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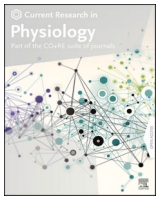

# Physiological and performance effects of live high train low altitude training for elite endurance athletes: A narrative review

G. Bonato [a,b,*], Goodman S.P.J.[a], Lathlean Tjh [a,c,d]

[a] Exercise and Sports Science, School of Science and Technology, The University of New England, Armidale, 2350, Australia
[b] College of Arts, Society and Education, James Cook University, Townsville, 4811, Australia
[c] The Adelaide Medical School, Faculty of Health and Medical Sciences, The University of Adelaide, Adelaide, 5000, Australia
[d] South Australian Health and Medical Research Institute (SAHMRI), Adelaide, 5000, Australia

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ABSTRACT

Altitude training has become an important training application for athletes due its potential for altering physiology and enhancing performance. This practice is commonly used by athletes, with a popular choice being the live high - train low approach. This model recommends that athletes live at high altitude (1250–3000 m), but train at low altitude or sea-level (0–1200 m). Exposure to altitude often leads to hypoxic stress and in turn stimulates changes in total haemoglobin mass, erythropoietin, and soluble transferrin receptors, which alter further underlying physiology. Through enhanced physiology, improved exercise performance may arise through enhancement of the oxygen transport system which is important for endurance events. Previous investigations into the effects of altitude training on exercise performance have been completed in a range of contexts, including running, cycling, swimming, and triathlon. Often following a LHTL altitude intervention, athletes realise improvements in maximal oxygen consumption capacity, time trial performance and peak power outputs. Although heterogeneity exists among LHTL methodologies, i.e., exposure durations and altitude ranges, we synthesised this data into kilometre hours, and found that the most common hypoxic doses used in LHTL interventions ranged from ~578–687 km h. As this narrative review demonstrates, there are potential advantages to using altitude training to enhance physiology and improve performance for endurance athletes.

## 1. Introduction

The Mexico City Olympic Games in 1968 sparked an interest in altitude training to improve performance, given as a result of the superior performances of athletes who resided or trained at altitude over their counterparts who prepared at sea-level (Wilber, 2004). Thus, altitude exposure as an environmental stressor was grounded as a prominent factor to elicit physiological responses. However, an array of approaches exists to facilitate such adaptations, with prominent models including the live high - train high (LHTH) and live high - train low (LHTL). Both approaches require athletes to live at an altitude range of 1250–3000m and while they remain at this range under the LHTH model, LHTL involves individuals training at sea-level (0–1200m). Other models include the live low - train high (LLTH), live low – train low (LLTL) and intermittent hypoxic training (IHT) or intermittent hypoxic exposure (IHE). Table 1 provides an overview of these models and their corresponding altitude range classifications (Ashenden et al., 1999a; Bonetti and Hopkins, 2009; Bartsch and Saltin, 2008). One of the most popular approaches and the focus of this narrative review is the LHTL method. Although this model has a range of interpretations based on classification ranges and divergent methodologies available, we use the ranges described in this document as the foundation for how this model is classified but provide some insight into the complex factors underpinning this.

To perform at the highest level across international competition, endurance athletes are continuously seeking marginal improvements in performance. Altitude exposure has the potential to evoke physiological adaptations to promote such gains. Previously, exposure to different stimuli, including various approaches to altitude training, have shown promise in terms of developing physiological and performance outcomes. When discussing potential 1% gains, and the ultimate impact this may have on success, an almost 8% gain in performance is certainly of practical interest (Hamlin et al., 2013, 2015).

Hypoxia can be defined as the reduction of normal levels of oxygen

* Corresponding author. The University of New England, Australia.
*E-mail address:* graeme.bonato@jcu.edu.au (G. Bonato).

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**Table 1**
Living and training altitude ranges for the common models of altitude training.

| Altitude Model | Altitude Range |
|---|---|
| LHTH | 1250m–3000m |
| LHTL | Live High = 1250m–3000m<br>Train Low = 0m – ≤ 1200m |
| LLTH | Live Low = ≤ 1199m<br>Train High = ≥ 1200m |
| LLTL | Live Low = ≤ 1199m<br>Train Low = ≤ 1200m |
| IHT/IHE | Live = ≤ 1199m<br>Train = ≥ 1200m |

**Notes:** IHE = intermittent hypoxic exposure, IHT = intermittent hypoxic training, LHTH = live high train high, LHTL = live high train low, LLTH = live low train high, LLTL = live low train low.

within cells and tissues of the body and can be achieved through either natural or simulated altitude training strategies (Mujika et al., 2019). Due to rationalized and restricted resources applied to the elite endurance context, logistical factors (travel distances and costs) have led coaches to develop different types of simulated altitude models. In cases where costs have been less restrictive, approaches such as nitrogen dilution (e.g., normobaric hypoxic rooms/apartments), oxygen filtration (e.g., normobaric hypoxic rooms/tents), and pressure reduction (e.g., hypobaric hypoxic chambers) have been used to produce simulated altitude (Wilber, 2007).

Despite several investigations into the physiological and performance effects of altitude training, there is still no clear consensus regarding optimal protocols i.e., duration, intensity and hypoxic dose (Girard et al., 2017; Hahn and Gore, 2001a). Due to the nature of modern-day training cycles for elite athletes, there are a number of limitations within the current literature with particular studies only investigating single bout exposures due to factors such as travel/relocation to hypoxic training environments (Burtscher et al., 2018). Given the variability in the literature regarding altitude training protocols (i.e., altitude levels, hypoxic doses, time of exposure, training volume, and timing of protocol testing) it is difficult to establish definitive guidelines and protocols for athletes and coaches. Additionally, if altitude training protocols are not implemented appropriately, this has the potential to cause harm to athletes (Sinex and Chapman, 2015). This review aims to examine the popular altitude model LHTL and provide guidelines and recommendations of the associated physiologic and performance considerations associated with it.

## 2. Live high train low

Different models of altitude training have been proposed depending on whether the activity is at sea level or at altitude. The LHTL model has been proposed as a suitable method for physiological and performance improvement (Hamlin et al., 2013). The LHTL method involves hypoxic exposure up to 16 h per day (Sinex and Chapman, 2015) and typically may produce a 0.3%–7.7% improvement in exercise performance at sea level (Bonetti and Hopkins, 2009). This approach proposes living at altitude (1250–3000m) but training at or near sea level (0–1200m) (Ashenden et al., 1999a; Bonetti and Hopkins, 2009). This allows athletes to train in an environment comparable to competition environments, and hence maintain appropriate intensities and volumes of training, without excessive adverse effects whilst still producing physiological adaptations by living at altitude (Levine and Stray-Gundersen, 1997; Chapman et al., 1998a).

Debate continues regarding the current effectiveness of altitude training for well-trained endurance athletes (Millet et al., 2019; Lundby et al., 2012). Whilst hypoxic training has been reported to increase total hemoglobin mass ($tHb_{mass}$), erythropoietin (EPO) and soluble transferrin receptors (sTfR) (Wehrlin et al., 2006; Gore et al., 2013), others (Lundby et al., 2012; Lundby and Robach, 2015; Robach and Lundby, 2012), have suggested $tHb_{mass}$ as not increasing. Comparatively for exercise performance, improvements in time trial (TT) performance, maximal oxygen consumption capacity ($VO_{2MAX}$), and peak power output (PPO) are reported benefits of the LHTL model (Levine and Stray-Gundersen, 1997; Garvican et al., 2012; Wachsmuth et al., 2013; Neya et al., 2013; Garvican-Lewis et al., 2013; Humberstone-Gough et al., 2013; Coppel et al., 2015). Similar to the effects concerning physiology, these findings may be context specific and are not universal. For instance, (Hinckson et al., 2006) have shown TT performance to remain stable with respect to an appropriate control group for rowers, while (Robach et al., 2018) reported no improvement in skiers. With varied results alongside the pressures of resource availability and time pressures on athletes, the feasibility and pursuit of altitude training, or

**Table 2**
Acute and chronic physiological responses to hypoxia.

| System | Acute Exposure | Chronic Exposure |
|---|---|---|
| Hematological | ↑ $tHb_{mass}$ ↑ EPO ↑ sTfR ↓ plasma volume | ↑ $O_2$ carrying capacity of blood ↑ risk of polycythemia |
| Pulmonary | ↑ ventilation ↓ arterial oxygen saturation | ↑ risk of pulmonary hypertension<br>↑ lung diffusion capacity<br>↑ lung capillary blood volume<br>↑ risk of hypoventilation<br>↑ risk of chronic lung disease |
| Cardiovascular | ↑ heart rate ↑ blood pressure ↑ cardiac output<br>↑ risk of peripheral edema | ↑ risk of blood pressure disorder ↑ risk of heart failure ↑ risk of ventricular hypertrophy<br>↑ risk of arterial oxygen desaturation |
| Neurophysiological | ↑ central respiratory drive ↓ central respiratory output<br>↓ cognitive function ↓ motor function<br>↓ sensory function ↑ risk of cerebral vasodilation<br>↑ risk of mood changes | ↓ cognitive function ↓ sleep quality ↑ mood disorders ↑ risk of cerebral hypoxia |

**Notes:** EPO = erythropoietin, sTfR = soluble transferrin receptor, $tHb_{mass}$ = total hemoglobin mass.

specifically incorporating the LHTL model may be difficult.

Much of the current literature examining altitude training has focused on studies conducted at high altitude within a hypobaric hypoxia (HH) environment (Coppel et al., 2015). However, current 'field' studies present practical and logistical challenges especially considering the current COVID-19 pandemic (Manferdelli et al., 2020). As such, research teams have sought to replicate hypoxic conditions at low altitudes through normobaric hypoxic (NH) laboratories and testing facilities (Coppel et al., 2015). Fundamentally, the major difference between these two approaches is the partial pressure of oxygen ($Pa_{O2}$), which is considered to be a major factor regarding physiological adaptations at altitude (Conkin and Wessel, 2008). Although this assumption is held by many research teams regarding hypoxic physiology, opinion remains divided regarding the most suitable approach (Debevec and Millet, 2014). The notion that HH and NH methodologies are interchangeable remains unproven and further research is needed (Coppel et al., 2015).

## 3. Physiological adaptations following LHTL

One of the key justifications for adopting altitude training is the proposed positive effect of increased oxygen-carrying capacity (i.e. EPO response through hematological adaptation) (Saunders et al., 2019). Non-hematological parameters may also be of benefit and include increased muscle buffering capacity (Gore et al., 2007), and an elevated glycolytic enzyme promotion (Katayama et al., 2004a). Evidence suggests that on returning to sea level, performance improvements are likely due to hematological mechanisms (Ploszczyca et al., 2018).

Upon exposure to hypoxia, there are several acute (hours) and chronic (days to weeks) physiological responses which occur (Table 2). Acute responses to hypoxia can often occur within hours of exposure, with onset dependent upon the degree of exposure (Ploszczyca et al., 2018), while chronic responses may arise after 1–3 days following hypoxia which include longer lasting complications resulting from the absence of oxygen (Neubauer, 2001). Balancing the positive adaptations that result from hypoxic exposure with minimising negative consequences that may arise is the challenge for athletic stakeholders. Initially, acute responses may be disadvantageous for endurance athletes (Sinex and Chapman, 2015).

Within hours of hypoxic exposure, plasma volume decreases which is dependent upon elevation levels (Ploszczyca et al., 2018). This reduction in plasma volume results in impairment of maximum cardiac output ($\dot{Q}$) (Sinex and Chapman, 2015). Additionally, increases in $\dot{Q}$ are the consequence of accelerated heart rate (HR), while stroke volume (SV) is initially unaffected (Naeije, 2010). Furthermore, quantity of $tHb_{mass}$ and hematocrit (HCT) confounding by hypovolaemia via plasma concentration leads to reduced SV (Convertino et al., 2019).

A challenge that coaches encounter when determining the viability of hypoxic training is the dosage required to elicit alterations in physiology. Principally, this is attributed to the diverse number of approaches and altitude ranges used to form altitude interventions within the literature and emphasis is commonly placed on the altitude range (metres), duration (hours), and number of days. Despite the substantial heterogeneity, a further study (Garvican-Lewis et al., 2016) has innovated new approaches to quantifying hypoxic dose. These authors have collated these variables into a single formula (Equation 1) and express dose in "kilometre hours" (Garvican-Lewis et al., 2016). Although this metric has the potential to unify study methodologies, resultant outcomes may also prove meaningful for the coach or athlete. Indeed, this may enable such stakeholders to devise altitude interventions with greater flexibility and suitability with available resources. For instance, when devising this metric, (Garvican-Lewis et al., 2016) examined the target range required to elicit changes in $tHb_{mass}$, establishing a criterion of 500 km h. With this known quantity, coaches could manipulate altitude exposure parameters (altitude range, exposure duration, days) within the athlete's current training program to attain this milestone, and subsequently increase the possibility of observing physiological improvements. Further research into this prospect would be of great practical significance to coaches and athletic stakeholders.

$$km.h = \left(\frac{Elevation\ (m)}{1000}\right) \times hours\ of\ exposure\ (h)$$

**Equation 1**. Kilometre hours (km.h) equation proposed by (Garvican-Lewis et al., 2016) to capture the hypoxic dose of altitude training. m is metres and h is hours.

Table 3 provides a summary of the available literature examining physiological outcomes within the LHTL approach identified by this review. The most reported parameters examined include $tHb_{mass}$, EPO and sTfR. The mean altitude range and duration used within the literature examining the effects of altitude exposure on physiology was ~2976m and ~211 h of total exposure. Using the combined kilometre hours metric proposed by (Garvican-Lewis et al., 2016), the mean hypoxic dose was ~578 km h.

### 3.1. Non-hematological adaptations

#### 3.1.1. Respiratory adaptations

Ambient air can be defined as a combination of mixed gasses that are present to make up the Earth's atmosphere. These gases are typically made up of ~78% nitrogen, ~21% oxygen, with the remainder consisting of an array of trace elements (Wilber, 2001). The respiratory system is conventionally described as a two-gas model involving oxygen and carbon dioxide (Kulandavelu et al., 2015). However, a third gas, nitric oxide (NO) is thought to be responsible for regulating hypoxic vasodilation (Singel and Stamler, 2005). Hypoxic exposure results in a reduction in oxygen exchange from the alveoli to the blood (oxygen perfusion) and in turn, decreases circulating oxygen (Calbet et al., 2009). Under such stresses, activity of hypoxia inducible factor-1 (HIF-1a) has been identified as an important factor in the promotion of adaptations resulting from hypoxia (Sinex and Chapman, 2015). Within hypoxia, HIF-1a increases stability allowing binding to target genes including those responsible for angiogenesis and upregulation of glycolysis (Semenza, 2009). Consequently, these alterations spur on hemodynamic adaptations such as EPO, reticulocytes and $tHb_{mass}$ (Bonetti and Hopkins, 2009).

When exposed to hypoxia, the respiratory system adapts by increasing pulmonary perfusion and also lung capacity by ~20–25% during exercise (Sheel et al., 2010). By and large, respiratory adaptations are positive when hypoxic exposure arises, however, some may experience periodic breathing (PB) discrepancies at varying hypoxic doses. Periodic breathing can be defined as respiratory pauses occurring in a series of three or more and lasting longer than 3 s (Insalaco et al., 2012). These can be problematic because it reduces oxygen consumption in an already compromised environment. Continued exposure to hypoxia induces physiological changes which enhance the body's ability to tolerate reduced $Pa_{O2}$ (Tellez et al., 2016). However, periodic breathing discrepancies may occur because of hypoxic exposure which can be detrimental to the health and wellbeing of athletes (Kinsman et al., 2005). As a result of the complexities of varying literature specifically focusing on respiratory adaptations, further exploration of the evidence may be needed to determine optimum hypoxic duration for different endurance athletes. Coaches should therefore be vigilant and monitor athletes for any periodic breathing discrepancies to better optimize the hypoxic exposure experience.

#### 3.1.2. Cardiorespiratory neurophysiology

The central nervous system (CNS) is extremely sensitive to decreases in oxygen availability (Siebenmann and Rasmussen, 2016). During hypoxia, exercise tolerance may be reduced and neuromuscular fatigue arises (Siebenmann and Rasmussen, 2016). This can be attributed to the progressive changes that occur within the CNS and/or muscles, resulting in a diminished force output other than what may have been anticipated

**Table 3**
Research findings relative to physiological adaptations following altitude for LHTL.

| Study | Level | Sport | Altitude (m) | Duration (h) | Hypoxic dose (km/h) | Physiological Parameters Measured | Key Results |
|---|---|---|---|---|---|---|---|
| Ashenden et al., 1999b | Sub-Elite | Cycling Triathlon Skiing | 3000 | 184–230 | 552–690 | $tHb_{mass}$, RET | $tHb_{mass}$ no change RET no change |
| Ashenden et al., 1999c | Elite | Cycling | 2650 | 96–120 | 254.5–318 | $tHb_{mass}$, RET, sFerritin | $tHb_{mass}$ no change RET no change |
| Basset et al., 2006 | Sub-Elite | Skiing Skating | 3636 | 48 | 175 | $V_E$, RER, *bm*, $tHb_{mass}$, EPO, HCT, RBC, WBC, RET, sTfR, Ferritin, PLT | ↑ RBC ↑$tHb_{mass}$ ↑HCT ↑ PLT ↑ EPO |
| Bonetti et al., 2006 | Sub-Elite | Kayaking | 3600–6000 | 7.5 | 27–45 | $tHb_{mass}$, HCT, Ferritin | ↑$tHb_{mass}$ ↑ HCT ↓ Ferritin |
| Bonetti et al., 2009 | Sub-Elite | Cycling Triathlon | 3600–6000 | 75 | 270–450 | $tHb_{mass}$, HCT, Ferritin, RET, WBC | ↑ $tHb_{mass}$ ↑ RET ↓ Ferritin |
| Brugniaux et al., 2006 | Elite | Running | 2500 3000 | 84 168 | 210 504 | $tHb_{mass}$, HCT, sTfR, Ferritin, RETIC, EPO, PV, BV | ↑ $tHb_{mass}$ ↑ sTfR |
| Clark et al., 2009 | Elite | Cycling | 3000 | 294 | 882 | $tHb_{mass}$, sEPO | ↑ $tHb_{mass}$ of 3.3% following altitude exposure |
| Dehnert et al., 2002 | Sub-Elite | Triathlon | 1956 | 182 | 356 | $tHb_{mass}$, sEPO | ↑ EPO |
| Garvican et al., 2011 | Elite | Cycling | 3000 | 416 | 1248 | $tHb_{mass}$ | ↑ $tHb_{mass}$ of 2.9% in the response group |
| Garvican et al., 2012 | Elite | Cycling | 2760 | 504 | 1391 | $tHb_{mass}$, RET, EPO, sFerritin, sTfR | ↑ $tHb_{mass}$ |
| Garvican-Lewis et al., 2013 | Elite | Water Polo | 3000, 2500, 2800 | 154–266 | 385–798 | $tHb_{mass}$ | ↑ $tHb_{mass}$ of ~4.0% |
| Gore et al., 2001 | Elite | Triathlon | 3000 | 184–230 | 552–690 | bm | ↑*bm* of 18% |
| Gore et al., 2006 | Sub-Elite | Running Swimming | 4000–5500 | 60 | 240–330 | EPO, sTfR, $tHb_{mass}$, HCT, RET, RETHb, Ferritin | ↑ $tHb_{mass}$ of 1.0% no change ↑ RCV of 2.3% no change ↑ EPO |
| Gough et al., 2012 | Elite | Swimming | 3000 | 294 | 882 | $tHb_{mass}$ | ↑ $tHb_{mass}$ of ~4.0% |
| Hahn et al., 2001 | Elite | Cycling | 2650 | 96–132 | 254–349 | sEPO, RET, RBC, $tHb_{mass}$, HCT, | ↑ sEPO of 80% in early stages of hypoxic exposure |
| Hauser et al., 2016 | Sub-Elite | Triathlon | 2250 | 324 | 729 | $tHb_{mass}$, RBC, HCT, RBC, Ferritin, | ↑ $tHb_{mass}$ HCT no change RBC no change ↓ EPO ↓ Ferritin |
| Hamlin and Hellemans, 2007 | Sub-Elite | Multisport | 3400–5000 | 11.25–22.5 | 38.25–112.5 | $tHb_{mass}$, HCT, RET, Ferritin | ↑ $tHb_{mass}$ ↑ HCT ↑ RET ↓Ferritin |
| Hinckson and Hopkins, 2005 | Sub-Elite | Running Triathlon | 2500–3500 | 200 | 500–700 | $tHb_{mass}$, HCT, Ferritin, RET | ↓ total mean value of $tHb_{mass}$ ↓ total mean value of HCT |
| Hinckson et al., 2006 | Elite | Rowing | 3600–6000 | 19 | 68.5–114 | HCT, Ferritin, | ↑ HCT |
| Humberstone-Gough et al., 2013 | Elite | Triathlon | 3000 | 240 | 720 | $tHb_{mass}$, $_s$Ferritin, sTfR | ↑ $tHb_{mass}$ likely ↑ $_s$Ferritin ↑ sTfR likely |
| Julian et al., 2004 | Elite | Running | 3600–5000 | 11.75 | 42.25–58.75 | $tHb_{mass}$, HCT, RET, EPO, sTfR | ↓ $tHb_{mass}$ ↓ RET ↓ EPO ↓ sTfR |
| Katayama et al., 2003 | Sub-Elite | Running | 4500 | 94.5 | 425.25 | $tHb_{mass}$, HCT, RBC, RET, EPO, Ferritin | $tHb_{mass}$ no change HCT no change RBC no change RET no change EPO no change Ferritin no change |
| Katayama et al., 2004b | Sub-Elite | Running | 4500 | 42 | 189 | $tHb_{mass}$, HCT, RBC, RET, EPO, Ferritin | ↓ $tHb_{mass}$ ↓ HCT ↓ RBC ↓ RET ↓EPO ↓ Ferritin |
| Levine and Stray-Gundersen, 1997 | Sub-Elite | Running | 2500:1250 | 672 | 1680 | $tHb_{mass}$, RBC, EPO, PV, BV, HCT | ↑ RBC of ~9.0% |
| Mattila and Rusko, 1996 | Elite | Cycling | 3000 | 198 | 594 | La, EPO, RET, RBC | ↑ EPO ↑ RET |
| Robach et al., 2006 | Elite | Skiing | 2500 3000 3500 | 66 66 66 | 165 198 231 | Hb, HCT, RBC, RET, sTfR, sEPO, sFerritin | ↑ Hb ↑ HCT ↑ RBC RET no change ↑ sEPO ↑ sTfR sFerritin no change |
| Robach et al., 2018 | Elite | Skiing | 2207 | 416 | 918 | $tHb_{mass}$, RCV, PV, BV, RBC, RET, WBC, EPO, Ferritin | $tHb_{mass}$, no change RCV no change PV no change BV no change RBC no change RET no change WBC no change EPO no change ↓ Ferritin |
| Robertson et al., 2010a | Elite | Swimming | 2600 | 360–400 | 936–1040 | $tHb_{mass}$ | ↑ $tHb_{mass}$ |
| Robertson et al., 2010b | Sub-Elite | Running | 3000 | 420 | 1260 | $tHb_{mass}$, HCT, RET, sTfR, EPO, Ferritin | ↑ $tHb_{mass}$ ↑ RET ↑ sTfR ↑ EPO ↓ Ferritin |
| Rusko et al., 1999 | ? | Skiing Triathlon | 2500 | 300–400 | 750–1000 | EPO, RCM | ↑ EPO of 14% ↑ RCM of 5% |
| Saunders et al., 2004 | Elite | Running | 2000–3100 | 180–240 | 360–744 | $tHb_{mass}$, RER | ↑ RE |
| Saunders et al., 2009 | Elite | Running | 2860 | 415 | 1186 | $tHb_{mass}$ | ↑ $tHb_{mass}$ |
| Saunders et al., 2010 | Elite | Walking | 3000 | 294 | 882 | $tHb_{mass}$, RCV, PV, BV, HCT, RET, Ferritin, sTfR | ↑ $tHb_{mass}$ of 8.6% |
| Schmitt et al., 2018 | Elite | Skiing | 2700 | 210 | 567 | Erythrocytes, Hb, HCT, RET, Ferritin | ↑Erythrocytes ↑ Hb ↑ HCT ↓ RET ↓ Ferritin |
| Siebenmann et al., 2012 | Elite | Cycling | 2500–3000 | 448 | 1120–1344 | Hb, HCT, RCV, PV, BV, Urine EPO | Hb no change HCT no change PV no change BV no change Urine EPO no change |
| Wood et al., 2006 | Elite | Hockey Soccer | 3600–6000 | 9 | 32.5–54 | $tHb_{mass}$, HCT, WBC | ↑ WBC |
| Mean ± SD | | | 2976 ± 611 | 211 ± 164 | 578 ± 431 | | |

**Notes:** bm = muscle buffering capacity, BV = blood volume, EPO = erythropoietin, Hb = hemoglobin concentration, HCT = hematocrit, HiHiLo = live high train high and low, LHTH = live high train high, LHTL = live high train low, LLTL = live low train low, PLT = platelets, PV = plasma volume, RBC = red blood cells, RCM = red cell mass, RCV = red cell volume, RE = running economy, RER = respiratory exchange ratio, RET = reticulocytes, RETHb = reticulocyte hemoglobin mass, sEPO = serum erythropoietin, sFerritin = serum ferritin, sTfR = soluble transferrin receptor, $tHb_{mass}$ = total hemoglobin mass, $V_E$ = minute ventilation, WBC = white blood cells.

in normal muscular work (Mahamed and Duffin, 2001). Blood gases within the human body are controlled via the central and peripheral respiratory chemoreceptors located within the brain stem (Nattie and Li, 2009). The quick-responding peripheral chemoreceptors are located within the carotid arteries and respond to changes of low arterial $O_2$ and high arterial $CO_2$. The $O_2$–$CO_2$ interaction is then compromised by hypoxia resulting in a diminished carotid body response however, the ventilatory response to $CO_2$ is restored through acclimatisation to hypoxia (Dempsey et al., 2014). Upon exposure to hypoxia there is an immediate increase in alveolar ventilation known as the hypoxic ventilatory response (HVR) (Schoene, 2001). HVR involves increases in ventilation due to hypoxia, which allow the body to utilise and process oxygen at significantly higher rates as a result of specific proteins such as HIF-1a (Moya et al., 2020). This increase is characterized by both the carotid (~90%) and aortic bodies (~10%) (Timmers et al., 2003). These factors then play a significant role in controlling the drop of arterial $Pi_{O2}$ and assist with ventilatory responses to hypoxia (Timmers et al., 2003).

#### 3.1.3. Skeletal muscle adaptations

In addition to the hematological and non-hematological (respiratory and neurological) adaptations outlined above, there are a range of physiological changes that can occur distally, including skeletal muscle. Adaptations include increases in capillarisation, muscle buffering capacity, myoglobin content and mitochondrial capacity (Hahn and Gore, 2001b). Furthermore, these may also contribute to increases in muscle oxidation leading to a reduction in the production of lactate (Hahn and Gore, 2001b). These changes can often be categorised into three specific adaptation categories according to a) mechanical b) chemical and c) intra-cellular. An important component of skeletal muscle adaptation is mechanical efficiency (ME) which is defined in terms of the cost of oxygen needed for a particular task (Hahn and Gore, 2001b). Previously (Green et al., 2000) have shown that ME improved by 5% when combining submaximal cycling with altitude training, these authors propose this is due to suggesting that this may have been because of the reduced energy needs of the processes involved with muscle excitation and contraction.

Skeletal muscle adaptations due to altitude training may also occur as a result of the fusion process of human myoblasts and mature fibres by satellite and adult stem cells (Mancinelli et al., 2016). These cells help with skeletal tissue remodelling, with the gene and protein balance being regulated via transcription factors such as HIF-1a (Hoppeler et al., 2003). Ultimately, these changes have been linked with increased muscle mass due to hypoxic exposure as a result of upregulation of glycolysis and angiogenesis (Mancinelli et al., 2011). Therefore, altitude training may have the ability to induce angiogenesis as well as promoting oxygen maintenance in regard to increasing RBC and capillaries (Wahl et al., 2013).

#### 3.1.4. Lactate metabolism

During hypoxic exposure, metabolic responses differ depending upon altitude ranges and duration of exposure (Lundby et al., 2000). A metabolic abnormality which was first referred to in the 1930's is the 'lactate paradox' (Lundby et al., 2000). This paradox describes the phenomenon that blood lactate accumulation during exercise increases with arrival to hypoxic environments, but decreases with acclimatisation without changes in muscle oxygen delivery (Hochachka et al., 2018). However, some studies have challenged this 'lactate paradox', instead suggesting that prolonged exposure (>6 weeks) results in similar blood lactate concentrations at sea level following hypoxia ~5,300m (van Hall et al., 2001) and ~5,400m (Lundby et al., 2000). What is difficult to ascertain is whether changes to metabolic responses of lactate occur similarly between moderate and high altitudes and between natural and simulated environments. However, the extent of these adaptations is yet to be fully investigated.

### 3.2. Hematological adaptations to altitude training

#### 3.2.1. Hemoglobin

A key reason why altitude training is considered a performance enhancing strategy, is the evidence supporting higher hemoglobin concentrations at altitude, as opposed to sea-level (Saunders et al., 2019). Hemoglobin is an iron containing protein molecule that is transported within RBC and is responsible for carrying the majority of oxygen within the blood (Otto et al., 2013). Total $Hb_{mass}$ is the absolute mass of hemoglobin which is circulated within the body (Otto et al., 2013). A range of studies within the literature support LHTL for inducing adaptations in both $tHb_{mass}$ and RCV, and improvements may range from ~2 to 5% (Ploszczyca et al., 2018; Clark et al., 2009; Rusko et al., 1999). As shown in Table 3, there is much heterogeneity among the studies examining how LHTL approaches to altitude training influence $tHb_{mass}$. However, (Garvican-Lewis et al., 2016) have previously presented several regression analyses that collate this outcome with the unifying kilometre hours metric. Through exponential modelling, these authors suggest that $tHb_{mass}$ may increase by 7.7% before plateauing, however, this would correspond to a hypoxic dose exceeding 2500 km h (Garvican-Lewis et al., 2016), which is well beyond the mean of interventions quantified in this review (~578 km h; Table 3). Whilst alterations in $tHb_{mass}$ are considered the premier adaptation because of hypoxic training, more research needs to focus on the practical translation of these findings for coaches and athletes.

#### 3.2.2. Erythropoietin

Another key hematological adaptation arising from altitude training is changes in EPO. This hormone is produced in the kidneys and assists with the formation of RBC by bone marrow (Turner et al., 2017). The major function of EPO is to promote the development of RBC and initiate the synthesis of hemoglobin which in turn promotes oxygen carrying capacity (Wentao, 2008). Interestingly, adaptations in EPO in response to altitude training may be evident within 48 h of exposure with improvements ranging from 8.0 to 37.5 mU/ml at 2,500m (Turner et al., 2017). An initial increase in EPO concentration is typically evident within the first few days but gradually decreases over time regardless of hypoxic dose. The rate of decline varies, however, may not depend on the protocol used, rather the hypoxic level i.e. below ~2000m (Ploszczyca et al., 2018).

If sufficient hypoxic exposure occurs, heightened EPO concentrations will result in increased reticulocyte development after ~4–7 days (Klausen et al., 1991). Reticulocytes are newly produced, immature RBC which develop into full sized mature RBC ~2 days after they form (Riley et al., 2001). These newly formed RBC then assist in oxygen delivery throughout the body. Increased reticulocyte production and iron supplementation has previously been reported following 3 weeks of LHTL (Friedmann et al., 1999), while (Mattila and Rusko, 1996) have also shown increased production in competitive cyclists following a hypoxic dose of 594 km h completed within 11 days. Comparatively, (Ashenden et al., 2000) have reported no elevations in reticulocyte production for endurance athletes following 2–3 weeks of simulated LHTL at ~2650 m (8–11 h·d-1), despite the commonly observed initial increase in EPO production, however, these authors speculate that this may have been attributed to an insufficient hypoxic dose duration.

## 4. Performance adaptations following LHTL

The LHTL method of altitude training has previously been used across a range of endurance based disciplines including distance running, swimming, cycling, triathlons, and in team-sport settings such as Australian rules football, soccer, and hockey (Sinex and Chapman, 2015; McLean et al., 2013). Among such athletes TT performance (Levine and Stray-Gundersen, 1997), increased $VO_{2MAX}$ (Schmitt et al., 2018), and heightened mean PPO (Bonetti et al., 2006) may be realised after completing a LHTL intervention. Previously, (Robertson et al.,

**Table 4**
Research findings relative to performance adaptations following altitude for LHTL.

| Study | Level | Sport | Altitude (m) | Duration (h) | Hypoxic dose (km/h) | Performance Parameters Measured | Key Results |
|---|---|---|---|---|---|---|---|
| Bejder et al., 2017 | Elite | Triathlon | 2500 3000 3500 | 112 112 112 | 280 336 392 | MPO, PPO, 2615 m TT | MPO no change PPO no change 2615 m TT no change |
| Bonetti et al., 2006 | Sub-Elite | Kayaking | 3600–6000 | 180 | 648–1080 | PPO, 500 m TT, RSA $VO_{2MAX}$, Peak La | ↑ PPO of 6.8% ↑ RSA of 8.3% |
| Bonetti et al., 2009 | Sub-Elite | Cycling Triathlon | 3600–6000 | 75 | 270–450 | PPO, RSA, $VO_{2MAX}$, Peak La, LPP, HRPP | ↑ PPO ↑ LPP ↑ HRPP |
| Carr et al., 2019 | Elite | Walking | 3000 | 196 | 588 | 5 × 2000m TT, La, $VO_{2MAX}$ | ↑ 5 × 2000m TT ↓ La $VO_{2MAX}$ no change |
| Clark et al., 2004 | Sub-Elite | Cycling Triathlon | 2650 | 480 480 - 576 | 1272 1272 - 1526 | $R_a$ | ↓ $R_a$ |
| Dehnert et al., 2002 | Sub-Elite | Triathlon | 1956 | 182 | 356 | $VO_{2MAX}$ | ↑ $VO_{2MAX}$ of 7.0% |
| Hahn et al., 2001 | Elite | Triathlon | 3000 | 184–253 | 552–759 | $VO_{2MAX}$, La | ↓ $VO_{2MAX}$ of 0.28% |
| Hamlin and Hellemans, 2007 | Sub-Elite | Multisport | 3400–5000 | 11.25–22.5 | 38.25–112.5 | 3000 m TT | ↑ TT performance of 2.3%, 2 days following hypoxic exposure and 2.2%, 17 days following hypoxic exposure. |
| Hinckson and Hopkins, 2005 | Sub-Elite | Running Triathlon | 2500–3500 | 200 | 500–700 | RUN-EXH | ↑ RUN-EXH of 1.6% (800m), 1.7% (1500m) and 1.8% (3000m) |
| Hinckson et al., 2005 | Sub-Elite | Running | 2500–3500 | 240–300 | 600–1050 | RUN-EXH | ↑ RUN-EXH of 16% |
| Hinckson et al., 2006 | Elite | Rowing | 3600–6000 | 19 | 68.5–114 | $VO_{2MAX}$, 500 m TT, 5000 m TT, La | ↓ 500 m TT mean power of 2.2% compared to control ↑ 5000 m TT mean power 0.6% compared to control ↑ La mean power 0.4% compared to control |
| Humberstone-Gough et al., 2013 | Elite | Triathlon | 3000 | 240 | 720 | $VO_{2MAX}$, RUN-EXH, TTE, La, Running Economy, 3 mM [La] | $VO_{2MAX}$ no change ↓La ↑ Running Economy of 2.8% ↑ 3 mM [La] of 4.4% |
| Julian et al., 2004 | Elite | Running | 3600–6000 | 11.75 | 42.25–58.75 | $VO_{2MAX}$, La, VE, 3000 m TT | ↓ 3000 m TT |
| Katayama et al., 2003 | Sub-Elite | Running | 4500 | 94.5 | 425.25 | $VO_{2MAX}$, $VCO_{2max}$, $V_{Emax}$, RER, $HR_{max}$ | $VO_{2MAX}$ no change $VCO_{2max}$ no change $V_{Emax}$ no change |
| Katayama et al., 2004b | Sub-Elite | Running | 4500 | 42 | 189 | 3000 m TT, $VO_{2peak}$, $VCO_{2peak}$, $V_{Epeak}$, RER, $HR_{peak}$ | ↓ $VO_{2peak}$ ↓ $HR_{peak}$ ↑ 3000 m TT |
| Levine and Stray-Gundersen, 1997 | Sub-elite | Running | 2500:1250 | 672 | 1680 | 5000 m TT | ↑ TT performance post altitude camp of 13.4s |
| Martin et al., 2002 | Elite | Cycling | 2650 | 96–120 | 254–318 | MMP | ↑ MMP of 2.3% for the 4-min test |
| Nummela and Rusko, 2000 | Elite | Running | 2200 | 160–170 | 352–374 | MART | ↑ 400m run performance |
| Park et al., 2019 | Sub-elite | Running | 3000 | 504 | 1512 | 3000 m TT | ↑ TT performance of 2.7% |
| Robach et al., 2006 | Elite | Skiing | 2500 3000 3500 | 66 66 66 | 165 198 231 | $VO_{2MAX}$, $T_{exh}$ | ↓ $VO_{2MAX}$ of 3.7% $T_{exh}$ no change |
| Robach et al., 2018 | Elite | Skiing | 2207 | 416 | 918 | $VO_{2MAX}$, 3000 m TT | $VO_{2MAX}$ no change 3000 m TT no change |
| Roberts et al., 2003 | Sub-elite | Cycling | 2650 | 40–50 80–100 120 - 150 | 106–133 212–265 318 - 398 | MMP, MAOD $VO_{2MAX}$ | ↑ MMP ↑ MAOD ↑ $VO_{2MAX}$ |
| Robertson et al., 2010a | Elite | Swimming | 2600 | 360–400 | 936–1040 | 4 mM [La], 2000m TT (freestyle), or 1200 m TT (breaststroke) | ↑ 4 mM [La] 2000m TT small non-significant increases 1200 m TT small non-significant increases |
| Robertson et al., 2010b | Sub-Elite | Running | 3000 | 420 | 1260 | $VO_{2MAX}$, 4500 m TT | ↑ $VO_{2MAX}$ of ~ 2% |
| Rodriguez et al., 2007 | Sub-elite | Running Swimming | 4000–5500 | 60 | 240–330 | 3000 m TT, 100 m TT, 400 m TT, $VO_{2MAX}$, $VE_{max}$, $VO_2$ at VT | ↓ TT performance |
| Rusko et al., 1999 | ? | Skiing Triathlon | 2500 | 300–400 | 750–1000 | $VO_{2MAX}$ | ↑ $VO_{2MAX}$ of 3% |
| Saunders et al., 2009 | Elite | Running | 2860 | 415 | 1186 | $VO_{2MAX}$, VE, La | ↑ $VO_{2MAX}$ (trivial increase) |
| Saunders et al., 2010 | Elite | Walking | 3000 | 294 | 882 | $VO_{2peak}$, 10-min Walking Test | ↑ $VO_{2peak}$ |
| Schmitt et al., 2018 | Elite | Skiing | 2700 | 210 | 567 | $VO_{2MAX}$, $\dot{V}\,O_{2VT2}$, Roller-Ski Performance | ↑ $VO_{2MAX}$ ↑ $\dot{V}\,O_{2VT2}$ ↑ Roller-Ski Performance |
| Siebenmann et al., 2012 | Elite | Cycling | 2500–3000 | 448 | 1120–1344 | $VO_{2MAX}$, 2615 m TT | $VO_{2MAX}$ no change ↑ 2615 m TT of 2%, however not statistically significant. |
| Stray-Gundersen, 1994 | Sub-elite | Running | 2500:1250 | 672 | 1680 | 5000 m TT | ↑ TT performance post altitude from week 0 to week 10 of 1.19% |
| Stray-Gundersen et al., 2001 | Elite | Running | 2500:1250 | 648 | 1620 | 3000 m TT, $VO_{2MAX}$ | ↑ TT performance of 1.1% ↑ $VO_{2MAX}$ of 3.0% |
| Wehrlin et al., 2006 | Elite | Orienteering | 2456 | 432 | 1060 | 5000 m TT | ↑ TT performance of 1.6% |
| Witkowski et al., 2001 | Sub-elite | Running | 1780:1250 2085:1250 | 672 | 1196 1401 1649 1884 | 3000 m TT, $VO_{2MAX}$ | ↑ TT performance for the 2085m group of 2.8% and the 2454m group 2.7% |

(*continued on next page*)

**Table 4** (*continued*)

| Study | Level | Sport | Altitude (m) | Duration (h) | Hypoxic dose (km/h) | Performance Parameters Measured | Key Results |
|---|---|---|---|---|---|---|---|
| | | | 2454:1250<br>2805:1250 | | | | ↑ $VO_{2MAX}$ for the 2085m group, the 2454m group and the 2805m group |
| Wood et al., 2006 | Elite | Hockey Soccer | 3600–6000 | 9 | 32.5–54 | ISR, RSA | ↑ ISR ↑ RSA |
| Mean ± SD | | | 2903 ± 636 | 261 ± 206 | 687 ± 501 | | |

**Notes:** 3 mM [La] = running speed, $HR_{max}$ = maximum heart rate, $HR_{peak}$ = peak heart rate, HRPP = heart rate profile power, ISR = incremental shuttle run, La = lactate, LPP = lactate profile power, MAOD = maximal accumulated oxygen deficit, MART – maximal aerobic running test, MMP = maximal mean power, Peak La = peak lactate, PPO = peak power output, $R_a$ = rates of lactate appearance, RER = respiratory exchange ratio, RUN-EXH = run to exhaustion, RSA = repeated sprint ability, $T_{exh}$ = time to exhaustion, TT = time trial, $VCO_{2max}$ = maximum carbon dioxide output, $VCO_{2peak}$ = peak carbon dioxide output, VE = minute ventilation, $VE_{max}$ = maximal ventilation, $V_{Epeak}$ = peak minute ventilation, $VO_{2MAX}$ = maximum rate of oxygen consumption, $VO_{2peak}$ = peak oxygen uptake, $VO_2$ at VT = oxygen uptake at ventilatory threshold, $\dot{V}\ O_{2VT2}$ = second ventilatory threshold.

2010b) have suggested for such benefits, an intervention should comprise 2–3 weeks of exposure with >12 h·d-1, which corresponds to a hypoxic dosage of 1260 km h. As with the methodologies surrounding changes in physiology, considerably heterogeneity between studies exists. Table 4 provides a summary of key findings and intervention characteristics used within LHTL models. Here, the mean altitude range and duration used within the literature examining the effects of altitude exposure on physiology was ~2903m and ~261 h of total exposure. Using the combined kilometre hours metric proposed by (Garvican-Lewis et al., 2016), the mean hypoxic dose was ~687 km h (Table 4).

### 4.1. Performance effects

For TT there are a range of running, swimming, and cycling based assessments. Among running based TT performances, several studies (Levine and Stray-Gundersen, 1997; Park et al., 2019; Stray-Gundersen, 1994; Stray-Gundersen et al., 2001) have shown significant benefits from undertaking a LHTL training protocol. The intervention from these studies ranged from 1620 to 1680 km h. This contrasts with (Julian et al., 2004; Rodriguez et al., 2007) who did not identify improvements with the intervention in these studies ranging from 42.25 to 330 km h. For swimming based TT performances, (Robertson et al., 2010a) recorded a small increase in TT performance with an intervention range of 936–1040 km h. For cycling based TT performances, studies (Bonetti et al., 2009; Siebenmann et al., 2012) demonstrated marginal improvements with the intervention in these studies ranging from 270 to 1344 km h.

Studies (Dehnert et al., 2002; Robertson et al., 2010b; Rusko et al., 1999; Schmitt et al., 2018; Stray-Gundersen et al., 2001; Witkowski et al., 2001) have shown significant benefits for $VO_{2MAX}$ utilising LHTL training protocols. The intervention from these studies ranged from 356 to 1884 km h. This contrasts with studies (Humberstone-Gough et al., 2013; Robach et al., 2006, 2018; Hahn et al., 2001; Katayama et al., 2003; Carr et al., 2019) who did not identify improvements in $VO_{2MAX}$. The intervention from these studies ranged from 165 to 918 km h. For PPO, studies (Bonetti et al., 2006, 2009) reported significant benefits from undertaking a LHTL training protocol, with the intervention of these studies ranging from 270 to 1080 km h.

### 4.2. Considerations for future research

It appears likely that LHTL does induce performance improvements that may be considered beneficial to most athletes (Wehrlin et al., 2006). A previous meta-analysis (Bonetti and Hopkins, 2009), reported that natural LHTL provides the best protocol for enhancing endurance performance for elite athletes, as a result of the performance inducing physiological adaptations that LHTL provides, however, simulated altitude has also been proven to be effective. Despite the likely benefits of altitude training for exercise performance, this is not without drawbacks. Specifically, when managing athletes, logistical issues may arise which require the development and use of hypobaric chambers, hypoxic tents and breathing apparatus to induce hypoxia (Seifert et al., 2016). When examining normobaric LHTL studies, results are ambiguous with positive outcomes being less frequent (Bonetti and Hopkins, 2009).

What has become problematic with the LHTL protocol, is that limited studies include testing protocols mid exposure. Rather, testing is usually completed post exposure (1–28 days) to determine whether performance improvements are evident (Robertson et al., 2010c). The longer the post exposure testing occurs, the greater the likelihood of decaying effects being present. Testing mid procedure would provide valuable data regarding any improvements up to that point and should be considered in future research. Introducing early and mid-exposure testing would also be of practical importance to coaches especially if it is evident that the protocol is not eliciting the desired effects. In this instance, athletes (non-responders), could be moved elsewhere or use another modality e.g., heat acclimation. Furthermore, several hypobaric LHTL studies have been conducted without the use of control groups reflecting the observational (non-experimental) design of the majority of studies in this area (Bejder and Nordsborg, 2018). As a result it cannot accurately be ascertained whether improved performance was as a result of the hypoxic exposure or simply the training camp effects (Bejder and Nordsborg, 2018).

Additionally, a concern of altitude training studies that needs to be addressed is the post-altitude decay. Studies examined within this paper failed to incorporate appropriate protocols regarding the optimal timing of returning to sea level before competing. This is significant because following an altitude training protocol, if the decay begins too quickly and the timeframe between completion of altitude training and competition is too long, then by the time athletes compete they would have lost some or if not all positive benefits of the hypoxic protocol. It is important for athletic stakeholders to acknowledge that individual rates of decay may vary in hematological, biomechanical and ventilatory adaptations upon returning to sea level. It is important for researchers to be aware of this because the degree of decay may negate any positive physiological benefits derived from future altitude training studies.

Finally, a limitation of this study and something that future researchers need to consider is that numerous confounding factors are present such as the performance levels of subjects, prior experience to LHTL protocols, training intensity, duration, and volume within hypoxic environments which prevented direct comparison of the reviewed papers.

## 5. Conclusion

Small variances in physiological adaptations are likely to alter sports performance outcomes. This review has appraised the literature examining physiological and performance adaptations that may arise from a LHTL altitude training intervention. This approach is likely to induce several prominent non-hematological (respiratory, cardiorespiratory neurophysiology, skeletal muscle, and lactate metabolism) and

hematological (hemoglobin and EPO) adaptations. Pulmonary perfusion is also improved as the respiratory system and associated neuromuscular anatomy adapt to exposure. When hypoxic exposure is sufficient and prolonged, $tHb_{mass}$, RET and EPO elevate and collectively increase systemic oxygen carrying capacity (Viscor et al., 2018; Chapman et al., 1998b). In turn, enhanced physiology is thought to positively improve exercise performance, and within LHTL based approaches, athletes are likely to experience enhanced $tHb_{mass}$, EPO, sTfR resulting in improved $VO_{2MAX}$ and TT performance. However, coaches and athletic stakeholders should also be mindful of acute and chronic hypoxic responses, as these have the potential to negatively influence exercise performance. This review found that the most common hypoxic dose used by studies to elicit physiological and performance benefits ranges from ~578–687 km h. Though more research is required to investigate these ranges, athletic stakeholders should consider this when planning within an evidence-based range for altitude interventions. Collectively, there are potential advantages to using altitude training to enhance physiology and improve performance for endurance athletes.

## CRediT authorship contribution statement

**G. Bonato:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Goodman S.P.J:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Lathlean Tjh:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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