Chapter 7

Real and Simulated Altitude Training and Performance

Michael J. Hamlin, Nick Draper and John Hellemans

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/53724

1. Introduction

The use of altitude training to compliment normal training at sea level is widely used by coaches and athletes. There are a number of different altitude training models which range from living and training at moderate and high altitude to breathing hypoxic gas while living and training normally at sea level. In this chapter we will briefly overview the history of altitude training and touch on the science and practice of the various models of altitude training. We also discuss the beneficial effects reported in the scientific literature and give first-hand accounts of the effectiveness of the various methods from high performance coaches. Benefits and drawbacks from each altitude method will be discussed along with advice on preparing athletes prior to altitude training.

Approximately 80% of the world's population lives at low altitude (< 500 m) [1] which has an optimal atmospheric pressure and oxygen concentration for the human body's functioning. However as we ascend in altitude, the air volume expands due to the lowering of atmospheric pressure, which results in the reduction of oxygen availability to the muscles. This drop in oxygen concentration results in decreased oxygen pressure in the inspired air (P_IO_2) and a subsequent drop in the amount of oxygen in the arterial blood (P_aO_2). A reduction in the concentration of oxygen in the circulating arterial blood results in a decreased ability to extract oxygen for the working muscles and a reduced oxygen uptake. This reduced oxygen uptake is a major problem for mountaineers at high altitude and is responsible for the steady decline in maximal oxygen uptake ($\dot{V}O_2$ max) and subsequent performance at high altitude. Traditional altitude training uses these oxygen concentration changes that occur with changes in elevation to induce beneficial adaptations in the performance of athletes either at altitude or closer to sea level.

Aviation physiology research has contributed significantly to the understanding of how the human body responds and adapts to a hypoxic (low oxygen concentration) environment. In

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the 1880's an Italian physiologist, Angelo Mosso, (1846-1910) was one of the first to conduct experiments in the Italian Alps on the physiological effects of altitude on humans. Mosso's studies on respirational changes at altitude made him a leader in the field and Mosso's work was soon followed by other scientists in the late 1800's and early 1900's who were particularly interested in the medical effects of high altitude. Last century a number of famous high altitude expeditions were designed to collect data on the physiological effects of high altitude. These included the 1911 Anglo-American Pikes Peak Expedition, the 1921-1922 International High Altitude Expedition to Cerro de Pasco, Peru, the 1935 International High Altitude Expedition to Chile, and the 1960-1961 Himalayan Scientific and Mountaineering Expedition (Silver Hut) [2]. Research into the effects of high altitude on the human body became of great interest during the race to conquer Mt. Everest and research into the effects of altitude, particularly on exercise performance, became popular after the Olympic Games were awarded to Mexico City (elevation 2,300 m, 7,544 ft). It was found that during the Games, athletes that came from sea-level countries were affected by the low oxygen concentration in the air at Mexico City and struggled to gain medals. In particular, the sea-level middle and long distance runners' performance times were significantly slower at Mexico City compared with their performance times at sea-level the same year. On the other hand, the athletes from high altitude-based countries won many of the medals available in the middle and long distance track events. For example, from the 800m through to the marathon, out of a possible 18 medals up for grabs, 9 (50%) were won by athletes from Kenya and Ethiopia. Since the Mexico City Olympic Games a plethora of research has occurred in the area of altitude training. The main focus of this research has been to answer important questions around what the ideal altitude and length of stay is and what the effects of altitude are on the physiology of the human body.

It is now well established that exposure to real altitude produces a drop in $P_IO_{2,}$ P_aO_2 and subsequently arterial oxyhaemoglobin saturation (S_aO_2) resulting in a decrement in kidney oxygenation. This reduction in oxygen concentration stimulates the synthesis and release of erythropoietin (EPO), a hormone produced in the kidney, which subsequently stimulates erythropoiesis in the red bone marrow, finally resulting in red blood cell (RBC) and haemoglobin production. Over a period of time these haematological changes may significantly improve aerobic performance in endurance athletes by enhancing the delivery of oxygen to working muscles and the ability of the muscles to use oxygen to produce energy. Indeed Levine and Stray-Gundersen (2005) argued that the primary mechanism responsible for improved sea-level endurance performance following prolonged exposures to altitude is an enhanced erythropoietic response, which results in an elevated red blood cell volume and a resultant enhanced rate of oxygen transport [3]. However, in response to Levine and Stray-Gundersen (2005), Gore and Hopkins maintained that the improvements in submaximal oxygen efficiency, or even cardiovascular adaptation, rather than the haematological changes alone should be considered when assessing the mechanisms responsible for the improved sea level performance after altitude training [4].

Debate continues over the mechanisms involved in performance improvement after altitude training. While some studies have reported increases in haemoglobin mass (or red cell mass) after classical altitude training at altitudes of 1900m or above [5-8], others have reported no such change after training at such altitudes [9-13], or at slightly lower altitudes (1740-1800m) [14, 15]. Indeed, recent research has indicated that performance can actually improve as a result of altitude training in the absence of any significant increase in haemoglobin mass [16]. So what other mechanisms might explain the improvement in performance at sea level after altitude training. Gore and colleagues argue that altitude training improves exercise economy [17] through an increased ability to metabolise carbohydrate during oxidative phosphorylation, a decreased cost of ventilation, or by an increased ability of the muscle contractile machinery to produce work more efficiently [18]. Early reports from other researchers suggest an increase in muscle buffering capacity may be a possibility [19, 20]. An increase in buffering capacity of the muscle or blood would allow a greater build-up of acidity during exercise. Because a limiting factor to exercise is an increase in acidity, such a change would allow the athlete to exercise for longer before fatiguing.

More recently, research at a genetic level has started to uncover some more clues as to what may be happening during altitude training [21]. It has been shown that a transcription factor called hypoxia inducible factor-1 (HIF-1), which is present in every cell of the body, is the universal regulator of oxygen homeostasis and plays a vital role in the body's responses to hypoxia. During periods of normoxia the level of HIF-1 are very low, with the HIF-1 sub-units being quickly degraded, however, under hypoxic conditions the sub-units are not degraded as quickly and HIF-1 levels increase in the cells allowing it to transcribe specific genes. A summary of the genes HIF-1 activates gives us some idea of the plethora of ways in which altitude training may enhance performance. HIF-1 activates EPO, and transferrin involved in iron metabolism and erythropoiesis. HIF-1 also stimulates angiogenesis and glycolytic enzyme activity, cell glucose transporters, muscle lactate metabolism, carbonic anhydrase for enzymes that regulate pH and others that produce vasodilators such as nitric oxide [22, 23]. Since hypoxia causes a multitude of responses in the human body including but not limited to changes in red cell mass [5], angiogenesis, glucose transport, glycolysis, pH regulation, and changes in the efficiency of energy production at the mitochondrial level which could all potentially have a positive impact on exercise performance, potentially all of these mechanisms either solely or combined could be the cause of enhanced sea-level performance after altitude training. Further research is required to further elucidate the mechanisms involved.

Training at real altitude is expensive and time consuming and in some cases may in fact work to decrease rather than increase performance due to a number of problems occasionally encountered at altitude. These problems include weight loss (particularly lean body mass), diarrhoea, headaches, insomnia, immune suppression, appetite suppression, drowsiness, dehydration, and nausea. Perhaps one of the biggest problems athletes face when going to altitude is the drop in training velocity (pace) at training intensities comparable to those at sea level which can potentially result in detraining of the athlete. Because of the altitude-associated decrements in oxygen concentration which result in a reduction of the $\dot{V}O_2$max and P_aO_2 which ultimately reduces oxygen to the muscles it is difficult for athletes (particularly endurance athletes) to maintain their normal sea level training intensity. This drop in performance is particularly noticeable in the first few days after arriving at altitude and many coaches insist on reduced training loads during this period to reduce the risk of illness, injury or overtraining. Dr.

John Hellemans (currently the National Triathlon Coach for the Netherlands Team) gives great attention to this early period of acclimatization and suggests that endurance athletes should limit their high intensity intervals to repetitions of no more than 3 minutes, alternated with longer recovery periods than would normally occur at sea level [24]. In general, over the first week or so after arriving at altitude, athletes should somewhat decrease their training frequency and duration and reduce their training intensity considerably to avoid these problems.

2. The different models of altitude training

2.1. Conventional altitude training

2.1.1. Live high-train high model

The traditional and probably the most commonly practiced form of altitude training is the Live High-Train High (LHTH) approach, in which athletes live at altitude for a period of time and perform all their training and "living" in one location. It is suggested that the optimal altitude dose for such training is 2000-2500 m for 3-4 weeks [25]. Going to very high altitude is unproductive as the stress on the body and the resultant side effects from such high altitude usually outweigh any performance benefits. For example at high altitudes, the large drop in arterial oxyhaemoglobin saturation results in large decreases in $\dot{V}O_2$max which necessitates a decrease in training intensity which can therefore lead to detraining. Moreover, at higher altitudes athletes are more susceptible to acute mountain sickness, nausea, lethargy which may all effect training quality and quantity. Table 1. shows the various altitude classifications commonly used in the literature. Altitude above 5000 m is tolerated for relatively short periods of time and altitudes above 7500 are dangerous to health [26]. Most LHTH altitude training for athletes occurs at moderate altitude.

Death Zone	> 7500m
Extreme Altitude	5000- 7500m
High Altitude	3000- 5000m
Moderate Altitude	2000- 3000m
Low Altitude	1000- 2000m
Sea Level	< 1000m

Data adapted from Pollard and Murdoch 1998.

Table 1. Altitude classification

However, some coaches (such as John Hellemans) suggest the optimum altitude for this type of training is lower (1500-2000 m) since athletes suffer fewer side-effects at lower altitudes and are able to maintain training quality [24]. Examples of some of the world's altitude training bases are presented in Table 2.

Altitude Training Site	Country	Elevation (m/ft)
Thredbo Alpine Training Centre	Australia	1365/4478
Crans Montana	Switzerland	1500/4920
Snow Farm, Wanaka	New Zealand	1500/4920
Albuquerque, New Mexico	USA	1525/5000
Fort Collins, Colorado	USA	1525/5000
Davos	Switzerland	1560/5117
Issyk-Kull	Kirgizstan	1600/5248
Denver, Colorado	USA	1610/5280
Medeo	Kazakhstan	1691/5546
Tamga	Kirgizstan	1700/5576
Boulder, Colorado	USA	1770/5800
Ifrane	Morocco	1820/5970
St. Moritz	Switzerland	1820/5970
Nairobi	Kenya	1840/6035
Font Romeu Odeillo	France	1850/6069
Colorado Springs, Colorado	USA	1860/6100
Kunming	China	1895/6216
Pontresina	Switzerland	1900/6232
Zetersfeld/Linz	Austria	1950/6396
Piatra Arsa	Romania	1950/6396
Tzahkadzor	Armenia	1970/6462
Belmeken	Bulgaria	2000/6560
Kesenoy-Am	Russia	2000/6560
Sestriere	Italy	2035/6675
Flagstaff, Arizona	USA	2134/7000
Los Alamos, New Mexico	USA	2208/7240
Quito	Ecuador	2218/7275
Alamosa, Colorado	USA	2300/7544
Mexico City	Mexico	2300/7544
Sierra Nevada/Granada	Spain	2320/7610
Addis Ababa	Ethiopia	2400/7872
Park City, Utah	USA	2440/8000
Mammoth Lake, California	USA	2440/8000
Bogota	Colombia	2500/8200
Toluca	Mexico	2700/8856
La Paz	Bolivia	3100/10168

Adapted with permission from Wilber (2004)

Table 2. Commonly used altitude training bases throughout the world.

2.1.2. Live high-train low model

To overcome the problems associated with living and training at altitude, Benjamin Levine and James Stray-Gunderson investigated the effects of living at altitude but training much closer to sea level. In a comprehensive study they compared 3 groups of runners; one group lived low and trained low (San Diego, California, 150 m), another lived high (Deer Valley, Utah, 2500 m) and trained low (Salt Lake City, Utah, 1250 m), while the last group lived high and trained high (Deer Valley, Utah). Upon initial return to sea level runners in the Live High-Train Low group improved their 5-km time trial performance by 1.3% as a result of the altitude training, the Live High-Train High runners showed a small detrimental change (-0.3%), whereas the Live Low-Train Low runners got much worse (-2.7%) After 4 weeks back at sea level all groups improved but the Live High-Train Low and Live High-Train High groups remained significantly faster than the Live Low-Train Low group. While this ground-breaking study was the first to point towards the Live High-Train Low model as the most appropriate to enhance subsequent sea-level performance a number of problems within this study do not make the results clear cut. Firstly, the fact that the researchers used Salt lake City as the training base for the Live High-Train Low model when 1250 m is not strictly low altitude. In fact, Gore and associates found that altitudes as low as 580m can have an effect on performance [27]. Another major problem is that the control group (Live Low-Train Low) actually decreased performance during normal training at sea level which may suggest inadequate or improper training for this group compared to the other two groups. Finally, the groups were not blinded to the intervention, therefore we cannot rule out a placebo effect (positive in the case of the altitude groups, and negative in the control group). However, in theory the Live High-Train Low model has an advantage over the Live High-Train High model because high intensity training can continue at lower altitudes enabling the athlete to gain sport-specific peripheral and neuromuscular adaptations that are normally lost at high altitude.

2.1.3. High high low model

This is a slight modification on the Live High-Train Low model whereby athletes live at high altitude and perform low to moderate-intensity training at high altitude but travel down to low altitude to perform high intensity training sessions. This model was developed to overcome the difficulties of performing high intensity training in a hypoxic environment

2.2. Altitude simulation

In attempts to provide more convenient and time efficient but less expensive ways to train in low oxygen environments, a number of new technologies have been developed to simulate real altitude training. The main types of simulated altitude provide their hypoxic stimulus through pressure reduction (hypobaric chamber), nitrogen dilution (hypoxic apartments and rooms) or oxygen filtration (hypoxicator machines). These simulation devices have given rise to a number of new procedures that aim to improve athletic performance.

2.2.1. Altitude apartments

As a means of supplying a hypoxic stimulus, individual rooms, apartments or houses are sealed off and the concentration of oxygen within these rooms or apartments is lowered either via nitrogen dilution or oxygen extraction. In most cases these apartments are designed for comfortable living by the athletes for periods between 12 to 18 hours per day. Finnish sport scientist were probably the first to develop an altitude room or apartment solely for the use of athletes in the early 1990's. The hypoxic rooms (via Nitrogen dilution) were situated at the Research Institute for Olympic Sport in Jyvaskyla, Finland. Other examples of altitude apartments can be found all over the world including the Australian Institute of Sport in Canberra Australia, the Karolinska Institute in Stockholm in Sweden and the recently constructed National Altitude Training Centre at the University of Limerick, Ireland. However these apartments are expensive to build and run and are not always convenient for athletes. In addition, such apartments require close monitoring of oxygen and carbon dioxide concentrations to ensure a safe environment for all athletes.

2.2.2. Altitude tents

These are portable small altitude systems that allow the athlete to travel with the equipment and set up the altitude in their own rooms. These systems have a generator and an oxygen extraction unit which feeds hypoxic air through a series of hoses into a portable sealed tent which is normally placed over the bed. This allows athletes to sleep in the hypoxic environment. Examples of this type of equipment include the GO2Altitude® Tent from Biomedtech, Melbourne, Australia, and the Altitude Tent systems from Hypoxico, New York, USA. However a number of issues exist with this technology including the generator noise. The generator is normally required to be placed in the room with the tent and some generators can be quite noisy. The hypoxic environment inside the tent can be variable due to leaks and subject movement, and in some cases the inside of the tent can become warm and humid which can affect sleep quality. Because of the small size of the tent the build-up of carbon dioxide is even more dangerous in altitude tents and needs to be monitored carefully.

2.2.3. Intermittent Hypoxic Exposure (IHE)

Intermittent hypoxic exposure (IHE) is exposure to short periods of hypoxic air at rest (9-15% oxygen, equivalent to approximately 6600-2700 m) alternated with normoxic air (21% oxygen). This technique was originally trialled by Russian aviators in attempts to preacclimatize pilots to the high altitudes encountered during sojourns in open cockpit planes [28]. The technique was subsequently refined and used by researchers and clinicians in attempts to provide a means of treatment from medical conditions ranging from asthma to hypertension [28]. After the cessation of the cold war between the east and west and the unification of Germany many of these previously unknown techniques started to surface in the west along with their eventual use by coaches and athletes. Athletes typically use a hypobaric chamber or a hypoxicator (machines that extract oxygen from the ambient air) to generate the hypoxic air. A typical protocol for this type of training is to breathe 5 minutes of hypoxic air followed by 5 minutes of normoxic air for a period of between 60 and 120 minutes per day for 2-3 weeks. The intermittent nature of this type of training allows for the oxygen concentration to drop to much lower levels than could be tolerated safely in other altitude training models. The drop in the inspired oxygen concentration of the air being breathed results in a drop of P_aO_2 and subsequently arterial oxyhaemoglobin saturation (S_aO_2) which stimulates the body to adapt. However, it is thought by some researchers that such a short altitude stimulus is not sufficient to cause significant haematological benefits for athletes and is therefore unlikely to produce performance change [29]. Others have argued that improved performance with such training is likely to be non-haemtological (i.e. enhanced skeletal muscle performance, improved muscle and blood buffering capacity, or beneficial changes in exercise economy) [30]. Recently a number of portable IHE devices have become available. These devices (AltiPower, GO2Altitude®, Australia and AltoLab, AltoLab Nominees, Auckland) usually require carbon dioxide scrubbers and are used in conjunction with pulse-oximeters that measure the oxygen concentration in the blood (SpO_2). Typical protocols for IHE (and IHT, see below) indicate a gradual lowering of the SpO2 values over a 3 week period (Table 3).

	Week 1	**Week 2**	**Week 3**
Athletes	84-80%	82-78%	80-76%
Mountaineers	84-80%	84-80%	80-76%

Targets are SpO2 levels (indicating arterial oxygen saturation as measured by pulse oximetery).

Adapted with permission from Hellemans and Hamlin (2009)

Table 3. Target blood oxygen saturation levels during intermittent hypoxia.

2.2.4. Intermittent Hypoxic Training (IHT)

IHT consists of breathing hypoxic air intermittently with normoxic air, however unlike IHE the athlete exercises while breathing the hypoxic air. This is similar to living at sea level and conducting training sessions at altitude (LLTH). The extra stress of training under hypoxic conditions is suggested to cause increased adaptations resulting in improved performance. The effectiveness of IHT for the enhancement of sea level performance, however remain controversial. Several studies have reported an enhanced athletic performance following IHT [31, 32] although a number have failed to demonstrate any substantial alteration in post-IHT performance measures [33, 34].

3. Aerobic performance change with altitude training

Research into the effects of altitude training on subsequent sea level endurance performance is equivocal with some researchers reporting significant improvements [5, 35-38] while others report decrements in performance [39] or in some cases no substantial change [40, 41]. A recent meta-analysis on the effect of various models of altitude training was published in

2009 and gives a good indication of what performance changes might be expected from the various methods (Table 4).

	Natural altitude models		Artificial altitude models			
	LHTH	**LHTL**	**LHTL prolonged continuous**	**LHTL short continuous**	**LHTL intermittent (IHE)**	**LLTH (IHT)**
			Mean Power Output			
Elite	↔	↑	↔		↔	
Sub-elite	↔	↑	↑	↔	↑	↔
			$\dot{V}O_2$max			
Elite	↓	↔	↔		↔	
Sub-elite	↑	↔		↔		↑

Data are very likely improvement in mean power output or $\dot{V}O_2$max (↑), very likely decrement (↓) and either trivial or unclear (↔) changes in variables. LHTH, Live High-Train High; LHTL, Live High-Train Low; LLTH, Live Low-Train High; LHTL prolonged continuous, spending between 8-18 hours per day in hypoxia uninterrupted; LHTL short continuous, spending between 1.5-5 hours per day in hypoxia uninterrupted; IHE, intermittent hypoxic exposure, which was typically less than 1.5 hours per day; IHT, intermittent hypoxic training, which was typically 0.5-2 hours per day. Missing data indicates insufficient research studies to calculate an effect.

Adapted with permission from Bonnetti and Hopkins (2009).

Table 4. Effects on sea level performance (mean power output) and maximal oxygen uptake following adaptation to hypoxia experienced by elite and sub-elite athletes in different models of natural and artificial altitude.

With the data published up until 2009, clearly Live High-Train Low is beneficial for elite athletes (Table 4). This model of altitude training typically produces a 4.0 ± 3.7% (mean ± 90% confidence level) improvement in performance at sea level. This indicates that the effect of this type of altitude training in more or less all elite athletes may be as small as 0.3% and as large as 7.7% improvement. Notice that such an improvement in performance is not always associated with an increase in $\dot{V}O_2$max indicating that other physiological measures may be causing the improved performance in elite athletes. Performance change in elite athletes as a result of other models of altitude training are either trivial or unclear or have not been tested to date (LHTL short continuous and IHT). For sub-elite athletes the Live High-Train Low method is again advantageous in terms of improving performance (4.2 ± 2.9%) along with the Live High-Train Low prolonged continuous (1.4 ± 2.0%) and the Live High-Train Low intermittent methods (2.6 ± 1.2%). There are obvious gaps in the research which require further investigation such as the effect of IHT on elite performance. Given this knowledge it is curious that many coaches and athletes continue to prefer the Live High-Train High model (see Table 5). Reasons for this choice are unclear but probably reflect practical issues such as adequate training venues, logistical and time issues required to travel up and down mountains, cost and proximity to high-class competition. This meta-analysis however, also highlights the applicability of new models of altitude training, particularly the use of Live High-Train Low prolonged continuous and Live High-Train Low intermittent models on sub-elite athletic performance. While there is undoubtedly a number of factors contributing to the conflicting results reported in the research literature (i.e. methodological differences including the duration and intensity of the hypoxic stimulus, type and intensity of training, subject training status and time-points following altitude exposure when re-retesting was completed), there remains a need for further investigation into the effects of all models of altitude exposure, particularly on elite athletic performance.

4. Anaerobic performance change with altitude training

The scientific rationale supporting the use of altitude training for anaerobic performance is less compelling than aerobic performance. Altitude-induced increments in RBC mass and haemoglobin are physiological adaptations which probably do not significantly affect the anaerobic performance in athletes. However, altitude training may also benefit anaerobic exercise performance, possibly via increases in muscle buffering capacity [42] and glycolytic enzyme activity [43]. IHE has been found to increase repeated kayak sprint power for mean and peak power [44] and repeated sprint run times [45] 3 days following hypoxia exposures. Similarly, 10 days of IHT at a simulated altitude of 2500 m improved anaerobic mean and peak cycling power at 9 days post-intervention compared to the placebo sea-level training group [46]. Our research group has also reported substantial increases in anaerobic power two (3.0%) and nine days (1.7%) post IHT training [47]. Conversely, some researchers have reported no beneficial effect of IHT [33] or IHE [48] on anaerobic performance over and above that of training closer to sea-level.

5. The current usage and effectiveness of altitude training by elite sportspeople

Debate into the effectiveness of altitude training continues with some coaches using altitude training 2-3 times per year [49], while others believe that the effects of altitude training are not conclusive and encourage coaches to invest their scare resources into other aspects of athlete development [50]. In a round table discussion on altitude training four international experts indicated that they used altitude training regularly with their athletes (average of 3 times per year), and during this training they went to an altitude of about 2200m for approximately 4 weeks [49].

In 2005-2006 a survey was given to 21 New Zealand coaches and high performance managers to assess the popularity and effectiveness of the various models of altitude training. Data was collected from 15 respondents representing approximately 40 separate altitude sojourns or interventions. The sports identified included triathlon, athletics, cycling, kayaking, snow-sports and rugby. Live High-Train High was the most popular altitude training method used, followed by the simulated altitude method Live High-Train Low intermittent (or IHE). Using altitude tents was the least popular method (Figure 1).

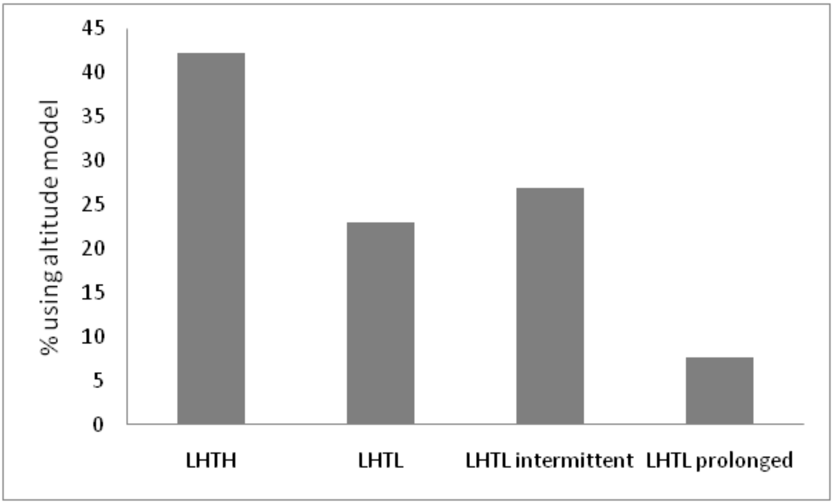

Figure 1. The proportion of respondents using the various methods of altitude training. LHTH, Live High-Train High; LHTL, Live High-Train Low; LHTL prolonged continuous, spending between 8-18 hours per day in hypoxia uninterrupted; LHTL intermittent, intermittent hypoxic exposure, which is typically less than 1.5 hours per day; *Adapted with permission from Sport New Zealand.*

Those coaches and high performance managers that indicated they used real altitude sojourns were then asked to rate the effectiveness of their altitude interventions on athletic performance (Table 5). In most cases altitude training at real sojourns was rated as moderately or very effective. Training sojourns ranged in elevation from 1100 m to 2500 m. Unfortunately the altitude model (LHTH or LHTL) was not examined in this question; therefore we cannot examine which of these methods is more effective from the coaches and managers perspective. The association between altitude elevation and the perceived effectiveness of the training camp is illustrated in Figure 2. The correlation between elevation and effectiveness score was -0.02 which indicates the effectiveness of the altitude camps is not solely due to the elevation. Indeed some very useful altitude camps were held at relatively low levels (e.g. Leutasch, Austria).

Altitude Venue	Altitude (m)	No. of Athletes	Sport Involved	No. of Weeks at Altitude	Effectiveness Score[a]
Aguascalientes, Mexico	1900	8	Cycling	2	5
Albuquerque, NM, USA	1525	10	Triathlon	4	2-4
Alp du Aez, France	1900	1	Triathlon	6	5
Bogota, Columbia	2500	10	Cycling	5	4
Boulder, CO, USA	1770	13	Triathlon	4-9	4-5
Davos , Switzerland	1560	6	Athletics	3	4
Flagstaff, Co, USA	2134	35	Triathlon	3-8	3-5
Font Romeau, France	1850	36	Triathlon Athletics	2-6	3-5
Gunnison, CO, USA	2300	2	Athletics	2	5
Leutasch, Austria	1100	1	Athletics	20	5
Los Alamos, NM, USA	2208	5	Athletics Triathlon	3-9	3-5
Quito, Equador	2218	8	Cycling	4	4
Sestriere, Italy	2035	12	Athletics	3	5
Sierra Nevada, Spain	2320	1	Athletics	3	4
Snow Farm, New Zealand	1500	38	Triathlon	2-3	4-5
St. Moritz, Switzerland	1820	18	Triathlon Athletics	2-9	5
Whakapapa, New Zealand	1730	1	Athletics	4	3

[a] *Effectiveness was rated on a scale from 1 to 5; 1, don't know; 2, adverse effect; 3, no effect; 4, moderately effective; 5, very effective. Adapted with permission from Sport New Zealand.*

Table 5. Effectiveness of real sojourns to altitude for elite athletes as described by their coaches and high performance managers.

Bonetti and Hopkins (2009) in a recent meta-analysis on altitude training found that both elite and non-elite athletes that live at altitude and train closer to sea level (LHTL) benefited from such training (by about 4.0%), whereas performance improvement in athletes (elite and non-elite) that trained and lived at altitude (LHTH) was unclear. However, due to the conflicting reports, uncontrolled studies, poor study design and variation in physiological adaptations found a consensus on the effects of altitude training is some way off.

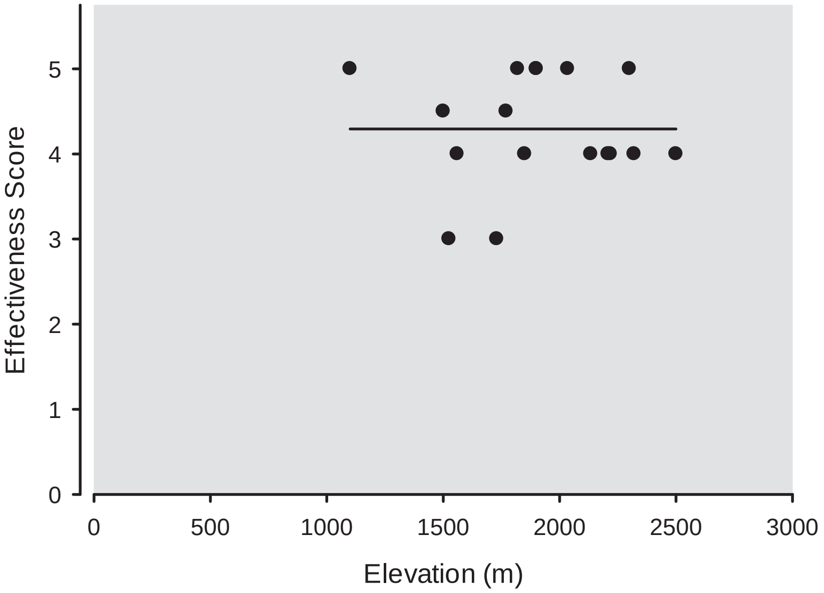

Figure 2. The association between altitude elevation and perceived effectiveness of the training sojourn. Effectiveness was rated on a scale from 1 to 5; 1, don't know; 2, adverse effect; 3, no effect; 4, moderately effective; 5, very effective. For effectiveness scores with a range we have calculated the mean score and inserted this into the above figure. Adapted with permission from Sport New Zealand.

In addition, coaches and high performance managers were also asked to rate the effectiveness of any simulated altitude training they had used previously. This produced some mixed responses with some reports of such devices even having a negative effect on performance (Table 6). However as with real altitude training the duration, hypoxic dosage and timing of the stimulus can have a substantial effect on results and therefore should be considered when deciding on altitude methods.

Type of Altitude Simulation	No. of Athletes	Sport Involved	Protocol Used	Effectiveness Score[a]
Hypoxicator	80+	Triathlon Athletics Cycling Kayaking Rugby	3 weeks duration for 60-90 minutes per day for 5-6 days per week. 5 minutes hypoxia interspersed with 5 minutes normoxia. Fraction of inspired oxygen 12-9% (⍰4500-6600 m)	Mixed responses with a relatively equal proportion at 5, 3, 2 and 1.
Altitude Tents	12	Triathlon Cycling	2-3 weeks duration sleeping for 8-10 hours per night at fraction of inspired oxygen of 14.5-16.5 (⍰3000-2000 m)	3-4
AltiPower or AltoLab	25	Triathlon Athletics Rugby	3 weeks duration for 60-90 minutes per day for 5-6 days per week. 5 minutes hypoxia interspersed with 5 minutes normoxia.	4 (Triathlon, Athletics), 2 (Rugby)

[a] Effectiveness was rated on a scale from 1 to 5; 1, don't know; 2, adverse effect; 3, no effect; 4, moderately effective; 5, very effective. Adapted with permission from Sport New Zealand.

Table 6. Effectiveness of simulated altitude training for elite athletes as described by their coaches and high performance managers.

Responders versus non-responders to altitude training

It is clear that there is considerable individual variation in the response to altitude (or hypoxia) [6, 51, 52]. This is clearly observed in mountaineering with some climbers having to use supplemental oxygen at moderate-to-high altitudes while others can climb just as high while breathing ambient air exclusively. Similarly, the response to altitude training in athletes can be just as variable. In a recent study the authors reported that some athletes significantly improved sea-level performance, while others showed a decrement after 28 days of Live High-Train Low training (LHTL) [51]. Similar levels of variation have also been reported after simulated Live-High-Train Low training via intermittent hypoxia [30]. While the mechanisms behind performance change with altitude training remain controversial it seems clear that not all athletes benefit from such training. It has been suggested that non-responders show a limited erythropoietin response in comparison with responders and therefore little improvement in $\dot{V}O_2$max and subsequent performance improvement [51]. However, other mechanisms must be at play since performance improvement after altitude training is not always related to positive changes in red blood cell indices or $\dot{V}O_2$max [10].

Our research group as well as others [53] have recently uncovered differences suggestive of neuro-vegetative imbalance in non-responders to altitude training. While still controversial, some researchers believe that ideal endurance training results in an increase in performance alongside a shift towards more parasympathetic activity as measured via heart rate variability (i.e. increased high frequency, HF) [54], whereas inadequate or ineffective training results in less parasympathetic and more sympathetic activity. Our research group has found that responders tend to have a decrease in sympathetic activity compared to non-responders, who have an increase in sympathetic activity (Figure 3).

We think that the effects of heavy training loads in association with the hypoxic stress of living at altitude may have a cumulative effect, whereby the normal adaptation processes are overwhelmed and athletes cannot cope, resulting in an increase in sympathetic stress. If recovery is not adequate and training and hypoxia continue, the athlete may move into a vicious cycle of inevitable stress resulting in an overtraining or overstress-type condition resulting in loss of performance. However more data needs to be collected over a longer period of time on a number of different athletes before we can be certain about this hypothesis.

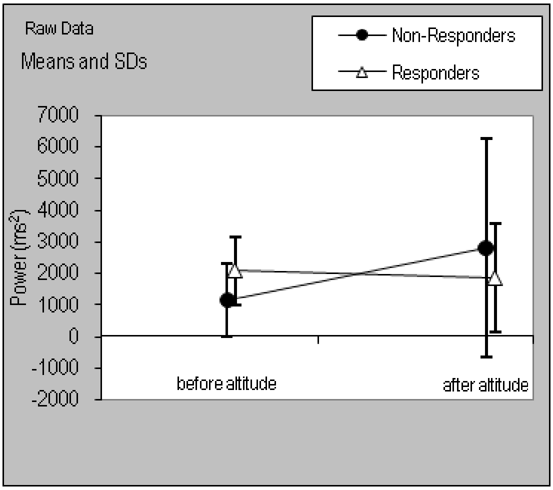

Figure 3. Low frequency component (sympathetic branch) of the heart rate variability: changes in standing position in non-responders and responders to 3 weeks of altitude training. Data are raw means ± SD of low frequency (0.04 – 0.15 Hz) reflecting sympathetic predominance. Pre, day 1 of altitude training; Post, day 20 of altitude training at 1550m.

We believe that in order to make the most of altitude training and to identify athletes who are perhaps not responding effectively to altitude training a number of subjective and physiological variables should be monitored over the training period. These variables range from subjective assessments of the athletes perception of how hard they are training along with their fatigue, stress and muscle soreness levels. We also record the athletes sleep quantity and quality which provides additional information on the adaptation to altitude. In many cases sleep disturbances may indicate overstress, and poor sleep quality can interfere with athletic training. Figure 4 shows a number of subjective variables collected on two elite athletes during a 20-day Live High-Train Low altitude camp. One of the athletes improved performance after the camp and was recorded as a responder, while the other failed to improve and in fact went backwards in terms of performance (non-responder).

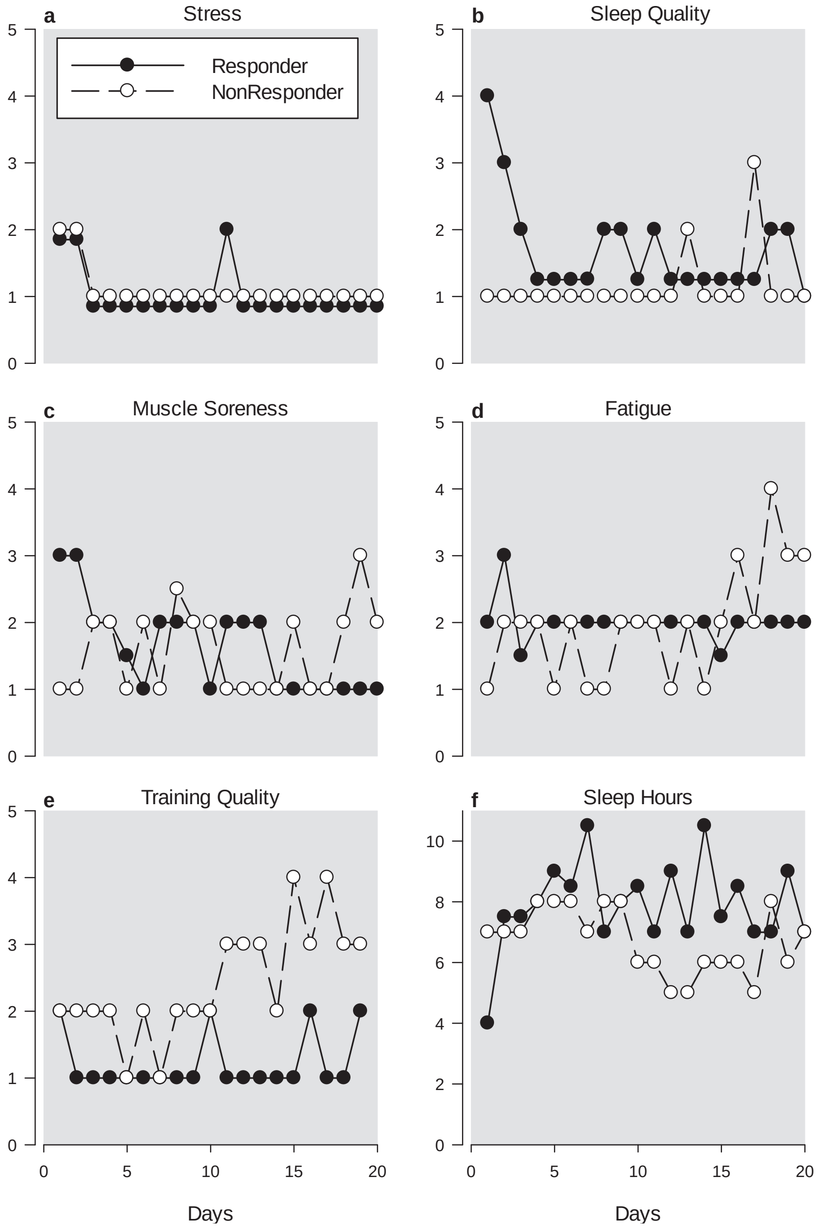

Figure 4. Subjective Perceptions from a Responder and Non-Responder to a 20-day Live High-Train Low Altitude camp. Subjective stress (a), sleep quality (b), muscle soreness (c), fatigue (d), training quality (e) and hours of sleep (f) in a responder (closed circles) and non-responder (open circles) throughout the 20-day altitude camp. Values are 1, excellent; 2, very good; 3, normal; 4, poor; 5, very poor.

It is apparent from Figure 4 that the non-responder to altitude training had increased feelings of fatigue, poorer training quality and fewer overall sleeping hours than the responder. Each of these parameters along with daily training schedules can give invaluable insight into whether athletes are coping with the altitude training or not.

6. Preparing the athlete for altitude training

As mentioned earlier in this chapter, altitude training provides an additional physiological stress in an attempt to enhance the athlete's response to training. However, there are a number of other stresses in the lives of athletes which need to be taken seriously when considering the use of altitude training, including, but not limited to; training, family, relationships, and psychological stress. Because of this added stress it is recommended that athletes decrease their training volume and intensity over the first few weeks of altitude [55], however there are also a number of other training and health-related factors that should be considered prior to any altitude training. It is suggested that athletes should only add the stress of altitude to their training when they have optimal nutritional status, and are free of illness, injury, and fatigue. Increasing the stress of altitude training on an already damaged or fragile athlete can result in inhibited performance.

One of the most important considerations is iron status, as adequate iron stores are necessary to develop new red blood cells. Iron supplementation with altitude training has been used for improved performance in athletes [56], whereas in some occasions exposure to altitude without a supplemental dose of iron, results in a marked decrease in serum ferritin [57]. Theoretically, iron is a requisite component of the haemoglobin molecule and serves as the exclusive site for oxygen binding and release. Iron is necessary for red blood cell multiplication which is part of erythropoetic process [55]. Ferritin, the storage form of iron, is significantly decreased after three weeks altitude exposure at 2,225 m in elite male swimmers [58]. Similar results were reported in elite female speed-skaters who lived at 2,700 m for 27 days and trained at an altitude between 1,400 m and 300 m [59]. These reports suggest that the hypoxic environment of altitude may exacerbate the requirement for iron among well-trained athletes [60]. In addition, recent studies have shown that endurance performance was decreased due to iron insufficiency in well trained non-anaemic athletes [61] signifying even if athletes meet guidelines for iron levels they may be disadvantaged if iron levels are not sufficient for their individual turnover rates.

In a recent randomised controlled study we examined the effect of iron supplementation (equivalent to 105 mg element iron, with vitamin C 500 mg as sodium ascorbate [FERRO-GRAD® C, Abbott Laboratories (NZ) Ltd, Naenae]), or a placebo tablet on 800-m swim performance in a group of elite triathletes completing a 20-day Live High-Train Low altitude camp (Live 1500m, train 300m). The performance measures before and after the altitude training camp can be seen in Figure 5. Compared to the placebo group, the triathletes who took the iron supplementation improved performance by 3.3% which suggests that coaches and athletes need to consider iron supplementation prior to altitude training. Low iron levels do not allow for the enhanced erythropoietic effect normally witnessed at real altitudes and therefore the athlete's body may take longer to adapt to the hypoxic environment and subsequently improve performance. We have also found that supplemental iron tablets helped to improve haematological parameters during IHE and IHT. After 2-3 weeks of either IHE [30], or IHT [47] athletes taking iron supplementation showed improved haematological indicators (Figure 6).

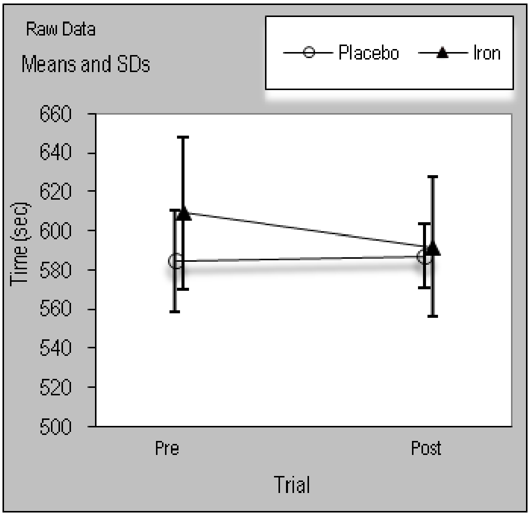

Figure 5. swim time trail performance (sec) in the triathletes who took iron supplementation or placebo tablets 1 week before (pre) and 1 week after (post) the LHTL altitude training camp.

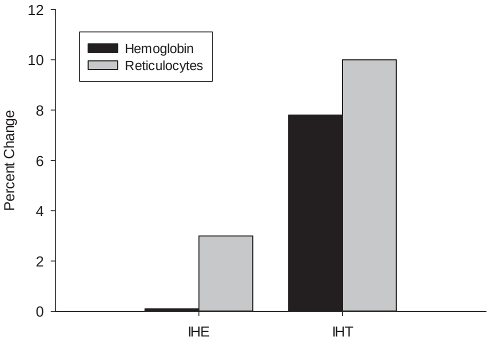

Figure 6. Change in blood variables in the simulated altitude versus control groups 2 days after a 2-3 week intermittent hypoxic intervention.

Altitude may also compromise the immune system and slow down the recovery from illness, so athletes with an illness are not recommended to go to altitude and close monitoring of athletes' wellbeing at altitude should be mandatory. We encourage a range of blood parameters including iron status, red and white cell count and EPO if available. In addition to monitoring changes in the haematological and immune responses other variables should be monitored including body weight, resting and exercise heart rate and haemoglobin saturation levels. Such monitoring is less subjective and gives a good indication of adaptation progress. For example, notice the overall lower haemoglobin saturation levels (S_PO_2) in the non-responder compared to the responder. Such a change probably reflects the inadequate ability of the non-responder to adjust to the hypoxic environment.

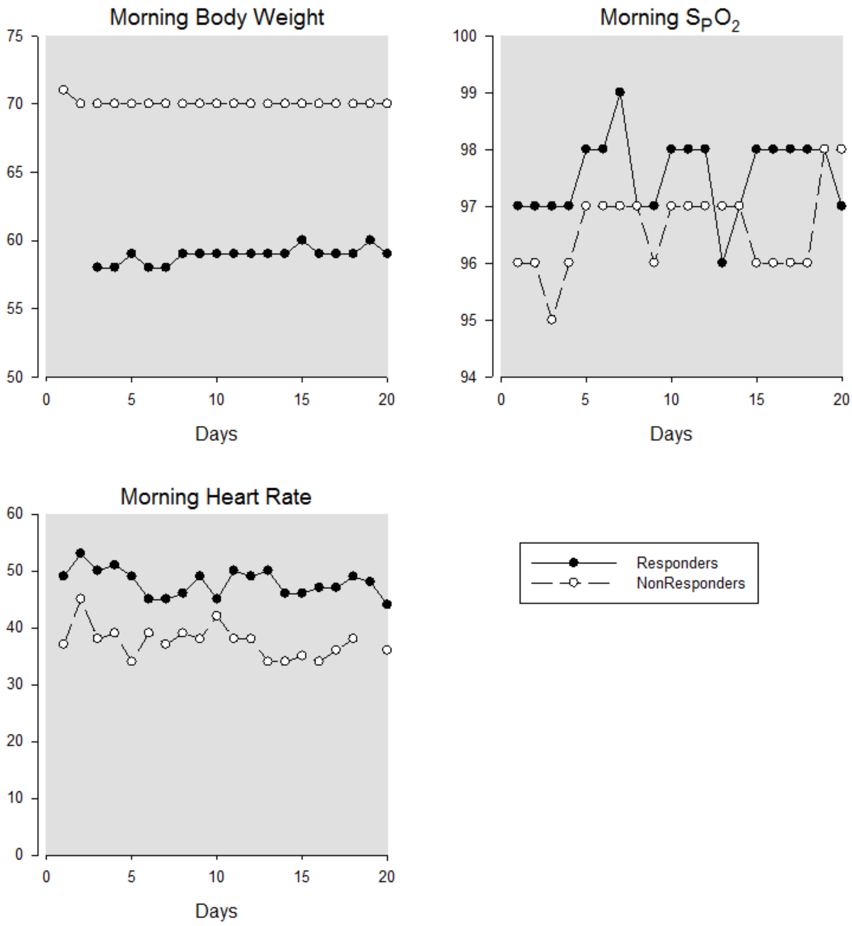

Figure 7. Physiological monitoring of a Responder (closed circles) and Non-Responder (open circles) to a 20-day Live High-Train Low Altitude camp.

7. Conclusion

We conclude that there is sufficient evidence to suggest that all methods of altitude training can benefit athletic performance in some way, however to gain improvement in sea-level performance for the top elite athletes, a Live High-Train Low method is recommended. Nevertheless, performance enhancement for athletes as a result of altitude training is not guaranteed. Indeed, some athletes may be unable to handle the extra stress that accompanies hypoxia, especially when they may be already working close to their physical limits. In such cases maladaptation and detraining may occur and the athlete's performance may decrease rather than increase. Through rigorous preparation, adequate training and recovery and thorough planning, the coach or performance manager can make altitude training sojourns successful. Maintaining detailed longitudinal data on individual athletes including subjective and objective measures of stress and performance will allow the early detection of problems and increase the chances of a positive altitude training block. However, questions still remain to be answered including; what is the most effective hypoxic dosage, what is the best way to monitor adaptation during hypoxia, and discovering the best way to delineate responders from non-responders.

Author details

Michael J. Hamlin[1*], Nick Draper[2] and John Hellemans[1]

*Address all correspondence to: mike.hamlin@lincoln.ac.nz

1 Department of Social Science, Parks, Recreation, Tourism & Sport, Lincoln University, Christchurch, New Zealand

2 School of Sciences and Physical Education, University of Canterbury, Christchurch, New Zealand

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