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BRIEF REVIEW

"Living High-Training Low" for Olympic Medal Performance: What Have We Learned 25 Years After Implementation?

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Background: Altitude training is often regarded as an indispensable tool for the success of elite endurance athletes. Historically, altitude training emerged as a key strategy to prepare for the 1968 Olympics, held at 2300 m in Mexico City, and was limited to the "Live High-Train High" method for endurance athletes aiming for performance gains through improved oxygen transport. This "classical" intervention was modified in 1997 by the "Live High-Train Low" (LHTL) model wherein athletes supplemented acclimatization to chronic hypoxia with high-intensity training at low altitude. ***Purpose:*** This review discusses important considerations for successful implementation of LHTL camps in elite athletes based on experiences, both published and unpublished, of the authors. ***Approach***: The originality of our approach is to discuss 10 key "lessons learned," since the seminal work by Levine and Stray-Gundersen was published in 1997, and focusing on (1) optimal dose, (2) individual responses, (3) iron status, (4) training-load monitoring, (5) wellness and well-being monitoring, (6) timing of the intervention, (7) use of natural versus simulated hypoxia, (8) robustness of adaptative mechanisms versus performance benefits, (9) application for a broad range of athletes, and (10) combination of methods. Successful LHTL strategies implemented by Team USA athletes for podium performance at Olympic Games and/or World Championships are presented. ***Conclusions***: The evolution of the LHTL model represents an essential framework for sport science, in which field-driven questions about performance led to critical scientific investigation and subsequent practical implementation of a unique approach to altitude training.

Keywords: altitude training, hypoxia, Live High-Train Low, practical implementation, podium performance

Since the late 1960s, altitude training in its classical form ("Live High-Train High"), wherein athletes live and train in a high-altitude environment,[1] continues to be a key aid for countless elite athletes chasing medals at major events.[2] "Live High-Train Low" (LHTL) is one model that emerged in the 1990s, which resulted in a paradigm shift regarding how altitude training is used. With LHTL, athletes acclimatize to hypoxia by residing at moderate real or simulated altitude but regularly train near sea level or at substantially lower altitudes to avoid the hypoxia-induced reduction of maximal training intensity.[3] A subsequent evolution of a mixed-method regimen, that allows for preservation of training intensity while limiting the frequency of travel to low altitudes, involves athletes residing and performing all low-intensity training at moderate altitude (~2500 m) while only high-intensity (interval) training is performed at lower elevations (~1250 m or below).[4–6]

The seminal work by Levine and Stray-Gundersen[3] challenged previous notions regarding what was deemed the best way to approach altitude training. Thirty-nine competitive runners first performed a 2-week "lead-in" phase near sea level where the training was supervised and familiarization with testing procedures took place. This was then followed by 4 weeks of training at sea level where all athletes trained together to bring them up to an equivalent degree of training readiness, and account for any potential "training camp effect." Participants were then randomized into one of 3 groups for 4 weeks: (1) "LHTL" (reside at 2500 m and train at 1200–1400 m), (2) "Live High-Train High" (reside at 2500 m and train at 2500 m), or (3) "Live Low-Train Low" (reside at sea level [150 m] and train at sea level [150 m]). Importantly, the volume and relative intensity of training was closely matched among groups and followed the same pattern as the previous 4 weeks of training at sea level.

This study found that both "Live High-Train High" and LHTL induce hematological adaptations but that only the LHTL model significantly increases sea-level 5-km time-trial performance. One key advantage of LHTL is to allow simultaneous benefits of acclimatization to chronic hypoxia, with negligible interruption to regular workouts since training at lower elevations allows preservation of oxygen flux. While an increased total hemoglobin mass (Hb_{mass}) likely is the primary mediator for performance enhancement,[7] other postulated mechanisms include increases in anaerobic capacity, muscle buffer capacity, and/or oxidative enzymes.[8]

Since its inception, LHTL has been regarded as the most popular approach to altitude training among competitive American endurance athletes, with the main incentive being to improve performance at sea level.[9] What practical knowledge has been gained 25 years after LHTL had emerged? This review will not provide an exhaustive evaluation of the usefulness of LHTL for maximizing hematological and performance responses; the reader is referred to existing literature.[10,11] Instead, our intention

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is to discuss 10 key "lessons learned" from published scientific literature and our applied experience, and present practical examples of successful LHTL camps by world-class athletes.

Lesson 1: There May Be a Relatively Narrow Window for "Optimal Dose" of Altitude to Be Used With LHTL

The notion that a sufficient "hypoxic dose" (ie, elevation, duration, and daily exposure) is needed to stimulate beneficial physiological adaptations, and eventually performance gains, is not new and has been discussed as early as in the 1970s.[12] While altitudes lower than 1800 m may not provide sufficient hypoxic stimulus for key physiological adaptations, elevations higher than 3000 m have greater potential to impair the recovery process (ie, sleep disturbances).[13] In support of this concept, one study varied only the living altitude, while keeping training consistent. Athletes living at 2085 and 2454 m achieved significant improvements in both sea level 3-km running time and maximal oxygen uptake, whereas athletes living at lower (1780 m) and higher (2800 m) elevations demonstrated no performance benefits after the altitude camp despite equivalent red cell mass increases (~6% in all groups).[14]

In terms of duration, the broad consensus is that less than 12 to 14 hours per day (ie, when using simulated altitudes) for less than 2 weeks (a total of <200 h) may be insufficient, with longer exposure (>14 h/d) for 3 to 4 weeks (more than 300 h) better suited to stimulate robust and sustainable acclimatization, including hematological adaptations.[15] It is possible that short daily (<10–12 h), or at the camp level (<200 h), hypoxic exposure time could be enhanced by an increased magnitude of hypoxia (ie, simulated altitude ≥3500–4000 m [at least during day time], which may maximize hematological responses), though this approach has not been proven. One modification to the classic LHTL approach involves interspersing blocks of nightly exposure to hypoxia with several nights of normoxia to eventually minimize any adverse psychological (ie, boredom) and physiological (ie, decreased plasma volume and muscle Na^+/K^+ ATPase) effects of prolonged room confinement.[16] However, these modifications have not been tested rigorously, and the sustained exposure to normoxia may prevent an adequate acclimatization response based on the evolving understanding of the biological response to hypoxia.[17] Overall, the optimal hypoxic dose for boosting performance and a range of hematological and nonhematological benefits associated with chronic hypoxia may differ depending on the specific physiological adaptation in question.

One literature shortcoming that prevents meaningful comparisons among available LHTL studies is the absence of a common and well-accepted metric for defining the hypoxic dose. For instance, the kilometer hours, calculated as km/h^{-1} = (elevation above sea level/1000) × hours of exposure, has recently been proposed.[18] Although attractive, a metric based upon the magnitude of the stimulus (ie, arterial oxygen saturation as a reflection of the "internal" physiological stimulation), as opposed to the altitude elevation (ie, only representing the "external" stress), might be more athlete-specific.[19] Both indicators, however, suffer from the failure of the calculation involving low altitudes, which are below the threshold for physiological acclimatization for very long periods of time (eg, an elevation of 1000 m for many years).

Lesson 2: Large Individual Variability of the Responses Exists and the Mechanisms Behind Responders Versus Nonresponders to LHTL Remain Obscure

Not all athletes benefit equally from LHTL. Even in athletes undergoing identical LHTL procedures (ie, working with the same coach and performing very similar training programs), there is often variable results with some individuals improving their sea-level performance or aerobic capacity, others experiencing no change and some even declining.[20] It is likely that some athletes will demonstrate a beneficial response using lower hypoxic doses (but still above a critical threshold), while others fail to do so, questioning what a minimum dose should be for each athlete to induce meaningful gains.[21] Measuring the erythropoietin in the blood,[4] either shortly after starting altitude exposure or in a laboratory setting, can be used to identify where athletes may sit on the *high-to-low responder* continuum.

The individual responses (physiology and performance) to altitude training may also partly be explained by normal biological variation and measurement error in the different parameters assessed (eg, Hb_{mass}). While genetic attributes (ie, transcriptional mechanism of erythropoietin gene expression[22]) likely influence tolerance to a hypoxic stress, differences in the magnitude of the biological response to LHTL should not necessarily be considered as the ultimate proof for the identification of responders and nonresponders. The diversity in the adaptative patterns may also include a timing issue, featuring *slow* and *fast* responders. When tested several weeks after a LHTL intervention, some athletes who were not responding initially may in fact be able to achieve similar (or even higher) Hb_{mass} gains.[23] That said, this variability may be heavily influenced by the training program after return to sea level, as well as the disappearance of the acclimatization response. A proposition would therefore be to identify those who will respond with a *fast/high*, *medium*, and *slow/low* response (ie, >2%, between −2% and +2%, <2%)[24] compared with the group mean response, allowing the delivery of a sufficient physiological stimulus for all athletes by regularly making individual adjustments. This type of individualized assessment though requires a lot of trial and error and may be impractical. What causes an ultimate nonresponse or failure to improve performance could also be that some athletes adapt quickly with respect to one marker, but not at all, or substantially slower for others. Support teams should always determine the time course of LHTL adaptation and the individual needs of their athletes based on their physiological responses, the specific demands of the individual athlete's sport, and psychological response to a given altitude dose.

Lesson 3: Iron Deficiency Impairs the Erythropoietic Response to Altitude So That Screening Athletes for Iron Status Before Embarking on a LHTL Camp Is an Absolute Necessity

Screening athletes for iron status is key to ensure any hematological adaptations resulting from LHTL are not compromised by insufficient iron availability.[25] Iron deficiency is common in endurance athletes, especially those who attempt to maintain a low body weight for optimal performance, or who are vegetarian. A baseline iron deficiency then is compounded by the need for iron during altitude acclimatization, which is mostly due to the hematopoietic effect of hypoxia and subsequent erythropoiesis-related augmented iron uptake.[26] In iron deficient athletes (serum ferritin <20 μg/L for females, <30 μg/L for males), the likelihood of an altitude-induced increase in Hb_{mass} is minimal.[27] A blunted erythropoietic response from LHTL can be due to depleted iron stores prior to, and/or as a result of, altitude exposure.[28] Low baseline ferritin levels are typically more prevalent in female athletes and endurance runners.[26] Whether individuals with otherwise healthy iron stores should also be supplemented with iron to facilitate LHTL adaptations is still debated.[25]

Iron status should be assessed in all athletes undergoing LHTL camps. Current guidelines for daily iron supplementation (ie, the maintenance of iron balance and enhancement of iron absorption in turn supporting erythropoiesis) could help iron deficient athletes to support accelerated erythropoiesis at altitude.[29] Iron deficiency per se could result in decreased LHTL efficacy, not only because of Hb_{mass}-related processes, but also due the role iron plays on other iron-regulated metabolic processes (ie, Krebs cycle activity[30]). Normalization of iron status is therefore required 2 to 3 weeks prior to LHTL, while supplementation should ideally continue throughout altitude exposure.

Lesson 4: If Performance Is the Key Outcome, Training Load (Volume/Intensity) Must Be Monitored and Adjusted Accordingly Before, During, and After the LHTL Intervention

Successful LHTL implementation starts by controlling the training load prior to embarking on the camp (known as "lead-in phase"), which acts as a minitaper.[31] Altitude residence causes an extra stress to the body that needs to be carefully managed to avoid overtraining. To date, however, how to modify exercise prescription variables for altitude training sessions relative to sea level in order to achieve the desired physiological and mechanical training loads is under-researched. Pacing is difficult to manage, especially with inexperienced athletes who are challenged to integrate the slower training speeds, with the other internal markers of training intensity such as ventilation and heart rate (ie, greater at altitude) as well as muscle metabolic status (ie, lactate higher during submaximal exercise though lower at maximal effort). While relative exercise intensity can be kept relatively similar to normoxic conditions, a conservative approach, where the overall volume is decreased (ie, up to 25% from full sea-level volume in the first week), is generally adopted when embarking on a LHTL camp. In order to minimize fatigue and avoid overreaching, modifications to the training structure (ie, altering the exercise-to-rest ratio by lengthening rest periods during intervals especially during the first week) are recommended. Implementing perceptually regulated workouts where athletes can self-adjust intensity based on their exercise-related sensations (eg, exercising at a given rating of perceived exertion during interval training sessions[32]) seems appropriate. Gaining experience with altitude exposure and training may be a key component of repetitive altitude camps over a macrocycle, a process which the renowned altitude physiologist/coach called "competitive acclimatization."

In addition to inducing altitude acclimatization to improve sea-level performance, there is a belief that LHTL can be used to improve training responsiveness after the camp (ie, high-quality training), due to increased physiological capacities. While this approach may allow a better sea level training block, due to the possibility to sustain higher exercise intensities, more work is needed to support anecdotal evidence.

Lesson 5: Successful LHTL Implementation Requires Careful Monitoring of Sleep Quality, Fatigue, and Hydration Status to Avoid Developing Infections, Illnesses, or Overreaching/Overtraining States

As a general rule (ie, in the absence of "gold standard" prescreening test battery) pre-LHTL evaluation should ensure that athletes are free of illness, injury, and fatigue.[31] A comprehensive screen should also verify that nutritional-hydrational status, body weight, and psychological attributes are "normal." Exposing athletes who are under-fit and/or noncoping well with low oxygen conditions is potentially counterproductive and the stress of hypoxia should not be added to their physical preparation.

Adequate planning, periodization, programming, and training monitoring during the camp are crucial factors to consider to avoid overreaching and/or detraining; for specific recommendations and suggested monitoring tools, the reader is referred to Mujika et al.[31] That said, caution is needed since measures typically recommended to monitor acclimatization and responses to altitude in elite endurance athletes do not always follow the patterns suggested in the literature (eg, an increase/decrease in resting arterial oxygen saturation/heart rate over time).[33] Increased feelings of fatigue (ie, athletes' perception of how hard they are training along with their general fatigue, stress, and muscle soreness levels), poorer training quality, and/or disrupted sleep structure are crucial to consider to optimize the characteristics of the camp, especially if significant amounts of training are being done at altitude. In particular failure to make individual adjustments to reduce disordered breathing during sleep and/or alter training content by frequent monitoring, through the use of wellness and well-being questionnaires,[34] may explain why the expected physiological and performance responses to LHTL do not always occur.

Increases in the frequency of upper respiratory and gastrointestinal tract infections are common during LHTL camps.[35] Also often overlooked is that, for many athletes, leaving their family (eg, spouse, parents) and regular training environment for the duration of a camp can be problematic. Paying more attention to several psychosocial concerns (eg, mood states), not only physiological ones, will allow a more thorough understanding of how individuals respond to LHTL interventions. Effective LHTL implementation may, therefore, require a foundation of several years of chronic exposure to hypoxia to maximize performance outcomes and limit potential biopsychosocial drawbacks.[36]

Lesson 6: Consideration of Current Training/Competitive Phase and Timing of Performance Evaluation Postintervention Directly Influences LHTL Outcomes

Traditionally, LHTL camps were designed to fit around athlete's competition schedule. It is now common for top athletes to use repeated altitude camps in their yearly plan, at multiple locations with mixed altitude training methods,[2] sometimes representing 45 to 60 days a year or even more.[31] Precompetition acclimatization (ie, 1–2 wk at the target altitude that may be of insufficient duration to induce worthwhile hematological benefits) versus using 2 to 4 weeks LHTL camps during the preparation phase or preseason to improve sea-level performance (ie, increased oxygen transport capacity of blood) have different objectives. To date, much of the LHTL literature has described the effects of a single camp at no particular time of the season, while measures to assess the changes that have occurred are often limited to the first few days postintervention.

Every practitioner has an opinion on the best time to compete after LHTL camps. While largely anecdotal, initial improvements soon after the camp (first week) followed after a brief period of attenuated performance (second week) by a longer period of improved performance (third to fifth week) are often reported.[37] Balancing the gradual decay of extra red blood cells, the readjustment of breathing patterns to oxygen-rich air, and possible neuromuscular adjustments—all having wide individual variation—likely dictate how long after a LHTL camp should athletes plan their competition.[38] Irrespective of any physiological adaptations, effective periodization (ie, appropriate taper) may also well influence when peak performance is achieved post-LHTL. As recommended by Saunders et al,[15] and incorporated in the original LHTL model,[3] the last few days to a week at altitude should be lighter in order to allow the athlete to "freshen up" before descent if competing immediately following the camp. Alternatively, if competition is delayed, an appropriate recovery block at sea level would then be necessary to absorb the general fatigue from training at altitude.

Lesson 7: LHTL Strategies Can Be Successfully Implemented to Increase Red Cell Mass and Maximal Aerobic Power With Both Natural and Artificial Altitude

Several terrestrial altitude sites (eg, Sierra Nevada, Spain; Yunomaru, Japan) allow relatively easy access to lower level training locations, facilitating implementation of LHTL. An alternative to commuting to lower elevations during LHTL is to breath supplemental oxygen, in turn allowing athletes to train at higher intensities (eg, Colorado Springs, USA).[39] Currently, LHTL interest continues to grow throughout the use of a wide range of normobaric (ie, nitrogen dilution or oxygen filtration) or hypobaric (eg, barometric pressure reduction) hypoxia simulation strategies that "bring the mountain to the athlete."[40] Special bedroom (eg, altitude tents) or complete altitude house blocks (ie, nitrogen houses) allow athletes to simultaneously adapt to chronic artificial hypoxia and train without having to travel up and down a mountain, also enabling more controlled studies (ie, double-blinded, standardized training programs). In addition to reducing the financial, time, and logistical challenges of traveling to altitude training sites, the use of artificial altitude represents a viable LHTL option for athletes from countries lacking suitable mountainous areas and enables individualization of the hypoxic stimulus.

Whether hypobaric hypoxia induces different adaptive responses (ie, ventilation, fluid balance or nitric oxide metabolism) than normobaric hypoxia is vigorously debated.[41] Changes in physiological (eg, acute rise in plasma erythropoietin[42]) and performance (eg, 3-km running test[43]) in response to a LHTL camp in normobaric versus hypobaric hypoxia are not different. Reportedly, natural and simulated altitudes of 2250 m evoke similar mean increases in Hb_{mass} and performance following an 18-day LHTL camp, despite a larger hypoxic dose in hypobaric compared to normobaric hypoxia (~315 vs 230 h).[44]

Most importantly, the duration of stay in the hypoxic environment must be sufficient to overcome the "off response" seen immediately on entering a normoxic environment. Many studies performed early in the evolution of normobaric hypoxia facilities (ie, altitude hotels or tents) suffered from an inadequate exposure, for example, only residing for 8 to 10 hours per day.[45] Such an exposure is clearly insufficient, and the cumulative evidence suggests that a minimum of 12 to 14 hours per day of hypoxia exposure is necessary. Moreover, ensuring that athletes do not spend the majority of their hypoxia exposure in bed is critical to avoiding the hemoconcentration of bed rest that may offset hematological adaptations.[46] Overall, LHTL camps using either natural or simulated altitude exposures can produce similar increases in red cell mass and endurance performance in well-trained athletes given sufficient exposure time. However, due to limitations in the time an athlete can actually stay in a confined normobaric hypoxic environment, it is likely more convenient to achieve an adequate altitude exposure using real altitude.

Lesson 8: Putative Adaptive Mechanisms (Hb_{mass}, Oxygen Cost of Breathing) as a Result of LHTL Are Often More Robust/Repeatable Than Performance Changes

The strong sense one gets from reading the Chapman et al[38] review is that changes in performance during the weeks after a LHTL intervention are characterized by an undulating nature. Living at a higher altitude, for a longer period, or a combination of both, likely cause a greater acclimatization response.[47] However, the higher an athlete resides does not guarantee that performance gains postintervention will necessarily follow a similar trend. Preventing the sudden drop in erythropoietin concentration (and by extension the rapid loss of the hematological adaptation) upon return to sea level, via hypoxia re-exposure, may in theory extend hematological benefits.[48] To date, however, there is limited empirical evidence documenting whether a sustained hematological response after LHTL occurs with this practice, and if this also leads to sustained performance benefits.[31]

There are several possible reasons for not seeing a corresponding increase in performance despite improved physiology post-LHTL. The larger variability in performance than physiological indicators post-LHTL may also reflect the accumulated fatigue during the camp and the management of training after altitude exposure.[15] This factor may explain why there is often an uncoupling between the decay in physiological responses and fluctuation in performance indicators.[38,44] In fact, even individual athletes do not always respond similarly when embarking on a LHTL camp, reinforcing the importance of contextual variables. For instance, in 8 highly trained runners undergoing two 3-week LHTL blocks separated by a 5-week washout period, Robertson et al[49] reported reproducible group mean increases for both maximal oxygen uptake and Hb_{mass} (~2%–3%), but not for mean changes in 3-km running times.

Lesson 9: Despite Endurance Athletes (eg, Swimmers, Runners, Cyclists) Being the Most Common Users of Altitude Training Approaches, LHTL Is Now Increasingly Popular in a Wider Range of Athletes (eg, Team and Racket Sports)

The conventional wisdom has long been that *altitude training be offered only to Olympic competitors entered in continuous* *endurance events*.[50] In recent times, the use of LHTL has received a great deal of attention within the team-sport community,[51] with the ultimate objective of improving match-running performance of players. Mounting evidence suggests that Hb_{mass} increases by 3% to 4% can be achieved in highly trained team-sport populations (ie, field hockey,[52] water polo,[23] or soccer players[53]) using shorter (10–14 d or 150–200 h) LHTL camps than was previously implemented for endurance athletes (>18–20 d or >300 h).[10] The current consensus indicates an increase in Hb_{mass} of ~1% per 100 hours of exposure to either natural or simulated altitude.[47] While still debated,[54] the fact that team-sport players typically possess lower relative Hb_{mass} values compared with elite endurance athletes before embarking on a camp may explain substantially larger erythropoietic responses post-LHTL in this cohort.[55]

The intermittent nature of team sports, and the determinants of success in the events presents a very different challenge compared to the prolonged continuous performance in endurance sports, which are heavily influenced by aerobic power. Until recently, however, virtually all performance tests to judge the efficacy of LHTL camps have been based on indicators of endurance-like performance (eg, 3–5 km running time trials).[38,42] Mounting evidence indicates that LHTL has a positive impact on physical attributes that may also enhance team-sport performance (ie, larger distance covered during Yo-Yo Intermittent Recovery test[52]), where both aerobic and anaerobic capacities are important. For instance, 3 normobaric LHTL exposures (10–11 d using 2500–3000 m simulated altitudes) induced large increases in Hb_{mass} of elite female water polo players before the 2012 Olympics, which were also very largely correlated with performance benefits during a multistage shuttle swim test.[23] It is, however, nearly impossible to quantify the extent to which hematological adaptations derived from a LHTL intervention for each individual positively impact a team's game result.

Lesson 10: Additional Hypoxic and/or Heat Exposure (if Well Managed) May Boost LHTL Benefits

The addition of other complementary strategies, such as "Live Low-Train High" altitude training or a heat acclimation protocol, targeting different biological responses than the LHTL model, may represent an attractive strategy to use environmental exposure to enhance performance.[37,56] For example, "Live High-Train Low and High" is a method whereby athletes reside in hypoxic environments, while at the same time, they maintain a sea-level training intensity (ie, high rates of oxygen flux) and also undergo few workouts in low oxygen

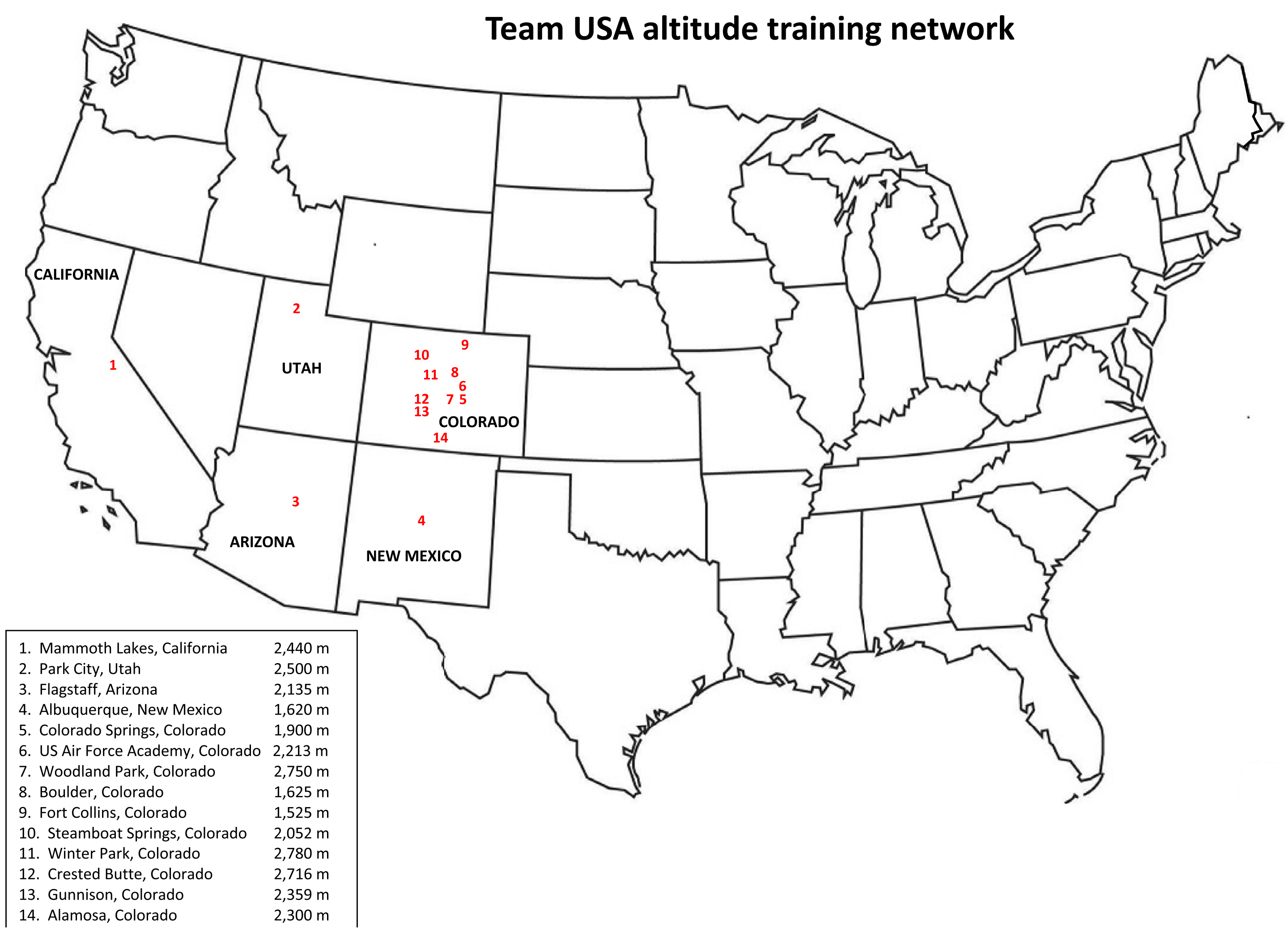

Figure 1 — Team USA altitude-training network.

conditions.[37,57] By adding "all-out" efforts conducted in hypoxia to the LHTL model to elicit concurrent aerobic and anaerobic adaptations, for instance, larger repeated-sprint ability gains were reported in field hockey players.[52] Analysis of muscle biopsy samples indicated an overexpression of transcription factors involved in oxygen-signaling and oxygen-carrying capacity and mitochondrial biogenesis for this modified LHTL method.[57] Alternatively, LHTL can be made logistically easier by allowing less intense training sessions to be conducted at altitude, where maximal oxygen flux is less important to the adaptation. The outcome of this "Live High-Train High and Low" approach, which minimizes the number of times workouts need to be performed at low altitude, has been documented to be identical to LHTL in terms of maximal oxygen uptake and sea-level 5-km time-trial performance.[6]

Another approach has been to combine heat acclimatization with a LHTL intervention.[56] The proposed rationale is that the increase in plasma volume encountered from heat exposure may counteract plasma volume decreases, due to diuresis and possibly extracellular-to-intracellular fluid shifts, in the early stages of altitude acclimation.[58] Improvements in plasma volume, Hb_{mass}, and maximal oxygen uptake were found when running heat training sessions on days where participants also lived at altitude.[56] However, this methodology has the potential to overstress the body to a point where the addition of chronic hypoxia (13 h/d at 3000 m) when completing a 21-day intermittent heat acclimation program may negate "normal" plasma volume expansion (despite increased Hb_{mass}) and impairs 3-km running performance, compared to if each intervention was conducted independently.[59] Perhaps greater hematological and ergogenic effects may be obtained if a heat acclimation block is instead used as "priming" (ie, via an increased plasma volume to offset the loss during the camp) in the period directly leading up to a LHTL camp. Future studies should therefore characterize the adaptive responses of LHTL with mixed environmental stressors, when used sequentially, or, both at the same time.

Practical Application—On the Successful Implementation of LHTL for Olympic Medal Performance

In 1996, essentially no Team USA athlete in the sport of athletics was using altitude training in their preparation for the 1996 Atlanta Olympics. Team USA athletes competing in the middle- (eg, 800 m, 1500 m) and long-distance events (eg, 3000 m steeplechase, 5000 m, 10,000 m, marathon, racewalk) failed to reach the podium in Atlanta, either female or male. With the publication of the first LHTL study in 1997 by Levine and Stray-Gundersen,[3] however, things began to change in terms of Team USA's approach to using altitude training in preparation for Olympic Games and World Championships. This new commitment to optimal use of altitude training included both the traditional, somewhat subjective "Live High-Train High" method, as well as the novel, data-based LHTL method.

Over the past 25 years, the use of altitude training, particularly LHTL, has grown among Team USA athletes who compete in several sports. This has resulted in the development of an altitude training "network" in the western region of the United States (Figure 1). Within the Team USA altitude training network, Colorado Springs, Colorado has served as the hub due to its geographical location in the Rocky Mountains, and, due to the fact that it serves as the home of the United States Olympic and Paralympic Training Center (USOPTC). The USOPTC campus includes the Team USA

Table 1 Team USA Athletes in the Sport of Athletics Who Have Used "LHTL" Altitude Training in Conjunction With Medal-Earning Performances at Recent Olympic Games and/or World Championships

Competition	Athlete	Event	Performance	Note
2016 Rio de Janeiro Olympics	Clayton Murphy	M 800 m	1:42.93/Bronze	
	Jenny Simpson	W 1500 m	4:10.53/Bronze	
	Matthew Centrowitz	M 1500 m	3:50.00/Gold	
	Emma Coburn	W 3000 m steeplechase	9:07.63/Bronze	AR
	Evan Jager	M 3000 m steeplechase	8:04.28/Silver	
	Paul Chelimo	M 5000 m	13:03.90/Silver	
	Galen Rupp	M marathon	2:10:05/Bronze	
2017 London World Championships	Ajee Wilson[b]	W 800 m	1:56.65/Bronze	
	Jenny Simpson	W 1500 m	4:02.76/Silver	
	Emma Coburn	W 3000 m steeplechase	9:02.58/Gold	CR
	Courtney Frerichs[a]	W 3000 m steeplechase	9:03.77/Silver	
	Evan Jager	M 3000 m steeplechase	8:15.53/Bronze	
	Paul Chelimo	M 5000 m	13:33.30/Bronze	
	Amy Cragg	W marathon	2:27.18/Bronze	
2019 Doha World Championships	Raevyn Rogers[b]	W 800 m	1:58.18/Silver	
	Ajee Wilson[b]	W 800 m	1:58.84/Bronze	
	Donavan Brazier	M 800 m	1:42.34/Gold	CR, AR
	Shelby Houlihan	W 1500 m	3:54.99/Fourth	AR
	Emma Coburn	W 3000 m steeplechase	9:02.35/Silver	

Abbreviations: AR, American record; CR, competition record; LHTL, live high-train low; M, men's; W, women's. Note: No Olympic Games or World Championships were held in 2018.
[a]Set the AR in W 3000-m steeplechase with a performance of 9:00.85 on July 20, 2018 (Monte Carlo, Monaco). [b]Did not use altitude training.

High Altitude Training Center, which offers the full range of altitude training experiences via natural and/or simulated altitude, including Live High-Train High, LHTL, and "Live Low-Train High."[39]

Team USA has enjoyed good success at the Olympic Games and World Championships in the sports of swimming (USA Swimming) and athletics (USA Track and Field). At the 2016 Rio de Janeiro Olympics, those 2 sports alone earned 54% (65/121) of the total medals won by the entire United States Olympic Team. Consistent with that success, USA Swimming and USA Track and Field have been committed to using altitude training with their top athletes for several years. For example, USA Swimming standouts Michael Phelps, Katie Ledecky, Simone Manuel, and Ryan Murphy have conducted regular "Live High-Train High" altitude training camps in Colorado Springs. USA Track and Field tends to follow the LHTL model, and they have had good success in implementing LHTL by residing in the states of Utah (Park City: 2500 m and Salt Lake City: 1425 m); Arizona (Flagstaff: 2135 m and Sedona: 1320 m); and Colorado (Woodland Park: 2750 m and Colorado Springs: 1900 m natural altitude, and train at simulated "sea level" [50 m] with the aid of supplemental oxygen via normobaric hyperoxia at USOPTC High Altitude Training Center).[2] In addition, USA Track and Field has conducted several LHTL altitude training camps internationally in San Moritz, Switzerland and Hida Ontake, Japan. USA Track and Field has expanded on the original LHTL model by living/sleeping "high," conducting moderate-intensity training "high," and conducting high-intensity training "low." At the 2016 Rio de Janeiro Olympics, USA Track and Field enjoyed one of their most successful Games in the middle- and long-distance events in almost 100 years. That trend continued at the 2017 London World Championships and 2019 Doha World Championships. Table 1 lists USA Track-and-Field athletes who have effectively used LHTL in preparation for medal-earning performances in recent Olympic Games and/or World Championships.

Additional Considerations

Despite positive observations arising from numerous research studies and real-world experiences (ie, podium performance), there are instances where no favorable effects occurred post-LHTL,[60] possibly due to decreased overall training adaptation (ie, disrupted sleep patterns, increased oxidative stress). In addition, it remains difficult to definitely establish the effects of altitude training alone since a number of factors other than altitude clearly influence

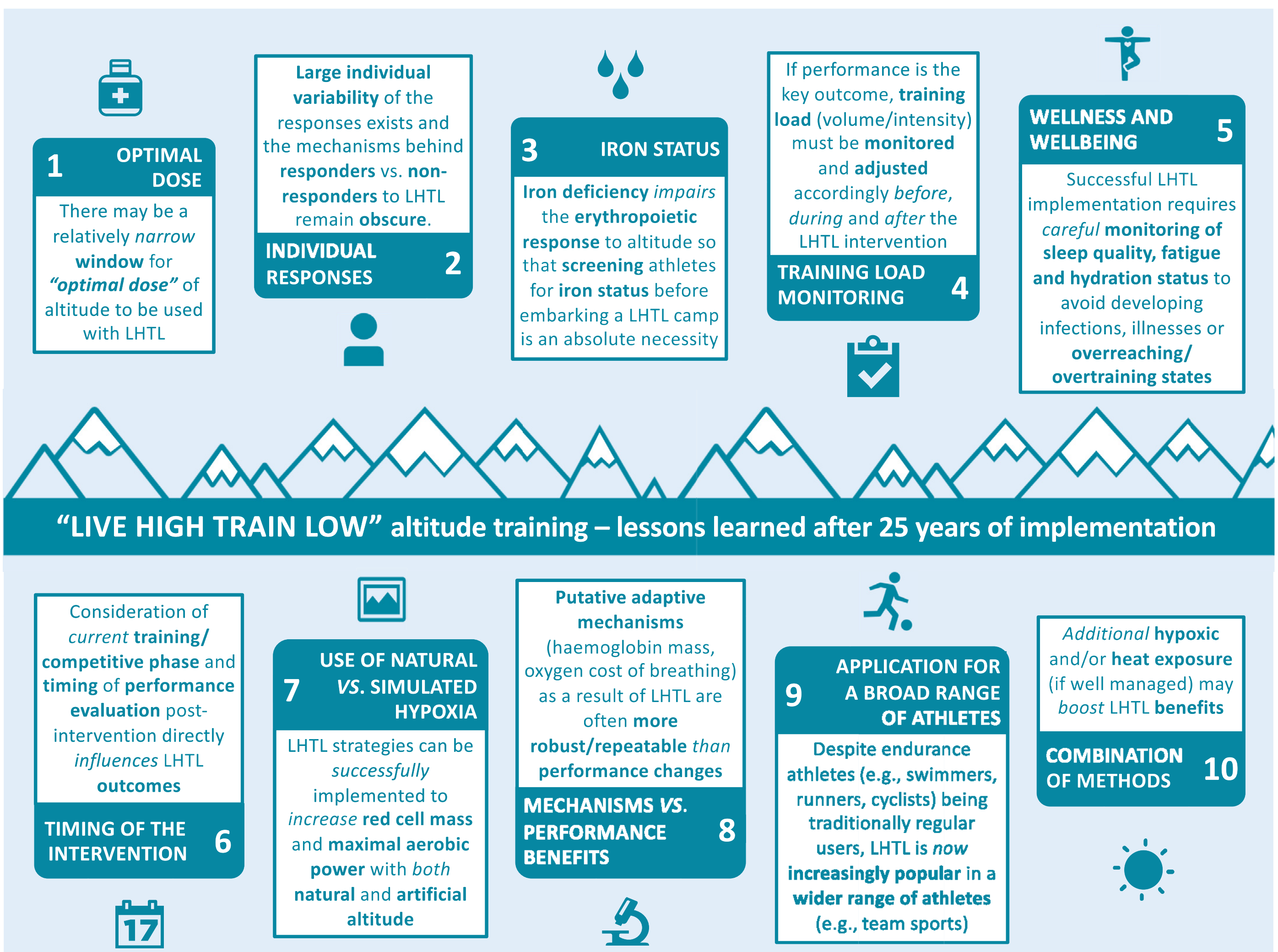

Figure 2 — "Live High-Train Low" altitude training: 10 lessons learned after 25 years of implementation.

performance. For example, the training load and periodization, due to different focus on volume/intensity at altitude versus sea level, can have a significant impact on performance[31] though these factors were well controlled when implementing the original LHTL model.[3] In some cases, the effects of altitude training may be confounded by other factors such as training camps or placebo effects, where the psychological benefits of being in a supportive environment or simply believing that the training will lead to improved performance is beneficial.[61] Overall, a range of factors can influence performance, independent of hypoxic exposure, making it challenging to isolate the true effects of LHTL. Altitude training should never be a substitute for a well-periodized training program in a well-prepared athlete with a supportive environment, good nutrition, and appropriate support.

Conclusion

Altitude-training research was initially guided by the experiences of elite practitioners. In the 1990s, specific scientific questions have driven the development of the LHTL model. While the time lag identified for the translation of research into “routine practice” often exceeds a decade,[62] a range of LHTL interventions have been implemented successfully in the “real world” in a much shorter time frame. Twenty-five years after its development, it is clear there are a variety of approaches using the LHTL model that can be implemented to effectively improve physiology and podium performance (Figure 2). Key variables such as the “hypoxic dose,” management of the training load, and the influence of contextual factors are essential to optimize and individualize benefits. While a solid body of knowledge indicates that LHTL is a viable and popular intervention, more work needs to be done to refine best practice for the largest number of athletes. Future research should focus on the multiplicity of factors that may interact with altitude to affect performance, notably genetic factors that influence the individual acclimatization response.[22,63] Finally, the evolution of the LHTL approach as a partnership among athletes, coaches, and sports scientists is an excellent model for the optimal implementation of sport science to improve athletic performance.

Acknowledgments

This review is dedicated to the memory of Dr James Stray-Gundersen, who passed away in the fall of 2022. Jim was a leader in the field of altitude training and will be sorely missed.

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