An Investigation Study on Physiological and Performance Effects of Altitude Training in Elite Athletes

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ABSTRACT
Despite widespread popularity of altitude training with athletes and coaches, and extensive research over the last 50 years, the transfer of improvements in physiological capacities to competitive performance remains uncertain. This research quantified the magnitude of performance gains required to improve placing in international competition, and the performance enhancements and physiological adaptations that can be obtained from altitude training and exposure in elite swimmers and runners. Performance was quantified by a novel analysis of the relationships between lap time and performance, which combined between-athlete correlations and within-athlete effects. Overall, the final lap for 100-m events and the middle two laps for 200-m and 400-m events had the strongest relationship (r~0.7-0.9) with final time. A change in these laps was associated with ~0.4-0.8% improvement in final time for finalists, and ~0.5-1.1% for semifinalists, depending on sex, stroke and event. However, a similar pattern of lap times was adopted in each event regardless of the sex, finish position, or the best and worst swims for an individual. To gain a competitive advantage, many athletes employ some form of altitude training in an attempt to elicit small enhancements in performance.

KEYWORDS: *Physiological, Performance Effects, Altitude Training, Elite Athletes*

1- INTRODUCTION

For elite athletes, continually improving fitness and performance capabilities within and between national and international competitions is a major challenge. To reach the upper limits of athletic ability, long hours of training are required to maximize aerobic and anaerobic fitness capacities and improve specific strength and power attributes. In endurance based sports where performance is largely determined by the rate of oxygen transport and oxygen utilization, training-induced increases in maximal aerobic power (V&O2max) and endurance performance often plateau in elite athletes. With only small margins separating competitors in many individual sports, athletes and coaches are continually searching for new and innovative ways of improving performance to gain a competitive edge [1].

Evaluation of athletic performance in individual sports is primarily based on analysis of race times. The smallest enhancement in performance that makes a difference to medal winning prospects is determined by variation in an athlete's performance between events (within athlete variation) and variation in performance between athletes in the same event (between athlete variation). A key question is the magnitude of the smallest worthwhile enhancement within and between competitions – estimation of this reference value is a growing area of interest for sport scientists. For closely matched opponents, the smallest worthwhile change in performance that will affect the athlete's chance of a medal is approximately half the within athlete coefficient of variation [2].

In addition to race-to-race variation, pacing strategies are considered an important element for success in many sports [3]. The appropriate pacing strategy is largely determined by the duration and the physiological requirements of the event [3]. Short duration (~60 s) events are typically characterised by a fast start, middle-distance events (2-4 min) are generally more evenly paced, and longer duration events are typified by a slower start with an increase in pace towards the finish. Although the pacing strategy will vary depending on the duration of the event, differences in pacing strategy in competition between top-ranked and lower-ranked competitors are not well characterized. Few studies have addressed differences in pacing strategy between competitors in international competition.

Velocity profiles were similar for finalists in international track cycling and speed skating competition [4], and pacing profile (pattern of 500-m split times) did not differ between winners and losers in international rowing competition [5].

However, variability in lap times and the relationship between change in lap time and overall performance in competition has not been quantified. Modelling of lap times in competition is needed to determine the magnitude of change in lap time that will substantially improve competition performance. These estimates will provide valuable information to the coach and athlete on how to pace a competitive event. Furthermore, establishing the magnitude of change needed in lap times to improve training and competition performance is important to evaluate the effectiveness of various training interventions undertaken by elite athletes.

There has been considerable interest in the physiological responses and performance benefits of altitude training over the last five decades. Traditional altitude training, where an athlete lives and trains at moderate altitude for several weeks (live high/train high, LHTH), can elicit beneficial physiological adaptations during acclimatization that underpin enhanced athletic performance. These physiological adaptations will improve competitive performance at altitude and LHTH has been reported to result in world-class performances in elite endurance athletes on return to sea-level [6].

Athletes choosing to undertake traditional LHTH should live and train at altitudes U 2,000 m for 3 to 4 weeks. However, a lack of transfer to improved performance upon return to sea level in the majority of controlled studies has led to several novel approaches to avoid the potentially detrimental effects of chronic hypoxia. Many athletes undertake several weeks of altitude or hypoxic exposure via either live high/train low (LHTL) for some or most of the day or live low/train high (LLTH) for a few hours during the day [7].

The LHTL model, which facilitates acclimatisation to moderate hypoxia but allows training velocities to be maintained near sea-level values has been extensively evaluated in both research settings and contemporary practice. It appears that maintenance of high training velocities is a key factor in facilitating the transfer of enhanced physiological capacities to improved performance at sea level in endurance athletes. In countries where the geography does not readily permit natural LHTL, facilities to simulate altitude have been developed to allow athletes access to this training methodology. The use of nitrogen houses, and other methods of providing normobaric hypoxia such as altitude tents and hypoxic breathing devices, has become increasingly popular. These new methods for simulating altitude have generated interest in the alternate strategy of LLTH, as a potentially time efficient means of stimulating physiological adaptations that underpin enhanced performance. In LLTH, moderate to severe hypoxia is provided for short durations (~1-3 h·d-1) at rest or during exercise. The rationale for training in hypoxia is to increase the metabolic stress on skeletal muscle beyond that achieved in normoxia. Both LHTL and LLTH are popular training approaches for many athletes, however, the optimal protocols to enhance athletic performance are unclear.

One factor which contributes to the equivocal findings in the literature is the between-athlete variability in physiological and performance responses to hypoxia. A retrospective study attributed individual performance enhancements following LHTL to an EPO-mediated increase in red cell mass. However, the relationship between individual change in EPO and change in Hbmass has not been supported in controlled studies at natural or simulated altitude. It is unlikely that individual variability in response to hypoxia can be explained by up-regulation of EPO alone. Given both haematological and non-haematological parameters play a role in performance enhancements following altitude training, an alternative mechanism acting at the molecular level is likely. One such candidate is hypoxia inducible factor-1 (HIF-1), a global regulator of oxygen homeostasis that plays a critical role in cardiovascular and respiratory responses to hypoxia. As such, improvements in performance which have previously been associated with an elevated EPO response may have been mediated by a combination of erythropoietic and non-erythropoietic responses to hypoxia. The underlying mechanism of individual variation has not been elucidated and it is unclear if an individual athlete will respond in the same way to repeated bouts of altitude training. Similarly, it has not been established if there is a dose-response relationship to hypoxia that elicits greater enhancements with longer exposures in the same athlete. Establishing the dose-response and reproducibility of responses to hypoxic exposure are important for many athletes that undertake multiple altitude exposures within and between training years, to evaluate the efficacy of this approach.

Despite many years of research on the performance benefits from either natural or simulated altitude training, there is still no consensus on the optimal duration and length of exposure. Current recommendations suggest a minimum of 3 weeks of altitude exposure for 12 h·d-1 to elicit substantial physiological adaptations and performance gains. A shortcoming in the existing literature is that previous investigations have focused on single altitude exposures, yet many athletes typically undertake multiple short duration (<2 weeks) exposures within and between training years. Further research is required to verify the effectiveness, or otherwise, of repeated bouts of simulated and real altitude exposure commonly undertaken by elite athletes to prepare for competition. Contemporary altitude training programs need to be evaluated in combination with controlled studies, in order that improvements or modifications can be identified and implemented in a timely and efficient manner. An observational study of contemporary models of altitude training by elite athletes is required to complement research studies with fully controlled experimental designs.

With so many variables that can be manipulated in LHTL or LLTH methodologies (such as altitude level, daily duration and length of intervention, training stimulus, timing of sea-level performance test) it is difficult to develop definitive guidelines for coaches. The majority of previous research has evaluated 2-4 week LHTL exposures. It is unclear if a dose-response relationship exists and if longer LHTL exposure can elicit greater enhancements in physiology and performance in the same athlete. Moreover, there is an apparent lack of reproducibility in the literature, with many investigators unable to repeat the results using the same experimental protocol. Evidence of individual variation and anecdotal reports following multiple bouts of altitude training indicate that reproducibility of responses is a key consideration for athletes. No previous study has addressed the issue of test-retest reliability of responses to simulated LHTL, or the dose-response relationship of length of hypoxic exposure on physiological and performance effects in the same athletes. Given the equivocal findings of many of the studies of either LLTH or LHTL alone, it is possible that a combined approach may be more effective for enhanced performance. Finally, to address the ongoing debate in the literature, haematological and non-haematological parameters need to be measured in parallel to clarify whether changes in performance following altitude training can be explained independently of increased red blood cells. A greater understanding of the physiological mechanisms and the time-course of their response to hypoxia is fundamental to establishing the most effective model of altitude training to gain small improvements in performance.

2- REVIEW OF LITERATURE

For elite athletes in individual sports, there are often only small margins between closely matched competitors. A major challenge for highly trained athletes is to continually improve fitness and performance capabilities within and between national and international competitions. As the magnitude of the physiological response to training depends predominantly on the duration, intensity, and frequency of the exercise bouts, athletes spend many hours training to maximise fitness capacities and technique. However, when the limits of training-induced improvements are approached, lite athletes and coaches must seek new and innovative means of enhancing competition performance. One popular approach for many athletes is to live and/or train at altitude in the belief it provides an additional metabolic stimulus to enhance athletic performance.

Despite over 50 years of research into the effects of altitude training, the underlying physiological mechanisms and their subsequent transfer to performance gains on return to sea-level remain uncertain. There is a lack of consistency in the dose of hypoxia (i.e. level of altitude, duration of daily exposure, and number of days or weeks) in the literature which limits our understanding of the physiological mechanisms underpinning enhanced performance upon return to sea-level. Both haematological and non-haematological adaptations are likely contributors to enhanced performance. However, the dose-response relationship of these physiological adaptations and subsequent performance responses to altitude training are unclear. Moreover, it appears that some individuals gain a greater benefit from altitude training than others, and there is evidence of substantial within-athlete variation in response. Given these uncertainties, it is unclear whether short (2-3 week) or longer (6 week) altitude training camps can elicit enhancements in sea-level performance of a sufficient magnitude to substantially improve competition performance, and at what time-point these performance gains are optimised upon return to sea-level. These issues are of particular interest to those athletes and coaches who typically undertake multiple altitude training camps within and between training years in preparation for competition.

For the purpose of this review ‘altitude training’ refers to the use of any form of natural or simulated altitude by athletes, ‘traditional altitude training’ refers to living and training at natural altitude, ‘altitude exposure’ refers to <24 h·d-1 at natural altitude and ‘hypoxic exposure’ refers to <24 h·d-1 at simulated altitude (hypobaric chamber or normobaric hypoxia in altitude houses, tent or via breathing apparatus). Given the large volume of scientific literature that pertains to the physiological responses to altitude, where possible this review will be limited to studies at moderate natural altitude or hypoxic exposure (<3,000m). This corresponds to the practices of athletes undertaking traditional altitude training (live and train high, LHTH) or live high/train low (live high/train low, LHTL) exposure. Higher altitudes (>3,000 m) will only be considered in relation to controlled studies examining performance measures and key physiological parameters of short duration intermittent hypoxic exposure (live low/train high, LLTH).

2.1. Performance

At the elite level, athletes are often very close to their performance limits. For these athletes, success in competition relies on a complex interaction of many factors, with small differences often determining a competition outcome [8].

2.1.1. Evaluation of performance

Traditionally, maximal aerobic power (V&O2max) was considered the most important physiological measure in the assessment of potential for endurance performance. More recently, other factors such as lactate threshold and energy cost of submaximal work have been acknowledged to contribute to endurance performance. These parameters can be routinely measured in the laboratory to evaluate the efficacy of various training interventions on physiological determinants of performance. However, enhancing competition performance is the ultimate goal and therefore time trials or performance tests are arguably the most appropriate measures of progress during a season. In many individual sports, competition performance is typically assessed by considering the final time, technical components and pacing strategy. In the lead up to competition, or as an alternative in the absence of scheduled competition, time trial events or criterion efforts may be used and have a similarly high level of reliability as competition [9].

2.1.2. Effect of pacing on performance

In many individual sports, particularly in middle-distance and distance events, pacing strategies are considered an important element of performance. Appropriate pacing in an event can be the difference between winning or losing for closely matched athletes. Observations during Olympic competition indicate sprint cycling and speed skating events had a marked reduction in pace in the latter stages, while longer duration 4000-m cycling and 3000-m speed skating events demonstrated a comparatively even pace. These findings have been confirmed experimentally. In shorter duration events (<2 min), a fast start to generate high velocities with a progressive slowing has been identified as the most successful strategy. The fastest finish times in middle-distance events (2-4 min), are characterised by a fast start followed by a transition to relatively even pacing for the rest of the race (Ansley et al., 2004; de Koning et al., 1999; van Ingen Schenau et al., 1994). Longer duration events such as distance running (Foster et al., 1994; Tucker et al., 2006) and 20km cycle time trial typically have a slower start with an increase in pace towards the finish [10].

Recent competition analysis has confirmed that world records in 800-m running events (<110 s) are typified by a fast first lap and a notably slower second lap (Tucker et al., 2006). In 2000-m rowing events (6-8 min), the strategy employed by most athletes in international competition is a fast start in the first 500 m, a progressive slowing through the second and third 500 m, and a comparatively faster final 500 m.

2.2. Physiological adaptations to altitude

The 1968 Olympic Games in Mexico City (~2,300 m) provoked a great deal of interest in the use of altitude training in preparation for competition. Decreased oxygen availability at altitude, results in a reduction of maximal oxygen uptake (V& O2max) by approximately 1% for every 100 m above 1,500 m (Buskirk et al., 1967). At altitude, performance in events with a large aerobic component are impaired due to reduced oxygen availability, while shorter duration and wind-resisted events benefit from lower air density (Fulco et al., 1998). The physiological adaptations that occur during acclimatisation to enhance oxygen uptake and transport are very similar to those resulting from exercise training (Wolski et al., 1996). In fact, these enhancements in aerobic performance and oxygen-carrying capacity have been reported to be greater than aerobic training alone (Rusko et al., 2004; Sawka et al., 2000).

Given the performance gains reported in runners following LHTL but not LHTH (Levine & Stray-Gundersen, 1997), normobaric hypoxic chambers were developed to simulate LHTL (Rusko, 1996) in countries where the geography does not readily permit natural LHTL. Further modifications of this protocol have involved the use of hypobaric chambers or normobaric hypoxic tents or breathing apparatus. Using this approach, intermittent exposure to hypoxia at rest is proposed to stimulate acclimatisation to hypoxia while maximal aerobic capacity is maintained through training in normoxia. A summary of the published studies of natural and simulated LHTL with measures of performance and haematological parameters in athletes are reported in Table 1

Using simulated LHTL, mean time trial velocity was increased by ~4% in elite cyclists days (18 h·d-1) at 3,000 m (Mattila & Rusko, 1996), however there was no control group in this study. At lower simulated altitude, small performance enhancements (~0.8%) were observed in 400m runners after 10 days (16 h·d-1) at 2,200 m compared with no change in the control group (Nummela & Rusko, 2000). In a series of studies in elite athletes, there were no substantial changes in V&O2max (Gore et al., 2001; Hahn et al., 2001) nor erythropoietic markers/Hbmass (Ashenden et al., 2000; Ashenden et al., 1999a; Ashenden et al., 1999b) following 12-23 days of LHTL (8-11 h·d-1) between 2,650-3,000 m. However, performance lasting ~4 min showed a 1% improvement (Hahn et al., 2001). Although it appears that small enhancements in performance can be elicited by simulated LHTL, there is a wide variation in the magnitude of performance gains and uncertainty on the mechanisms underpinning this enhancement.

A multicentre approach was established to examine the effects of 13-18 nights of simulated LHTL (~2,500-3,500 m) in elite athletes. The studies examined physiological and performance responses to LHTL in cross-country skiers (Robach et al., 2006a), swimmers (Robach et al., 2006b) and runners (Brugniaux et al., 2006b). There was no substantial change in V&O2max of skiers after 18 nights (11 h·d-1), and a non-significant increase in swimmers after 13 nights (16 h·d-1). Runners improved V&O2max by 9.6% after 18 nights (14 h·d-1) which remained elevated two weeks later (5.2%). Collectively there appears to be a small performance benefit for some elite athletes following LHTL, however the underlying mechanisms of this enhancement is unclear. It seems likely that the dose of altitude exposure (daily exposure and length of exposure) influences the time course and magnitude of adaptations and physiological mechanisms responsible for enhanced performance on return to sea-level (Wilber et al., 2007).

Table 1. Summary of findings following hypoxic (simulated LHTL) or altitude (natural LHTL) exposure in athletes

Summary of findings following hypoxic (simulated LHTL) or altitude (natural LHTL) exposure in athletes

Type of athletes	n (alt/ con)	Baseline $\dot{V}O_{2max}$	Live High/ Train Low (m)	Live/Train Low (m)	Days; hours per day	Physiological and Performance Outcomes	Haematological parameters	Reference
SIMULATED LHTL								
Cyclists	5	-	3,000/SL	-	11d; 18h·d^{-1}	[1] ↑TT velocity (4%)	↑EPO, ret	(Mattila & Rusko, 1996) [ab]
Endurance	12/10	66/65	2,500/SL	SL	25d; 16h·d^{-1}	[1] ↑ $\dot{V}O_{2max}$ (3%)	↑tHb (4%); ↑EPO	(Rusko *et al*., 1999) [ab]
Sprinters	8/10	-	2,200/SL	SL	10d; 16h·d^{-1}	[1] ↑400m run (0.8%)	↔[Hb]	(Nummela & Rusko, 2000)
Skiers	6/5	62/59**	<3,500/1,200	1,200	18d; 11h·d^{-1}	[2] ↔ $\dot{V}O_{2max}$ (-2%); ↔T_{exh}	↔RCV; ↑EPO, sTfR;	(Robach *et al*., 2006a)
Swimmers	9/9	58/58**	<3,000/1,200	1,200	13d; 16h·d^{-1}	[0] ↔ $\dot{V}O_{2max}$ (+5%); ↔TT_{3k} swim (+3%)	↑RCV (8%); ↔EPO, sTfR	(Robach *et al*., 2006b)
Runners	5/6	63/63**	<3,000/1,200	1,200	18d; 14h·d^{-1}	[2] ↑ $\dot{V}O_{2max}$ (+6%); ↓HR in TT_{10min}	↔RCV, EPO; ↑sTfR	(Brugniaux *et al*., 2006b)
Endurance	11	-	<3,500/SL	cross-over	25d; 10h·d^{-1}	[1] ↑$TT_{800-3000m}$ (1-1.9%)	↓[Hb], Hct	(Hinckson & Hopkins, 2005)
Runners	10/6	~60	3,000/SL	SL	29d; 11h·d^{-1}	[1] ↓ $\dot{V}O_2$ (3%); ↔$\dot{V}O_{2max}$ or T_{exh} (+9%)	↔tHb	(Neya *et al*., 2007)
Runners	9/9	71/71*	2,860/600	600	46±8d; 9h·d^{-1}	[1] ↓ $\dot{V}O_2$ (3%); trivial ↑ $\dot{V}O_{2max}$ (1.5%)	↑tHb (5%)	(Saunders *et al*., 2009)
Combined	***20/23***	***~4.5****	***2,650-3,000***	***600***	***11-23d***	***[0] ↓ $\dot{V}O_{2max}$ (2.4%); ↑0.9% TT effort***	***↔ tHb, ret; ↑EPO***	***(Hahn et al., 2001)***
Cyclists	*5/6*	*3.9/3.7**	*2,650/610*	*600*	*12d; 8-11h·d^{-1}*	*[0] ↔ $\dot{V}O_{2max}$; ↔TT_{4min} (+2%)*	*↔ tHb; ↔ret*	*(Ashenden et al., 1999b)*
Kayakers	*4/5*	*4.1/4.2**	*2,650/610*	*600*	*11d; 8-11h·d^{-1}*	*[0] ↔ $\dot{V}O_{2max}$; ↔TT_{4min} (+2%)*	-	
Runners	*5/5*	*4.7/4.9**	*2,650/610*	*600*	*15d; 8-11h·d^{-1}*	*[0] ↔ $\dot{V}O_{2max}$ (-3%); ↔1500m run*	*↑EPO; ↔ret*	*(Ashenden et al., 2000)*
Endurance	*6/7*	*5.1/5.0**	*3,000/610*	*600*	*23d; 8-11h·d^{-1}*	*[0] ↓ $\dot{V}O_{2max}$ (-4%); ↔TT_{4min}*	*↔ tHb; ↔ret*	*(Ashenden et al., 1999a; Gore et al., 2001)*
NATURAL LHTL								
Runners	13/13	64/62	2,500/1,250	150	28d; ~20h·d^{-1}	[0] ↑ $\dot{V}O_{2max}$ (5%); ↑TT_{5K} (1.4%)	↑RCV (9%); ↑EPO	(Levine & Stray-Gundersen, 1997)
Endurance	10/7	57/70	2,500/<1,800	500-1,600	24d; ~18h·d^{-1}	[1] ↑ $\dot{V}O_{2max}$ (4%); ↑TT_{3K} (1.6%)	↑tHb (5%); ↑EPO, ret	(Wehrlin *et al*., 2006)
Runners	21	72	2,500/1,250	-	27d; ~20h·d^{-1}	[0] ↑ $\dot{V}O_{2max}$ (3%); ↑TT_{3K} (1.1%)	↑EPO, sTfR	(Stray-Gundersen *et al*., 2001)
Triathletes	11/10	62/60	1,956/800	SL	14d; ~15h·d^{-1}	[1] ↔ $\dot{V}O_{2max}$ (+12%); ↔PPO	↔tHb (con ↓5%); ↑EPO	(Dehnert *et al*., 2002)

n=number of participants in altitude (**alt**) and control (**con**) groups; **Baseline $\dot{V}O_{2max}$** (maximal aerobic power) in ml·kg^{-1}·min^{-1} or L·min^{-1}; * $\dot{V}O_{2max}$ measured at 600m; ** $\dot{V}O_{2max}$ measured at 1200m; **$\dot{V}O_2$**=submaximal oxygen uptake; **PPO**=peak aerobic power output; **TT**=time trial performance; **T_{exh}**=time to exhaustion; **HR**=heart rate; **EPO**=erythropoietin; **tHb**=haemoglobin mass; **RCV**=red cell volume; **sTfR**=soluble transferrin receptor; **Fer**=ferritin; **ret**=reticulocytes; **[Hb]**=haemoglobin concentration; **Hct**=haematocrit;

Post-test: [0] within ~1-3 days; [1] within one week; [2] after two weeks. ↑ increased/faster; ↓ decreased/slower; ↔ unchanged compared with control group;

All changes marked ↑ or ↓ were statistically significant. Where differences in change scores were non-significant compared with the control condition, percent differences have been calculated from the raw data and differences in performance greater than 1% presented.

2.3. Summary

The findings of this review emphasize that small differences in performance can determine a competition outcome in closely matched competitors. By modelling competition performance, reference values can be established to determine the magnitude of improvements required in lap or split times to substantially increase the likelihood of success. Pacing strategies are an important determinant of performance. Quantifying lap or split times in relation to final time may yield further insight for coaches on where the most improvement to competition performance can be made.

Altitude training is a popular approach for many athletes seeking small enhancements in performance. Both natural and simulated LHTL have been evaluated extensively in both research settings and contemporary practice. Studies of LHTL from four independent laboratories indicate ~1% performance enhancement in events lasting between ~45s to 14 min, which will substantially increase the likelihood of success in competition. However, the dose-response to hypoxia seems to be a key issue, and differences in the methodologies employed in the literature may be a limiting factor in establishing the most effective protocol.

Using the results of the meta-analysis, it appears traditional LHTH is the most successful strategy to improve performance for elite and subelite athletes. A greater benefit from simulated LHTL may be gained by increasing the altitude level (>3,000 m) and daily hypoxic exposure (14 h·d-1), over a shorter duration (~2 weeks instead of ~3 weeks). The LLTH protocols may be enhanced by training at low to moderate intensity at lower altitudes (~2,400 m), for more days of exposure (~18 days) with a later post-altitude test day.

One major shortcoming of the literature is that the programs of altitude training currently used by elite athletes in preparation for competition often differ from those investigated in research settings. Previous research studies have examined only single altitude exposures, yet athletes typically undertake multiple bouts of altitude training during their preparation for competition. Further research is needed to verify the effectiveness, or otherwise, of repeated bouts of altitude training commonly used by elite athletes. In addition, many athletes undertake a combination of real and simulated altitude in preparation for competition, but the efficacy of this approach has not been established. To complement research studies with fully controlled experimental designs, an observational study of contemporary models of altitude training by elite athletes is required.

Another key issue is that of individual variation in response to altitude, which has previously been considered under the responder or non-responder paradigm based on erythropoietic response. A systematic approach is required to quantify the dose-response relationship of altitude or hypoxic exposure on physiological and performance responses, and ascertain the reproducibility of these responses. Given the equivocal nature of the literature on haematological and non-haematological mechanisms underlying enhanced performance, these parameters should be measured in parallel. Although there is growing interest in brief periods of LLTH (IHE or IHT) as a means of stimulating physiological adaptations to hypoxia, the experimental findings are inconclusive. IHT has emerged as a potentially time-efficient alternative to LHTL for athletes and theoretically could be a useful complement to LHTL.

Whether a combined approach is more effective to elicit substantial improvements in performance is unknown. In any altitude training intervention, the critical outcome for elite athletes is an enhanced performance capability. Unfortunately, despite the abundance of studies, there is a lack of a consistent performance measure (and parallel physiological parameters) which makes the existing experimental results somewhat difficult to interpret. Moreover, there is an apparent lack of reproducibility in the literature, with many investigators unable to repeat the results using the same experimental protocol. With so many variables that can be manipulated in LHTL or LLTH methodologies (such as altitude level, daily duration and length of intervention, training stimulus, timing of sea-level performance measure), combined with substantial individual variability in response, it is difficult to develop definitive guidelines for coaches. Subject numbers are often low in studies of elite athletes, so conventional statistical approaches (involving hypothesis testing and statistical significance) may not be able to detect small changes in performance that are important for athletes. A more appropriate statistical approach to establish the practical significance of altitude training interventions and quantify the variability in response to the intervention is magnitude-based inferences. Use of this analytical approach will permit rigorous but practical interpretation of the effects of altitude training on athletic performance.

Establishing the reproducibility and dose-response of physiological adaptations to short (2-3 week) and longer (6 week) hypoxic exposures in individual athletes is of particular interest to athletes and coaches who undertake multiple altitude training camps within and between training years. Furthermore, quantifying the transfer of physiological adaptations to enhancements in performance at sea-level should assist coaches and sport scientists in evaluating the practical impact (and cost-benefit analysis) of altitude training interventions on performance.

3. RESULTS

For the eight athletes who completed the additional 3-wk block, change in time trial performance was trivial after both Block 2 (LHTL: 0.9%; ±2.5%, control: -0.6%; ±1.3%) and Block 2+3 (LHTL: -0.3%; ±1.1%, control: -0.3%; ±1.1%). V&O2max was substantially higher in the LHTL group after Block 2+3 (4.3%; ±6.2%), but was not different after Block 2 or for the control group in either block. There were trivial changes in Hbmass after Block 2 (LHTL: 2.2%; ±3.6%, control: -0.7%; ±3.1%) and Block 2+3 (LHTL: 4.0%; ±6.1%, control: -1.4%; ±5.3%). Compared with the control group, the LHTL group had substantially higher V&O2max (7.6%; ±6.9%) and Hbmass (5.4%; ±6.8%) after Block 2+3, but there was no substantial difference between the groups in 4.5 km time trial performance (0.0%; ±1.4%).

The LHTL group had substantially higher submaximal V& O2 and lower post-test lactate after 3 weeks, but substantially improved V&O2max and velocity at V&O2max (vV&O2max) after 6 weeks. The control group had only trivial changes in parameters measured during the treadmill test after 3 weeks, and a substantial reduction in V&O2max after 6 weeks. Compared with the Control group, the LHTL group had substantially poorer economy and lower posttest lactate after 3 weeks, but were substantially faster at vV&O2max and had a higherV&O2max after 6 weeks. There were no substantial differences in the change (pre-post) in blood bicarbonate (HCO3-) or pH for either group after either 3 weeks or 6 weeks.

4. DISCUSSION

We are not aware of any studies that have examined the dose-response relationship of hypoxic exposure to performance, Hbmass andV&O2max . Despite greater enhancements in Hbmass and VO2max & after ~600 h LHTL exposure, time trial performance was not substantially improved compared to ~300 h of LHTL. The small number of athletes completing Block 3 precludes any definitive conclusion on the efficacy of extended LHTL exposure on performance.

5. SUMMARY

Altitude training can elicit substantial improvements in physiological capacities in well trained athletes, but the transfer to enhanced performance at sea-level is more variable. There is a dose-response relationship of hypoxia-induced changes in physiological parameters, but this does not correspond directly with the magnitude of change (improvements) in performance. A coach-prescribed altitude program of multiple 2-wk natural altitude and simulated LHTL exposures was insufficient to induce substantial physiological adaptations or improve competition performance. Two 3-wk simulated LHTL exposure elicited reproducible small mean increases in Hbmass and V&O2max , however, time trial performance was more variable (~1% faster and ~1% slower after each exposure respectively). Greater enhancements in Hbmass and V&O2max were elicited following 6-wk LHTL and 3-wk combined LH/TL+TH compared with 3-wk LHTL alone. However, these greater physiological enhancements did not transfer directly to greater improvements in time trial performance. There is an apparent uncoupling between the magnitude of improvements in physiological capacities elicited by hypoxic exposure and changes in performance at sea-level immediately or 2 weeks later.

Individual responses, of similar magnitude to the mean, indicate that some athletes may respond more favourably to altitude training than others. However, individual variation in response to repeated 3-wk LHTL exposures, demonstrates that a performance enhancement following one bout of LHTL does not necessarily guarantee the same response in subsequent bouts.

A key issue is the magnitude of improvement required by altitude training (or other training interventions) to substantially enhance performance at the elite level. Prior to conducting the observational study of altitude training in elite swimmers, the magnitude of improvement needed to substantially enhance competition performance had to be established. This became the first step in evaluating the transfer of altitude training-induced physiological adaptations to improved competition performance. The magnitude of change in lap time needed to enhance performance and improve final placing was modelled in international swimming competitions over 7 years. An achievable change in lap time for an individual swimmer was associated with similar improvements in performance for finalists (~0.4-0.8%) and semifinalists (~0.5-1.1%) depending on sex, stroke and event. This magnitude of change will substantially increase the likelihood of a medal in top-ranked swimmers (Pyne et al., 2004; Trewin et al., 2004). The novel finding of this study was that the final lap in 100-m events, and the middle two laps of 200-m and 400-m events, had the strongest relationship with final time and needed a smaller change to improve final placing in a race. For example, to move to 1st place from 2nd place in male 200-m freestyle events, an individual swimmer would need ~0.3s improvement in the second 50-m lap or ~0.6s in the final 50-m lap. However, examination of the pattern of lap times revealed a similar pattern for the top 16 swimmers and the best and worst swims for finalists. This finding is in agreement with previous research showing a similar pattern of pacing between winners and losers in 2000-m rowing events (Garland, 2005). The absence of differences in pacing between competitors implies that coaches should first look to address improvements in fitness or technique in the laps which should result in the greatest performance gain. The overall pattern of lap times, however, should not be disrupted. Taken together, these findings confirm that training interventions aimed at enhancing training and competition performance need to elicit improvements greater than ~0.4-1.1%. This magnitude of change in race performance is similar to the smallest important improvement (~0.5-1.5%) in well-trained runners, permitting comparisons of the efficacy of altitude training in swimmers and runners.

The subsequent three studies quantified the physiological and performance responses o different altitude training protocols, to determine the most effective approach to obtain small worthwhile enhancements in competition or time-trial performance in athletes. The main findings for a typical altitude-based preparation (contemporary), two matched 3-wk LHTL exposures (reproducibility), 6-wk LHTL exposure (dose-response), and 3-wk LHTL exposure plus intermittent training in hypoxia (combined) are summarised in Table 2. Our analytical approach of magnitude-based inferences permitted rigorous but practical interpretation of the effects of altitude training across each of the studies.

Table 2. Summary of the performance changes and physiological responses
to multiple 2-wk real and simulated altitude exposure

Summary of the performance changes and physiological responses to multiple 2-wk real and simulated altitude exposure (contemporary), repeated 3-wk LHTL (reproducibility), extended 6-wk LHTL (dose-response) and 3-wk LHTL plus training in hypoxia (combined)

		Contemporary altitude training in swimmers [1]		Reproducibility of responses to LHTL [2]		Dose-response of LHTL for 3-wk vs 6-wk [2a]		Combined LHTL plus TH [3]	
Experimental Group		4 x 2-wk LHTL (10 h·d^{-1}, 2600m) and LMTM (1350m)		2 x 3-wk LHTL (14 h·d^{-1}, 3000m)		6-wk LHTL (14 h·d^{-1}, 3000m)		3-wk LHTL (14 h·d^{-1}, 3000m) + TH (train 4 wk^{-1}, ~2200m)	
Control Group		living/training at ~600m [a]		2 x 3-wk living/training at ~600m		6-wk living/training at ~600m		3-wk TH (train 4 wk^{-1}, ~2200m)	
		Δ combined	**Δ single** [b]	**Δ Block 1**	**Δ Block 2**	**Δ 3-wk**	**Δ 6-wk**	**Δ Post1**	**Δ Post2**
Performance	**Expt**	NC -0.4% (0.9),	CG 0.6% (0.6)	-1.4% (1.1) *	0.7% (2.0)	0.9% (2.5)	-0.3% (1.1)	-1.1% (1.0)	-0.4% (1.1)
	Ctl	NC -0.9% (0.5)*,	CG 1.2% (0.9)*	0.5% (1.5)	-0.7% (1.1)	-0.6% (1.3)	-0.3% (1.1)	-0.1% (1.0)	-0.6% (1.1)
	Diff	NC 0.5% (1.0),	CG 0.6% (0.9)	-1.9% (1.8)	1.4% (1.5)	1.5% (2.5)	0.0% (1.4)	-0.9% (1.4)	0.2% (1.5)
4mM speed	**Expt**	1.7% (1.9) *	0.9% (0.8)	6.5% (2.0) *	1.6% (2.5)	0.4% (2.4)	1.2% (1.4)	2.8% (2.5)	-
	Ctl	-	-	1.1% (1.3)	-0.3% (1.8)	-0.6% (1.6)	-0.9% (3.9)	0.4% (1.5)	-
	Diff	n.a	n.a	5.3% (2.2)	1.9% (2.9)	1.0% (2.5)	2.2% (4.0)	2.4% (2.8)	n.a
VO_{2max} or T_{2K}	**Expt**	2.4% (2.0) *	1.2% (1.6)	2.1% (2.1) *	2.1% (3.9)	3.0% (14.7)	4.3% (6.2) *	4.8% (2.8) *	-
	Ctl	-	-	0.9% (2.8)	0.7% (3.1)	-1.3% (7.1)	-3.1% (5.6)	2.2% (1.8)	-
	Diff	n.a	n.a	1.2% (3.3)	1.4% (4.6)	4.5% (15.4)	7.6% (6.9)	2.6% (3.2)	n.a
Hb_{mass}	**Expt**	-	0.9% (0.8)	2.8% (2.1)	2.7% (1.8)	2.2% (3.6)	4.0% (6.1)	3.6% (2.4) *	-
	Ctl	-	-	1.4% (2.7)	-1.5% (1.5)	-0.7% (3.1)	-1.4% (5.3)	-0.7% (3.8)	-
	Diff	n.a	n.a	1.3% (3.2)	4.2% (2.1)	2.9% (4.0)	5.4% (6.8)	4.3% (3.2)	n.a

Following contemporary altitude training in elite swimmers, performance at National Championships and Commonwealth Games was not substantially improved compared with a matched group who received no altitude exposure (Table 7.1). There were small enhancements in 4mM speed and 2000m timed swim after two consecutive 2-wk blocks.

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