



Contemporary Periodization of Altitude Training for Elite Endurance Athletes: A Narrative Review

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Abstract

Since the 1960s there has been an escalation in the purposeful utilization of altitude to enhance endurance athletic performance. This has been mirrored by a parallel intensification in research pursuits to elucidate hypoxia-induced adaptive mechanisms and substantiate optimal altitude protocols (e.g., hypoxic dose, duration, timing, and confounding factors such as training load periodization, health status, individual response, and nutritional considerations). The majority of the research and the field-based rationale for altitude has focused on hematological outcomes, where hypoxia causes an increased erythropoietic response resulting in augmented hemoglobin mass. Hypoxia-induced non-hematological adaptations, such as mitochondrial gene expression and enhanced muscle buffering capacity may also impact athletic performance, but research in elite endurance athletes is limited. However, despite significant scientific progress in our understanding of hypobaric hypoxia (natural altitude) and normobaric hypoxia (simulated altitude), elite endurance athletes and coaches still tend to be trailblazers at the coal face of cutting-edge altitude application to optimize individual performance, and they already implement novel altitude training interventions and progressive periodization and monitoring approaches. Published and field-based data strongly suggest that altitude training in elite endurance athletes should follow a long- and short-term periodized approach, integrating exercise training and recovery manipulation, performance peaking, adaptation monitoring, nutritional approaches, and the use of normobaric hypoxia in conjunction with terrestrial altitude. Future research should focus on the long-term effects of accumulated altitude training through repeated exposures, the interactions between altitude and other components of a periodized approach to elite athletic preparation, and the time course of non-hematological hypoxic adaptation and de-adaptation, and the potential differences in exercise-induced altitude adaptations between different modes of exercise.

Key Points

A long- and short-term periodized approach to altitude training seems to be necessary for elite endurance athletes to obtain maximal benefit from the hypoxic stimulus.

Detailed longitudinal monitoring of an athlete's physical and perceptual responses to training is required before, during, and after an altitude sojourn to maximize the benefits of altitude training and minimize the risk of maladaptation.

Other confounding interventions may need strategic periodization in combination with altitude training, such as nutrition, the combined use of terrestrial altitude and normobaric hypoxia, and/or heat adaptation.

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1 Introduction

Elite endurance athletes have been using low to moderate altitude (i.e., between ~ 1400 and 2500 m, with 2000–2500 m appearing optimal [1]) training for decades in an attempt to enhance both their altitude and sea-level performance [2–5]. Whether athletes choose to live high–train high (LHTH) or live high–train low (LHTL), the physiological rationale for altitude training is that the reduced barometric and partial pressure of oxygen results in lowered oxygen availability causing the signaling of hypoxia-inducible factor-1 α (HIF-1 α), which then causes an increased erythropoietic response [6] and increased hemoglobin mass (Hb_{mass}) [7–9]. However, there are also hypoxia-induced non-hematological changes, such as mitochondrial gene expression and enhanced muscle buffering capacity [10]. Combined hematological and non-hematological responses can result in increased maximal oxygen uptake ($\dot{V}O_{2max}$) and/or competition performance at sea level [11], although conflicting views still remain, particularly with regards to LHTL [12, 13]. Several factors impact upon altitude adaptation, such as the duration and degree of hypoxic exposure, absolute and relative intensity of training and its distribution, iron availability, injury/illness status, and inter-individual variability [14–21]. Both female and male elite athletes often show progressive increments in Hb_{mass} at increasing altitudes from 1360 to 2100 and 2320 m [22–24]. Conversely, illness and/or injury could inhibit altitude adaptations [22, 25–27] and the stress of altitude training may increase the risk of illness [28]. Therefore, poorly planned training programs may sometimes result in deleterious outcomes, such as underperformance, excessive fatigue, overtraining, illness, and/or injury [21, 29].

Thus, it is essential to meticulously plan and periodize altitude training camps by adequately designing and controlling training loads, and continuously monitoring an individual athlete's adaptation and health status [30]. For many athletes and coaches, periodization has traditionally focused on just the exercise training aspect of an athlete's preparation, while often neglecting the integration of other elements. Recently Mujika et al. [29] reviewed the scientific bases underpinning integrated periodization at sea level, featuring multiple periodization facets beyond just training loads. However, despite many previous reviews eloquently describing the physiological adaptations to hypoxia/altitude [10, 15–17, 31–35], there has not been a contemporary update on the various periodization and monitoring aspects of altitude training in elite endurance athletes. Therefore, the aim of this article is to review the available evidence underpinning the periodization of altitude training for elite endurance athletes, adopting an

integrated periodization approach and including coaching aspects of training load and recovery manipulation, athlete monitoring, and nutritional and other environmental stressor considerations. Whenever possible, evidence-based recommendations are made, but in some instances the authors also draw upon their extensive practical experiences over many years of working with elite endurance athletes at altitude. Finally, various gaps in the literature are highlighted to stimulate future scientific exploration.

2 Planning and Periodization of Altitude Training in Elite Endurance Athletes

Periodizing training programs for elite endurance athletes to fulfil maximal performance potential at the right time is a complex challenge [36]. Long-term career paths are ideally planned to peak at the end of a quadrennial period culminating with the Olympic or Paralympic Games. In the short-term, peak performances are usually attained by a periodized approach that skillfully intertwines lengthy phases of intensive training and shorter phases of reduced training [29]. It is the authors' contention that a long- to short-term periodized approach that integrates exercise training and other lifestyle, nutritional, and environmental stressors should also apply to altitude training for elite endurance athletes.

2.1 Long-Term Planning of Altitude Training: The Value of Repeated Exposures

Multi-year planning of annual altitude exposures over an athlete's career may be a sound strategy to maximize the benefits of altitude training (Table 1). Indeed, repeated intermittent exposures to high-altitudes (3–4 days at 3500 m followed by 3–4 days at sea level) in Chilean soldiers over a 22-year period induced Hb_{mass} values 11% higher than native lowlanders [37]. Moreover, elite Australian swimmers showed a linear increase of ~ 10% in Hb_{mass} over a 4-year period encompassing eight altitude training camps [38]. Short-term (3 weeks) relative retention of acclimatized high-altitude (5260 m) exercise performance occurs in healthy lowlanders upon re-ascent after de-acclimatizing at low altitude [39]. Furthermore, plasma adenosine levels are rapidly increased by initial ascent to high altitude, attaining even higher levels upon re-ascent, a feature that is positively associated with quicker acclimatization [40]. In other words, erythrocytes possess a 'hypoxic memory' that could facilitate faster hypoxic acclimatization when participants have previous altitude exposures [40]. In addition, a short-duration sojourn at moderate natural altitude (2220 m) is a very effective pre-acclimatization strategy for subsequent higher-altitude exposure (4300 m) in comparison with a direct ascent [41–44]. Although some of these findings were

Table 1 Long-term planning of altitude training for an Olympic and World Champion female swimmer. Over an 8-year period, this athlete utilized altitude training over a total of 120 weeks (34 separate camps, with 18 of the camps 4 weeks in duration; ~29% of total training time)

Season	Weeks of Training																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
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Altitude training camps: Sierra Nevada, Spain (2320 m); Font Romeu, France (1850 m); Pretoria, South Africa (1360 m)

EC European Championships, OG Olympic Games, QT qualification trials, WC World Championships

not obtained in elite athletes, they do suggest that repeated altitude exposures over time could be an adequate strategy for an elite athlete to maximally benefit from altitude training. This approach allows repeating the stimulus for Hb_{mass} increases and non-hematological training adaptations, while decreasing the negative effects of altitude ascents due to faster acclimatization via ‘hypoxic memory’, which together result in minimal chances of ‘non-responding’. In fact, based on the authors’ own extensive experience with elite endurance athletes training at altitude, we would contend that there is no such thing as a non-responding athlete to altitude training camps. Instead, ‘non-responder’ athletes are probably a product of ‘one-off’ camps and/or inadequate planning, periodization, programming, and monitoring of altitude training. Indeed, several altitude training studies have used single exposures in non-acclimatized altitude novices [14, 45, 46], whereas elite endurance athletes typically utilize altitude training multiple times throughout a season in preparation for competition [5, 47]. In keeping with this suggestion, multiple altitude training camps (> 60 days/year) were an integral part of the world’s most successful female

cross-country skier of all time, but whether altitude training per se or training periodization in connection with altitude camps were the main drivers of the observed progress could not be determined [5]. The systematic altitude training approach of several of the top well-funded American endurance running groups (e.g., Bowerman Track Club, Nike Oregon Project) and British Athletics’ endurance running program feature three to six altitude camps per year [48].

Table 1 shows the long-term planning of altitude training for an Olympic and World Champion female swimmer, with a total of 34 altitude training camps over the last eight seasons (three to five camps per year of 3–4 weeks’ duration each). Table 2 shows the performance progression of an Olympic Champion race walker at altitude over a 4-year Olympic cycle. Although the long-term effects of accumulated altitude training through repeated exposures have not been systematically described, physiological evidence suggests that repeated exposure over the long-term may be necessary for some athletes to fully draw the potential benefit of living and training at altitude [49]. The capacity to train at a higher altitude level, achieved through repeated

Table 2 Race performance at altitude and sea level in an Olympic Champion male racewalker. The athlete engaged in a program of repeated altitude exposures over this period (40–60 days annually in 2- to 6-week blocks) and achieved a ~5% improvement in performance at altitude (completing the same race at ~1400 m elevation annually). Moreover, the athlete improved his 50 km personal best by

1.2% over this period, potentially the difference between achieving a silver medal at the 2008 Olympics and gold in 2012. The capacity to train at a higher level at altitude, achieved through repeated exposures, would likely be an important contributor to this overall improvement

Year	Chihuahua (1400 m) race time (h:mm:ss)	Post-Chihuahua sea-level race time (h:mm:ss)	50 km PB	Result
2008	1:25:40	1:20:11	3:39:27	Olympic Silver
2009	1:23:44	1:21:11	3:38:56	
2010			3:38:56	
2011	1:23:25	1:19:57	3:38:56	
2012	1:21:50	1:20:34	3:36:53	Olympic Gold
Improvement from 2008 to 2012 (%)	4.5	– 0.5	1.2	

PB personal best

exposures, would likely be an important contributor to an overall altitude-induced improvement.

2.2 Seasonal Periodization of Altitude Training for Elite Endurance Athletes

The periodization of altitude training within the year (or sports season) is a factor that needs to be carefully planned. Saunders et al. [31, 38] advised that endurance athletes should tailor altitude training to emphasize the training goals of the macrocycle. For example, an athlete attending an altitude camp in the general preparation phase, when training intensity is not critical, can focus on high training volumes at low-to-moderate intensities and capitalize on the hematological effects of the hypoxic stimulus [31]. An elite female cross-country skier spent 61 ± 9 days at altitude per year, mainly distributed across five altitude camps of 10–16 days' duration. Altitude training accounted for 18–25% of annual training volume [5]. Whilst 1- to 2-week camps are shorter than the 3–4 weeks typically recommended, their repeated use interspersed with similar duration stints at sea level for training and/or competition may be used by athletes to enhance sea-level performance, with improvements of $\sim 2\%$ being reported in elite endurance athletes [2, 49]. Such a strategy may allow athletes to achieve the higher overall dose of altitude exposure required to stimulate erythropoiesis and increase Hb_{mass} , whilst balancing the need to spend time at sea level to maximize training quality, and eliminate fatigue associated with prolonged periods at altitude. Athletes restricted to low-altitude (< 2000 m) training venues may find such a strategy particularly relevant; in elite 400 and 800 m runners, Hb_{mass} increased significantly by 5.1% after two 3-week camps at 1300 and 1650 m, interspersed

by 3 weeks at sea level, with non-significant changes in Hb_{mass} reported after each individual camp [50]. Additionally, beneficial effects on work economy, muscle buffering capacity and ventilation [32] appear to be temporally shorter adaptations and may be achieved within this time-frame [51].

Performing regular natural altitude training camps has been recommended as part of a season-long training program for swimmers [22], which fits with both published data [5, 49, 50] and our own observations of elite athletes over many years (Fig. 1).

Saunders et al. [31, 38] recommended that multiple altitude exposures within a season should be interspersed by prolonged periods longer than 8 weeks at sea level to capitalize on increased capacities gained at altitude and ensure that athletes are recovered and motivated for subsequent altitude camps. However, this suggestion is not always followed by elite endurance athletes, who sometimes undertake repeated altitude camps with only 1–3 weeks in between, most often moving from a lower-altitude venue (e.g., 1850 m) to a higher one (e.g., 2320 m; see Table 1 and Fig. 1). Some elite endurance athletes will also use normobaric hypoxia (NH) at sea level (simulated altitude) between sojourns to natural-altitude camps (see Sect. 4.3). Interestingly, this approach seems to be supported by high-altitude acclimatization studies (> 4000 m), indicating that the persistence of altitude acclimatization after return to low altitude is proportional to the degree of prior acclimatization, and that subsequent ascent to high altitude should be scheduled as soon as possible after the last altitude pre-exposure [42]. More investigation is needed on the magnitude and decay kinetics of adaptations induced by multiple altitude exposures in elite endurance athletes.

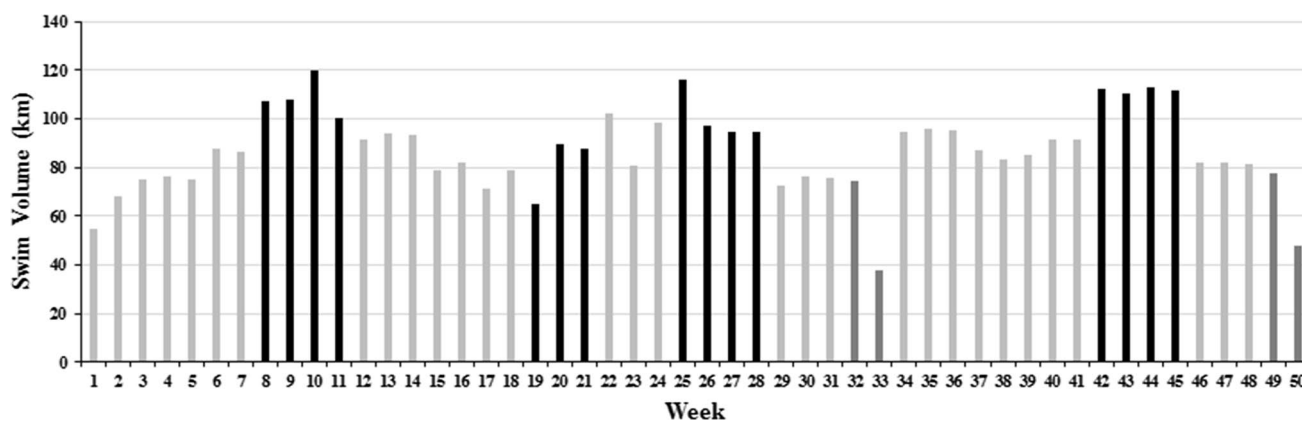


Fig. 1 Swim training volume of an Olympic and World Champion female swimmer during an entire season leading to the London 2012 Olympic Games. Light-grey bars are training weeks at sea level; black bars are training weeks at altitude (2320 m, except for weeks 19–21 at 1360 m); dark-grey bars correspond to the most important

competitions of the season (Olympic qualification championship, weeks 32–33; Olympic Games, weeks 49–50). Most weeks spent at altitude were characterized by very high swimming volumes (e.g., 9 weeks exceeding 100 km/week), and the highest weekly volumes of the season were repeatedly performed at an altitude of 2320 m

2.3 Programming of Altitude Training Camps for Elite Endurance Athletes

Specific training programs during altitude camps should be adapted to the training phase and the individual goals of each athlete in relation with their competition schedule. A generalized 4-week training camp approach for volume, intensity, and rest duration considerations for middle- to long-distance athletes is outlined in Table 3. It should be emphasized that the total volume and intensity of sustainable training will also be very sport- and athlete-specific based on historical altitude experiences. For example, runners can tolerate much less volume (maximally 12–14 h/week) due to the high neuromuscular demands of running (i.e., weight bearing, eccentric component) compared to weight-supported sports such

as cycling or swimming. Accordingly, runners may have many fewer accumulated hours of exercise-induced blood desaturation, a key driver of erythropoietin release [52], than other sports characterized by higher training volumes. In cross-country skiing, variable weekly training volumes of 20–22 h are reported, depending on the seasonal training phase. Interestingly, total training volume was typically 35% higher during the 2-week altitude camps than in the 2 weeks before and after the camps. The increase in training volume while at altitude was mainly achieved through increased frequency of long (≥ 2.5 h) low-intensity training sessions, and despite a reduction in strength training [5]. A similar pattern of increased training load at altitude has also been observed in elite Australian runners [53, 54], with the authors noting this was preceded by a period of lower-volume training

Table 3 Modifications to training at altitude for elite middle- to long-distance athletes undertaking a 4-week camp at moderate altitude with considerations for lower-altitude training

Week	Overall volume	Intensity	Rest during intervals
Week pre-altitude at sea level	↓ compared to normal—‘mini-taper’ to reduce fatigue prior to camp [53, 54]	Normal	Normal
Week 1	<i>Initial athlete altitude sojourn/conservative approach:</i> first 2–3 days—25% ↓ from full sea-level volume Can ↑ frequency from normal (e.g., longer session split into 2 shorter sessions) Last 4 days = normal <i>Altitude-experienced athletes:</i> emerging data suggest elite athletes can tolerate high training volumes upon immediate ascent to altitude [5, 53, 54]	Predominantly low intensity, aiming for [BLa] at or below lactate threshold (LT2) [60] Alactic work < 30 s with > 2 min rest Elite athletes frequently using altitude generally complete threshold or $\dot{V}O_{2\max}$ workouts at a ↓ speed/intensity (↓ volume and ↑ recovery as specified) [2, 47, 58, 74] When possible, it may be advantageous to do higher-intensity training at lower altitudes (LHTL)	Rest during intervals increase 50–100% [47]
Week 2	Normal–high May be increased beyond preceding volumes completed at sea level [5, 53, 58]	<i>Initial athlete altitude sojourn/conservative approach:</i> Predominantly low intensity, aiming for [BLa] at or below lactate threshold (LT2) [60] <i>Altitude experienced athletes:</i> emerging data suggest elite athletes can tolerate higher training intensities [53] Threshold or $\dot{V}O_{2\max}$ workouts can reach full volume and normal frequency for athletes habituated to altitude Longest interval at race pace: 60–90 s for 800 m 2–3 min for 1500 m When possible, it may be advantageous to do higher-intensity training at lower altitudes (LHTL)	Rest during intervals can start to shorten from 150 to 200% of sea-level rest toward 125–150%
Week 3	Normal–high ↓ volume final 2–4 days depending on timing of competition post-altitude	Training intensity at normal levels [47] Longest interval for distance at or close to race pace: 2 min for 800 m 4 min for 1500 m When possible, it may be advantageous to do higher-intensity training at lower altitudes (LHTL)	Rest still 25–50% longer than normal
Week 4	↓ volume final 2–4 days depending on timing of competition post-altitude	Race-pace sessions prioritized leading into competition When possible, it may be advantageous to do higher-intensity training at lower altitudes (LHTL)	Rest still 25–50% longer than normal

[BLa] blood lactate concentration, LT2 lactate threshold at onset of blood lactate accumulation, LHTL live high–train low, $\dot{V}O_{2\max}$ maximal oxygen uptake, ↓ indicates decrease, ↑ indicates increase

at sea level and that athletes were simply returning to full training volumes to which they were accustomed. Training adjustments during altitude camps and higher training volumes at altitude than during usual sea-level training can be observed in Table 3 and Fig. 1, respectively.

During the pre-competitive and competitive period, some coaches and athletes choose to perform their low- and moderate-intensity training at altitude but complete high-intensity sessions at lower altitude, as supported by the LHTL concept (Table 3) [45]. For instance, seven elite middle-distance runners lived at 1800 m, did all their low- to moderate-intensity running at 1700–2200 m, but completed all high-intensity sessions at 900 m to maintain the 800 and 1500 m race pace interval training required to maintain race fitness. This strategy resulted in improved competitive performance by 1.9% [49]. Some of the most popular altitude training locations in the world feature the possibility, within a ~ 1 h drive, to also carry out selected high-intensity training sessions closer to sea level (e.g., Flagstaff, AZ, USA; St. Moritz, Switzerland; Sierra Nevada, Spain). The hypoxic conditions encountered at altitude may indirectly impose a more polarized training intensity distribution, with a strong focus on low-intensity, long-duration training, in combination with fewer high-intensity training bouts [21]. Interestingly, such training intensity distribution is widely considered best practice to optimize adaptations and performance in elite endurance athletes [55, 56]. Indeed, a recent study observing elite cross-country and Nordic skiers completing a LHTL regimen reported performance improvements in athletes undertaking polarized training (82% low intensity and 12% strength/speed) compared with those completing a pyramidal (51/39%) training distribution [57].

In contrast to the LHTL concept, many elite endurance athletes currently continue to use ‘classic’ altitude training, where living and training occur at the same moderate altitude > 1800 m, with successful results [2, 5, 23, 58]. As previously alluded to, the capacity of elite endurance athletes to perform at altitude is likely increased through repeated exposures, thus allowing them to adequately maintain training intensity without the need to descend to lower altitude, a strategy that may be of benefit in increasing the physiological stress associated with training. Data from highly trained runners ($\dot{V}O_{2\max} > 70$ mL/min/kg) suggest there is little physiological difference in completing middle-distance race pace training (110% of velocity eliciting $\dot{V}O_{2\max}$) at 600, 1400, or 2100 m simulated altitude, but higher rates of oxygen flux were observed at the lower altitudes than at 2100 m for threshold and $\dot{V}O_{2\max}$ sessions [59]. The authors therefore recommended that endurance athletes completing altitude training prioritize descent to lower altitudes for $\dot{V}O_{2\max}$ sessions, whilst remaining at moderate altitude for race pace training, potentially taking advantage of the additional anaerobic load this would confer. Indeed, elite Australian runners adopting this LHTLH demonstrated performance improvements of ~ 1 to 2% in competition [53, 54].

Several case studies of elite endurance athletes [2, 53, 58] have specified the absence of a period of low-intensity training during the first 7–10 days of altitude acclimatization typically recommended [32, 60]. Instead, high-intensity training is observed within the days following ascent to altitude (Table 4). Elite Australian runners with several years of altitude training experience completed a threshold intensity session on day 2 and some short race pace efforts on day 4 of their altitude camp [53]. As previously discussed,

Table 4 Altitude training microcycle during a pre-competitive phase (final camp prior to the Rio 2016 Olympic Games) for an Olympic and World Champion female swimmer. The main focus of each session is given in parentheses, followed by each session’s total swimming distance. Note that the total training volume was 85,300 m in addition to 3.75 h running and cycling and 7.5 h strength training and

dryland conditioning, and that swim training times were adjusted to facilitate adaptation to the competition schedule in Rio 2016. All the swim sessions were performed at 2320 m, but some of the running and dryland conditioning sessions were purposely carried out at altitudes of 3000–3300 m to create even more hypoxic stress

Start time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
11:00	Strength training; 90 min	Running; 45 min	Strength training; 90 min	Running; 45 min	Strength training; 90 min	Running; 45 min	Physiotherapy
13:00	Swimming (speed + Aero 1); 8500 m	Swimming (speed + power); 5500 m	Swimming (speed + Aero 2); 8400 m	Swimming (speed + power); 5500 m	Swimming (speed + Aero 1); 8500 m	Swimming (race pace); 8700 m	
18:30	Indoor cycling; 45 min	Circuit training (Crossfit); 90 min		Circuit training (Crossfit); 90 min	Indoor cycling; 45 min		
20:30	Swimming (Aero 2 + threshold); 8800 m	Swimming (threshold); 9000 m		Swimming ($\dot{V}O_{2\max}$); 8800 m	Swimming (progressive to threshold); 8600 m		Swimming (speed + Aero 2); 5000 m
11:00		CWT		CWT		CWT	

CWT contrast water therapy, $\dot{V}O_{2\max}$ maximal oxygen uptake

elite athletes habituated to frequent altitude exposures may experience a more rapid acclimatization [32], allowing them to recommence high intensity at altitude within a few days. Such a strategy may be advantageous during the repeated short-duration altitude camps (1–2 weeks) used by some elite endurance athletes [2, 5, 49]; given the importance of maintaining training intensity and oxygen flux at altitude to stimulate adaptation [61], spending a disproportionate amount of a camp training at a reduced intensity can be detrimental, particularly if altitude is used during the competition phase of a season.

2.4 Altitude Training and Performance Peaking

One of the key issues for coaches and athletes attending altitude camps is the ideal timing of return from altitude prior to competition. Wachsmuth et al. [22] determined that Hb_{mass} , health status (illness and injury) and time after return from altitude had significant effects on swim competition performance after altitude training. On average, 47% of the Hb_{mass} gained in a 3- to 4-week camp was lost after 24 days, and although Hb_{mass} is positively related to $\dot{V}O_{2max}$ [62, 63], it had only a small positive effect on swimming performance, which increased only 25–35 days after return from altitude [22]. Based on these observations, it was recommended to schedule return from altitude training camps 3–5 weeks before important swimming competitions [22]. A period of reduced training is often prescribed prior to competing after altitude training, which constitutes a form of tapering (Table 3). Unfortunately, the extent of the benefit and the variation between individuals has not been adequately explored [64]. After reviewing the available recommendations of top coaches and applied sports scientists, Chapman et al. [65] concluded that the best time to return from altitude training prior to a major competition remains undocumented from a physiological standpoint, and that each athlete may display their own unique ‘signature’ of de-acclimatization with return to sea-level residence. Knowledge of personal decay rates may allow for individualized prescriptions of when it is best to compete after an altitude camp [65]. However, individual complexities in post-altitude camp performance hinge on many factors including acute and chronic fatigue states from the camp itself, the phase of the training, travel/jetlag to the event, and the time course of decay of Hb_{mass} : although the typical erythrocyte lifespan of red blood cells is 90–120 days, the active destruction of newly formed red blood cells, a phenomenon known as neocytolysis [66], does induce some apoptosis within 5–7 days after returning to sea level [67]. In addition, the time course of decay of non-hematological adaptations is relatively unknown.

Some elite endurance athletes are known to achieve outstanding performances at various timepoints upon return to sea level after altitude training. As can be seen in Table 1,

an Olympic Champion swimmer chose to participate in the main events of the season at variable times after altitude training camps over the years, including the day after return, and 1, 2, 3, and 4 weeks upon descent to sea level. An Olympic Champion cross-country skier held her final 12-day altitude camp 20–8 days before the first championship event, then continued training at the championship elevation during the week prior to the event [5]. Despite these complexities and individual variability, experts and practitioners often suggest that there might be an immediate sea-level performance window (first few days) upon returning from an altitude sojourn, followed by a second window (> 3 weeks post-altitude) when optimal performances might be best realized [65]. Supporting this notion, Sharma et al. [54], tracked the performances of 17 national-level and elite runners competing at sea level for up to 11 weeks following altitude training and found no effect of weeks post-altitude on performance. Season’s best performances were achieved both within the immediate post-altitude window and after a number of weeks post-altitude. Moreover, 60% of athletes competing between 3 and 14 days post-altitude, a window previously identified as suboptimal for competition [32, 65], achieved improvements on their pre-altitude race time. The authors contended the timing of a peak performance following altitude training is likely to be influenced by a combination of altitude acclimatization and de-acclimatization responses (hematological and non-hematological), but, more importantly, also by periodization of and responses to training and tapering conducted at altitude and immediately following. More research is obviously required on the optimal timing of post-altitude performance peaking, and an individualized approach may still be required even when such research becomes available.

3 Monitoring Adaptation during Altitude Training

To enhance the possible benefits of altitude training or exposure, it is paramount that an effective monitoring system is in place to assess fitness and fatigue responses to training, given that the additional stress imposed by the hypoxic environment may lead to an increased risk of illness, maladaptation, or overtraining [19, 31, 47, 68–71]. Detailed longitudinal monitoring of an athlete’s physical and perceptual responses to training is required: (1) in the lead-up period to ensure an appropriate physical condition to maximize the benefits of altitude training; (2) at altitude to minimize the risk of maladaptation and non-functional overreaching/overtraining; and (3) post-altitude, as training quality may be higher as a result of adaptations conferred from altitude, and optimal loads during this period are critical. A recent study described subjective and objective measures to monitor elite runners during 21 days of

altitude training [30]. The training load of the subsequent training session was reduced if two or more of the 11 measured variables (e.g., resting peripheral oxygen saturation and heart rate, body mass, body and sleep perception) were outside the athlete's normal individual range. Participants' running speed at lactate threshold improved and no athlete showed any signs of a maladaptive response [30]. Therefore, a multifaceted approach may have been effective in modulating training as required under conditions of additional physiological stress. Table 5 provides a summary of monitoring tools that may be used at altitude.

3.1 External and Internal Load Monitoring

Concurrent monitoring of internal and external training loads can be effective in determining an individual response to hypoxia (Table 5). The external training load is an objective measure of the work an athlete completes in training (e.g., distance completed, total elevation gain, or running speed). Alternatively, the internal workload assesses the biological stress imposed by the training session and is typically defined by the disturbance in homeostasis of physiological and metabolic processes [72].

Table 5 Altitude training monitoring tools

Factors affecting adaptation and performance	Monitoring tools	Rationale and interpretation	Priority
Training intensity	External intensity metrics: stopwatches, power meters, GPS devices, direct observation and timing of training Internal intensity metrics: heart rate monitors, RPE, blood lactate concentration	Reduction in absolute training intensity results in reduced oxygen flux and potential loss of adaptation Relative intensity of training is increased at altitude compared to sea level, potentially increasing the risk of maladaptation and non-functional overreaching/overtraining	Essential
Training volume	External volume metrics: training volume, time in zones	Choice of training structure may affect adaptation and performance following altitude exposure	Essential
Iron status	Iron profile blood test pre-altitude	Heavily influential in ensuring an optimal erythropoietic response	Essential
Hemoglobin mass response	CO rebreathing test	Related to performance improvement, particularly during longer endurance events	Important
SpO ₂	Pulse oximeters	Level of desaturation at rest indicates sensitivity to a certain degree of hypoxia, and may be used to individualize the dose of altitude administered Pre-screening of SpO ₂ during maximal exercise at sea level may help determine which athletes are more susceptible to performance decline at altitude Gradual increases in resting SpO ₂ over several days/weeks upon arrival to altitude can be an indicator of healthy hypoxic adaptation	Important
Athlete wellness, fatigue, recovery	Perceptual questionnaires, e.g., sleep quantity and quality, health, fatigue, recovery	Ensure athletes remain in an adaptive state and are able to meet the demands of training	Essential
	Objective measures:		
	Body mass		Essential
	Body composition (i.e., skinfolds)		Important
	Resting heart rate		Important
	HRV		Optional
Illness	USG	Illness during altitude exposure may compromise both adaptive and performance responses	Optional
	Urea, CK		Optional
	Glutamine, cortisol, testosterone		Optional

CK creatine kinase, CO carbon monoxide, GPS global positioning system, HRV heart rate variability, RPE rating of perceived exertion, SpO₂ peripheral oxygen saturation, USG urinary specific gravity

Submaximal and maximal training intensity is compromised at altitude due to the lower oxygen availability [31, 73, 74], but some individual athletes are more affected than others [18, 61]. For instance, running speed was impaired by 6% in elite runners training at 2100 m, but individual impairments of 10% or greater were observed in some athletes. Lactate threshold and $\dot{V}O_{2\max}$ intensity sessions were impaired the most [74]. An external measure of training such as swimming or running speed would be useful in determining which athletes are impaired to the greatest degree, and so allow for increased work/rest ratios to facilitate maintenance of training quality. This approach, however, is limited in that it does not account for the level of effort/exertion (i.e., physiological stress) required to produce a given training speed. Accordingly, athletes and coaches should consider also including measures of internal load. For example, rating of perceived exertion (RPE) expressed as a function of running speed to produce an “exertion/velocity ratio” [74] increased by up to 30% at altitude. This relatively simple method of monitoring training could be employed to trigger training modifications.

The lower absolute training intensity observed at altitude may have implications for performance at sea level. Runners showing a substantial decrease in running speed (~9%) during interval training at 2500 m also showed a significant decrement in 5000 m race performance (24 s slower) following altitude training [61] compared with those better able to maintain sea-level running speed. The reduction in training intensity at altitude is coupled with a lower oxygen flux as well as lower neuromuscular/mechanical stimulus. At 2500 m simulated altitude, running speed at an equivalent relative intensity (in this case lactate threshold) is reduced by 13%, leading to a 19% reduction in oxygen uptake ($\dot{V}O_2$) [75]. As a result, potential deconditioning may occur, thus impairing subsequent sea-level performance [45, 61]. As such, the maintenance of absolute exercise intensity is likely an important factor contributing to improved-sea level performance following altitude training, and thus necessitates close monitoring (e.g., stopwatches, power meters or global positioning system [GPS] devices) [76].

Critical to any performance are the prior training completed by an athlete [77] and the periodization strategy employed at altitude [57]. Extended low-intensity training sessions could be perceived by an athlete to require a moderate-to-hard level of effort at altitude [74]. This has implications for overall planning and resultant adaptation. Completing an ‘easy’ day at a greater perceived exertion than planned by the coach may result in an athlete being under-recovered for a subsequent high-intensity session [78, 79], compromising a positive outcome from altitude training. The divergence between athlete and coach perception of training may lead to undesirable maladaptive responses;

thus, effective monitoring of the load planned by coaches and the actual load completed by athletes at altitude should be a priority [80, 81].

3.2 Health Monitoring at Altitude

The combined stress of training and hypoxia may increase the risk and/or incidence of infection and illness in elite athletes, compromising beneficial physiological or performance adaptations [17, 68, 69]. Elite swimmers and runners reporting symptoms of illness during altitude training camps experienced no improvements in Hb_{mass} , with a negative effect of sickness also found on sea-level competition performance following altitude training [22, 27]. British elite runners completing 4 weeks of moderate-altitude training did not improve performance and reported a 50% greater incidence of illness during altitude training than at sea level [25]. Resting levels of plasma glutamine were observed to be decreased during altitude training, and were proposed as a potential reason for the increased incidence of illness, given the role of glutamine in maintaining healthy immune function [25]. The hematological response to altitude training may also be limited by incorrect prescription of training loads [34]. Maladaptation symptoms (e.g., illness, reduced serum testosterone) were reported in Australian World Champion track cyclists who failed to increase Hb_{mass} or $\dot{V}O_{2\max}$ after 4 weeks of altitude training, with the timing of the symptoms coinciding with an increased training volume [82]. Increased resting cortisol and decreased testosterone concentrations have been observed in athletes following altitude training, likely due to a combination of hypoxic exposure and increased training load [82, 83]. A marked reduction in the testosterone to cortisol ratio during altitude training may negatively affect erythropoiesis, especially at the commencement of acclimatization [84]. Although monitoring of markers such as glutamine, testosterone, and cortisol may provide some insight into the immune status of athletes during altitude training, these methods may be invasive (i.e., requiring venipuncture), unreliable [85, 86], and expensive.

3.3 Blood Monitoring with Altitude

Monitoring the Hb_{mass} response to altitude via established, reliable, and relatively non-invasive methods such as carbon monoxide rebreathing [87] is strongly advised. Given the interrelationship between changes in Hb_{mass} , $\dot{V}O_{2\max}$, and endurance performance observed with altitude training [62, 63, 88], facilitating an increase in Hb_{mass} during altitude exposure is often viewed as a required contributor towards a positive performance outcome following altitude training [89]. Sufficient iron stores are necessary to support increases in erythropoiesis and Hb_{mass} with chronic altitude exposure

[45, 90–92]. In the absence of adequate iron stores pre-altitude, hematological adaptations during altitude exposure may be absent [91]. Red cell volume remained unchanged in non-supplemented, iron-deficient runners, in contrast with their non-iron deficient counterparts, who experienced an increase in red cell volume [90]. As such, monitoring an athlete's full iron profile about 4–6 weeks prior to altitude exposure is critical [93]. Supplementation with iron prior to altitude exposure to normalize iron stores (especially in the event of a pre-screening test identifying iron deficiency in an athlete) and promote adaptation upon arrival to altitude, as well as during altitude exposure, has also been recommended [20, 91, 92]. To maximize the Hb_{mass} response at altitude, daily supplementation with ~ 100 to 200 mg of elemental iron may be required [93].

3.4 Blood Oxygen Saturation Monitoring

Measurement of peripheral oxygen saturation (SpO_2) at rest may reveal information regarding an athlete's hematological response to altitude [34, 71, 94]. The increase in erythropoietin levels is proportional to the level of hypoxia and decline in SpO_2 [52, 95]. Typical metrics proposed to quantify the hypoxic dose administered concern the hypoxic stimulus or altitude achieved [8], whereas the measurement of 'saturation hours' refers to the hypoxic response and accounts for the large inter-individual variability frequently demonstrated in response to a given hypoxic dose [14, 61, 96]. Athletes with a higher saturation value or faster rise in SpO_2 over the course of an altitude exposure may need to extend the length of an exposure, increase exposure to a higher altitude, or complete more high-intensity exercise at altitude to induce greater desaturation [34]. Alternatively, athletes with low values may be more suited to lower altitudes and greater modifications to training. This assertion, however, is speculative and warrants further investigation.

An athlete's ability to maintain SpO_2 has been strongly linked to the maintenance of both $\dot{V}O_{2max}$ and performance at altitude [18, 73, 97]. Low-saturation elite runners (SpO_2 during sea-level race pace exercise < 91%) had a significantly greater slowing of 3000 m time-trial performance at 2100 m altitude than high-saturation athletes (SpO_2 > 93%) [73]. The mechanism behind arterial oxyhemoglobin desaturation, leading to exercise-induced arterial hypoxemia, can be traced to limitations of oxygen diffusion, either at the lung or muscle microvasculature, as well as inadequate hyperventilation [18]. Elite athletes may be more susceptible to this phenomenon than lesser trained individuals due to elite athletes having exercise-induced arterial hypoxemia, even at sea level [98]. Even among elite athletes frequently utilizing altitude, some are more negatively affected during exercise in hypoxia than others [18, 99]. Pre-screening of

an athlete's desaturation response during maximal exercise, as well as the hypoxic ventilatory response, could provide information pertaining to their response to altitude, which could be used to make modifications to training at altitude (e.g., lengthened recoveries, more sessions at lower altitude) necessary to help maintain exercise intensity [18, 31].

3.5 Overreaching and Overtraining at Altitude

A well-managed period of intensified altitude training can be used to induce performance super-compensation in elite endurance athletes [5, 54, 58]. However, pushing athletes into an overreached state may have negative consequences for performance [100]. While altitude training can be very beneficial for performance in elite athletes, it can also induce a greater level of fatigue state than completing intensified training at sea level, given the higher relative intensity of exercise at altitude [57], and therefore render athletes more susceptible to undesirable outcomes. Monitoring of objective measures such as body mass and composition, resting heart rate, urinary specific gravity, blood/serum urea and creatine kinase concentration [30, 71], and heart rate variability [57] has been recommended to assess fatigue states, but subjective measures may be more responsive to training-induced changes in athlete well-being [81] (Table 5). The use of perceptual questionnaires including items pertaining to fatigue, health, and sleep quality (amongst others factors) is a simple yet valid method of monitoring athlete wellness, and this strategy can be recommended over measures that require an extended period of monitoring with frequent data collection for meaningful interpretation to occur [101].

4 Other Periodized Interventions to Consider during Altitude Training

Other confounding interventions may need strategic periodization in combination with altitude training, such as nutrition, the combined use of terrestrial altitude and NH (i.e., simulated altitude), and/or heat adaptation. Figure 2 displays a potential integrated approach to all periodized altitude interventions highlighted here for a typical elite middle-distance runner (10–12 training sessions per week; ~ 140 to 180 km/week; 9–10 h/week).

4.1 Nutrition and Altitude Periodization

The distinct environmental stresses of altitude also cause unique nutritional challenges that should also be periodized. These have been recently reviewed [93], and only the principal nutritional elements to consider are

highlighted here: the impact of iron and nitrate interventions, energy availability, and body composition periodization during altitude.

4.1.1 Iron Intake to Optimize Hemoglobin Mass Gain

Certainly, the most important micronutrient for consideration at altitude is iron. An appreciation of baseline iron status and appropriate supplementation are fundamental nutritional interventions that facilitate the Hb_{mass} responses at altitude. Govus et al. [91] examined 178 athletes who participated in altitude camps and found that those athletes who did not supplement with iron had minimal Hb_{mass} increases of only 1.2%, whereas athletes that supplemented with 105 and 210 mg of elemental iron per day increased Hb_{mass} by 3.3% and 4.0%, respectively. Moreover, 24 elite runners were randomized and stratified to either a single 200 mg dose or 2×100 mg daily doses (morning and afternoon) of iron over ~3 weeks’ training at 2100 m. Both groups significantly increased Hb_{mass} from baseline, but a single dose resulted in significantly greater Hb_{mass} gains than a split dose. Taken together, current evidence suggests nearly a dose–response

relationship between the amount of iron supplemented (up to ~210 mg of elemental iron) and Hb_{mass} gains at altitude, with the most effective micro-periodization protocol being a single 200 mg dose of elemental iron taken in the evening (Fig. 2) to potentially minimize the iron and exercise induced increases in hepcidin [102]. Interested readers are referred to a recent review on iron considerations for athletes, where the interaction between environmental hypoxia and iron metabolism is thoroughly discussed [103].

4.1.2 Dietary Nitrate Supplementation at Altitude

Nitric oxide (NO) is a pleiotropic signaling molecule and a regulator of many physiological and adaptive processes that are stimulated by hypoxia. When supplemented with nitrate (NO_3^- ; primarily in the form of concentrated beetroot juice) to augment NO availability, recreationally active subjects show a ~5% reduction in normoxic steady-state $\dot{V}O_2$ and improved performance. However, it appears that this effect is not nearly as consistent in endurance trained subjects with $\dot{V}O_{2max}$ values > 60 mL/kg/min [104]. Interestingly, similar

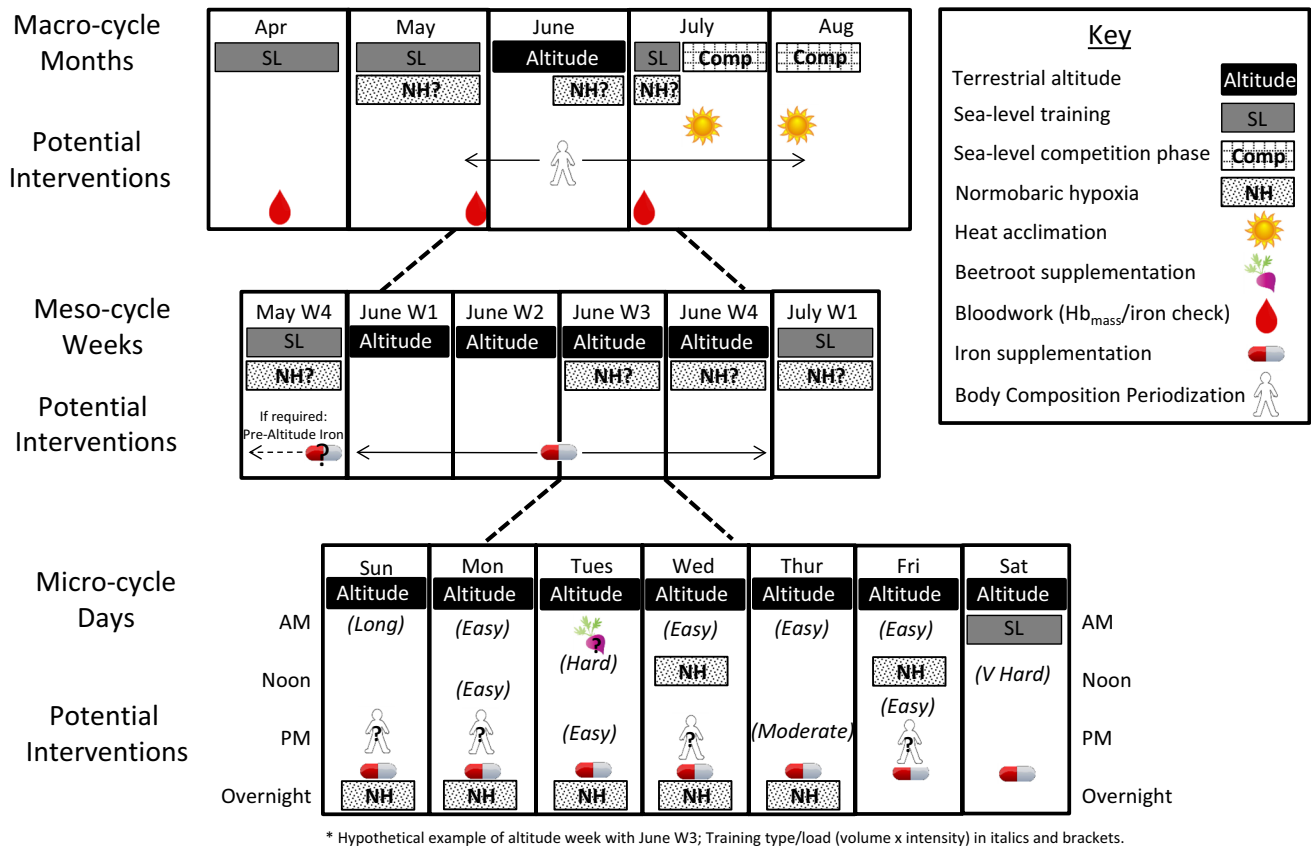


Fig. 2 Potential macro-, meso-, and micro-periodization and integration of nutrition, heat, and artificial altitude with terrestrial altitude. The hypothetical proposal features a 4-week terrestrial altitude block

in June to set up a competition phase from mid-July into August. ? indicates hypothetical interventions that require further scientific validation (as elaborated within the text)

to the effects in normoxia, NO_3^- supplementation reduces steady-state VO_2 by ~ 5 to 10% and enhances performance in hypoxia in recreationally active subjects [105–108], but it does not appear to have the same effects in well-trained subjects [109–112]. Given the lack of consistent performance and metabolic outcomes in well-trained endurance athletes, NO_3^- supplementation to improve performance or training adaptation in hypoxic conditions cannot be currently recommended.

4.1.3 Energy Availability and Body Composition Considerations at Altitude

Although very high altitudes (≥ 3500 m) can result in significant decreases in body mass, primarily from fat-free mass [113–116], body mass and/or fat mass losses are not a consistent outcome in studies at the moderate altitudes generally recommended for LHTH or LHTL (2000–2500 m) [27, 71, 93, 117, 118]. At extreme altitudes there is most certainly a ~ 10 to 15% increase in resting metabolic rate (RMR) [116, 119], and a recent study showed a 19% increase in RMR at moderate altitudes [118]. However, there were only five subjects in this study, and given the confounders and variability of RMR measurements [120], more research is required to elucidate the impact of moderate altitude on RMR in elite endurance athletes. In terms of long-term energy availability and Hb_{mass} , a recent altitude-based nutrition study (48 elite runners, 27% Olympians) found pre-altitude Hb_{mass} was significantly higher in eumenorrheic versus amenorrheic females, but training camp energy availability or sex hormones did not seem to have an impact on the change in Hb_{mass} while at altitude [27].

4.2 Use of Normobaric Hypoxia (NH) in Conjunction with Terrestrial Altitude

Although there are subtle differences in the physiological and performance responses to NH (e.g., altitude tents or houses) versus hypobaric hypoxia (HH; e.g., natural altitude or pressure chamber), these responses do appear minor when accounting for equivalent hypoxic dose [121–123]. It is therefore logical to hypothesize that a NH pre-acclimation approach could perhaps augment initial training and adaptation to altitude, or NH could further increase the resting hypoxic stress at altitude or assist in maintaining the altitude-induced adaptations post-altitude. However, to the best of the authors' knowledge, no studies to date have integrated the implementation of NH or HH before, during, and/or after natural altitude sojourns in elite endurance athletes at altitudes typical of elite endurance training camps (~ 2000 to 2500 m). It should also be noted that, based on the authors' experience, the use of NH in some athletes results in poor

recovery and sleep outcomes. Accordingly, adequate monitoring (Table 5) and subsequent adjustments, including not utilizing NH, may be required. Nevertheless, given that these interventions are already occurring as elite athletes and their respective coaches and sport science teams search for the elusive performance edge, the rationale and potential periodization approaches are highlighted here.

4.2.1 Use of NH Prior to Terrestrial Altitude Training

The initial 5–7 days at altitude typically feature initial decreases in training intensity, along with increased cardiac, respiratory, and sympathetic responses, which could potentially have profound negative effects on the training quality and performance of elite athletes [31, 124]. Interventions to reduce these initial deleterious adaptations would be attractive, and perhaps pre-altitude acclimation protocols could allow for this. There is evidence that pre-acclimation with NH or HH during rest and exercise before trips to very high altitudes (> 3500 m) are an effective way to potentially attenuate maladaptation and combat altitude mountain sickness [43]. Whether this also applies to the more moderate (~ 2000 to 2500 m) altitudes most often utilized by elite endurance athletes remains to be elucidated.

Short-term studies have looked at whether a series of short intermittent hypoxic training sessions could allow for more successful adaptation to moderate terrestrial altitudes, by implementing 75 min/day of aerobic training in hypoxia (fraction of inspired oxygen $[\text{F}_\text{I}\text{O}_2] = 0.149 = \sim 2700$ m) over 7 [125] or 8 days [126]. Interestingly, Whyte et al. [125] did show adaptive field measured responses with elite biathletes (Great Britain national team) with reductions in blood lactate, heart rate, and RPE compared with the control upon arrival to moderate altitude (2000–3000 m). However, in a laboratory-based study, Pedlar et al. [126] were unable to show any adaptive differences in physiology or performance. Other studies implementing short-term intermittent hypoxic breathing protocols at rest to stimulate subsequent lower/moderate altitude acclimation have generally not been effective [127–130]. Whether a classic LHTL (NH tent or house) protocol over many weeks (> 3 weeks) typically utilized by athletes at sea level would allow for enhanced initial acclimatization to natural altitude requires further investigation. One study, conducted in elite racewalkers [131], revealed that athletes completing 2 weeks of simulated LHTL experienced greater improvements in threshold walking speed and submaximal heart rate assessed at 1380 m than control group participants. The authors therefore suggested completing a LHTL protocol when travel to altitude prior to competition isn't possible. Given the typical NH outcomes, such as significant increases in Hb_{mass} [32, 122, 123, 132, 133], and the fact that some elite endurance athletes and coaches are already strategically implementing NH prior to

natural altitude, it can be hypothesized that this protocol would provide an improvement, but this requires scientific validation (Fig. 2).

4.2.2 Augmenting the Hypoxic Stimulus at Terrestrial Altitude with NH or Hypobaric Hypoxia

Some elite training groups sleep and recover at altitudes higher than the standard moderate altitudes (~ 2000 m) via either NH (use of altitude tents at terrestrial altitude) or HH (accommodation at higher natural altitude elevations). This approach is intended to counter the attenuated and relatively quick adaptive responses of erythropoietin to hypoxia. Indeed, after the initial 60–80% increase in serum erythropoietin upon ascent to > 2000 m of altitude, erythropoietin diminishes back to close to sea-level baseline values by ~ 10 to 14 days at a natural altitude [22, 134]. This attenuated erythropoietin effect appears even more pronounced in altitude tents, with nearly 40% less erythropoietin release on the fifth night in an altitude tent compared with night one [135]. Therefore, seeking a way to accumulate more hours in an augmented hypoxic state to drive HIF-1 α and/or erythropoietin-mediated mechanisms would perhaps further augment altitude adaptation. From a practical perspective, some of the more globally popular altitude training locations feature numerous altitude options. For example, within a short distance of St. Mortiz (1822 m) one can find accommodation at ~ 3000 m and also train at ~ 300 m within a 1-h drive. Anecdotal, two of the best distance runners in Swiss history utilized multiple altitudes to achieve remarkable Hb_{mass} responses and personal best performances [136].

Several studies have examined this type of terrestrial altitude combined with an artificial hypoxia approach [137–139]. In these studies, athletes trained at a moderate natural altitude of ~ 1300 m but then slept at ~ 2600 to 3000 m of altitude. The increased hypoxic stress of sleeping at ~ 3000 m does seem to translate into modest physiological improvements (e.g., Hb_{mass}) [137–139]; however, this does not seem to further augment performance outcomes [137, 139].

Given the scant research available, but based on the authors' practical experience with elite endurance athletes (e.g., the Olympic and World Champion female swimmer featured in Table 1 and Fig. 1 spent 7–9 of her 16 weeks at terrestrial altitude sleeping at a simulated altitude of 3200 m in the lead-up to the Rio 2016 Olympic Games and the 2017 FINA [Fédération Internationale de Natation] World Championships in Budapest, Hungary), the recommendation for implementing this type of NH or HH hypoxic stimulus beyond ~ 2000 to 2500 m would be to start only after 7–10 days following arrival to altitude (when erythropoietin responses start to attenuate), sleep at altitudes of 3000–3200 m (Fig. 2), prioritize adequate sleep

and recovery, and closely monitor adaptations to avoid any negative outcomes. However, this type of intervention on elite endurance athletes requires scientific validation.

4.2.3 Utilization of NH After Terrestrial Altitude to Retain Altitude-Induced Adaptations

Upon return from a natural altitude sojourn, decreasing plasma erythropoietin is a trigger for neocytolysis [66, 140]. In native Peruvian highlanders (4380 m) that descend to sea level there is a 7–10% decrease in red cell mass within a few days of arrival that coincides with large decrease in erythropoietin [141]. Interestingly, giving the subjects exogenous erythropoietin upon return to sea level prevented the decrease in red cell mass. This neocytolysis phenomenon has also been shown at more moderate altitudes (2760 m) in elite cyclists, as return to sea level caused a ~ 41% decrease in erythropoietin below pre-altitude baseline levels, with a small ~ 2% drop in Hb_{mass} from an altitude camp high of 3.5%, but still ~ 1.5 to 2% higher than the pre-altitude baseline [134].

It could be hypothesized that the use of sea-level NH may provide enough of an erythropoietin stimulus to attenuate the neocytolytic responses and/or prolong the augmented Hb_{mass} effects after a terrestrial altitude camp (Fig. 2). Although the authors are unaware of any published literature to support this approach, some elite athletes/coaches are already implementing it (e.g., the Olympic and World Champion female swimmer featured in Table 1 and Fig. 1 returned to sea level 18 days before the Rio 2016 Olympic Games but slept the first nine nights at a simulated altitude of 3200 m). Perhaps a common theme to this entire section is that a periodized use of NH and HH in combination with natural altitude training is ripe for further scientific investigation, and that elite athletes and coaches tend always to be ahead of the ability of sport scientists to conduct evidence-based research.

4.3 Heat and Altitude Periodization: An Emerging Field of Cross-Tolerance

In a recent consensus, Racinais et al. [142] clearly identified that heat acclimation or acclimatization (HA) over 5–14 days can significantly improve endurance-based performance in the heat. Despite considerable understanding on HA processes and outcomes, knowledge on the decay and periodization of HA is limited, especially at altitude [143–147]. There is an emerging trend of utilizing the environmental stressors of heat and hypoxia, termed cross-acclimation or cross-tolerance. Very little evidence is available thus far in athletes, but data in rodents shows that acclimation to one environmental stressor may enhance adaptation to other stressors involving the activation of common adaptive pathways [148]. From a mechanistic point of view, increasing plasma volume (PV)

via HA might have profound positive effects for exercise tolerance at altitude, as PV may be reduced by ~10–30% over prolonged stays at altitude [149–151], resulting in reduced left ventricular filling due to decreased venous return at rest and exercise at 3100 m [150]. We are unaware of any published terrestrial altitude studies that have implemented heat to enhance training adaptations, so this potential intervention requires more research (Fig. 2). We are aware, however, that some elite swimmers are using a sauna up to three times per week during altitude training camps in an attempt to boost PV and also recovery when used in conjunction with cold water immersion (i.e., intermittent thermotherapy and cryotherapy). Additionally, unpublished data from elite Australian racewalkers completing 2×60 min low-intensity walks per week in a heat chamber, whilst living and training at 1800 m for 4 weeks, demonstrated improvements of 3–4% in threshold speed, velocity at $\dot{V}O_{2\max}$, and 10 min time trial performance, all assessed in the heat.

Nevertheless, in the handful of human exercise studies using a cross-tolerance heat and hypoxic approach, the results have been variable, with either limited impactful physiological and performance changes [152] or minor changes that appear to be more heat driven than hypoxia induced [146, 147, 153]. Lee et al. [153] observed that 10 days of HA improved cycling time trial performance by a magnitude similar to hypoxic acclimation, and that HA induced a greater adaptive stimulus at lower levels of metabolic strain in a shorter timeframe than hypoxic acclimation. Similarly, McCleave et al. [146] showed that despite hematological adaptations with 3 weeks of LHTL hypoxia (significant increases in Hb_{mass}), the performance outcomes were no greater than temperate training alone. Recent research showed impaired heat adaptations from a combined heat training and LHTL approach [147], which suggests that if heat tolerance is of primary importance to performance, then combining a hypoxic stimulus may not be advisable. Indeed, it seems that the greater the combined effect of all physiological stressors, the greater the probability that one stress will be abolished by another—indicating that humans appear to respond to concurrent physiological stressors with the “worst-strain-takes-precedence” principle [154]. Therefore, it may be preferable to conduct exposures to heat and altitude separately and sequentially rather than concurrently to maximize adaptation, but research in this area is lacking.

5 Future Directions

Future investigations on altitude training as a performance-enhancing strategy for elite endurance athletes should determine the long-term effects of accumulated altitude training through repeated exposures, as well as the interactions between altitude and other components of a periodized

approach to athletic preparation while at altitude, such as recovery, nutrition, and psychological skills training.

Upon ascent to altitude there are nearly instantaneous non-hematological responses and adaptations to hypoxia, including an increase in intra- and extracellular buffering capacity [10, 51, 155–157]. However, these non-hematological responses are under-studied and require further elucidation, especially in elite athletic populations. For example, it appears that many of the muscle buffering-induced adaptations occur on a much shorter timeframe (< 2 weeks) [10, 156], which lines up with the real-world application of altitude in many middle-distance athletes utilizing mid-season 2-week ‘top-up’ camps (unpublished data). Much more work is required to understand the adaptive time course, and subsequent decay, of non-hematological hypoxic adaptations. Further investigation is also needed on the potential differences in exercise-induced hypoxic adaptations between different modes of exercise. For example, the exercise-induced time under tension is very different among rowers, swimmers, and runners, which may have profound effects on tissue desaturation at altitude. Further, weight-supported and unsupported sports, as well as sports of different velocity, may have differential effects at altitude due to differences in drag at altitude (e.g., swimming vs. cycling). Finally, given hypoxia results in lower oxygen flux as well as slower training speeds, sports with a high technical component (e.g., swimming) may respond to potential decrements in training quality differently than sports with a lower technical component (e.g., cycling). Obviously, more research is required to fully understand all these various complexities in altitude training between sports. Future studies should also evaluate the physiological and performance effects of very high-intensity and repeated-sprint training [158–162] and strength training [163, 164] in hypoxia on elite endurance athletes, and whether sufficiently long and adequately periodized and monitored training camps at high altitude (i.e., 3000–5500 m) could induce additional physiological and performance adaptations in elite endurance athletes accustomed to repeated exposures at moderate altitude.

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Compliance with Ethical Standards

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