxia. Moreover, interrupting hypoxic exposure by training in normoxia may be a key factor in avoiding or minimizing those noxious effects that are known to occur in chronic hypoxia. The effects of hypoxic training and short-term severe hypoxia at rest are not yet clear and require further study.

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Commentary

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The use of 'altitude' in its various forms has become popular among endurance athletes around the globe; however, to date the scientific literature has not provided *overwhelming* evidence to justify it. There are certainly difficulties in performing the necessary research with genuinely elite athletes in large enough cohorts to provide statistically significant results. Furthermore, the control required to provide meaningful research data does not always fit into the training programme of an elite endurance athlete, who rarely trains in a large group, injury free, with a control group in parallel. That said, it must not be forgotten that an athlete performing at his or her peak may only be able to improve some aspects of performance by a tiny amount, making statistical differences purely academic. It is the sum of this improvement and other tiny improvements that may tip the balance between failure and success.

Several recent reviews have provided information in this area (Hahn and Gore, 2001; Wilbur, 2001); however, uniquely the present review includes areas which are not typically mentioned, such as the effect of cerebral desaturation on the central nervous system, and the rapidly advancing areas of genetics and oxidative stress mediated by free radicals.

Few would argue against the importance of acclimatization to altitude for competition at altitude. We have successfully used daily exercise training in a normobaric hypoxic environment as a method of pre-acclimation for winter biathlon competition at a moderate altitude. Undoubtedly, the altered environment at altitude has a significant impact upon performance, where some athletes have superior abilities to cope than others, particularly if they are better acclimated. Both physiological and psychological advantages will impact on performance in these circumstances.

The impact of the acclimatization process upon sea-level performance is somewhat more difficult to define. In the training environment, there are a number of companies willing to sell hypoxic devices to athletes and coaches, based upon endorsements rather than solid research information. As this review demonstrates, there is evidence that altitude training may yield a small but significant physiological and performance gain at sea level, but only if some key points are followed. First, the athlete must spend long enough each day at a high enough altitude. Secondly, the athlete should be carefully monitored to try to avoid over-reaching, dehydration or upper respiratory tract infection, taking into account that hypoxia may impact upon sleep quality and therefore exercise recovery. Thirdly, the athlete must have healthy iron stores.

There is clearly not yet enough scientific evidence that will allow sports scientists to follow a formula to get the best out of altitude training for any one athlete; however, there are some suggestions on how to get an advantage before the logical process of trial and error begins. This review presents an up-to-date resource for the sports scientist to use in a support role to the coach and athlete.

References

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