Live High + Train Low: Thinking in Terms of an Optimal Hypoxic Dose

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“Live high–train low” (LH+TL) altitude training allows athletes to “live high” for the purpose of facilitating altitude acclimatization, as characterized by a significant and sustained increase in endogenous erythropoietin and subsequent increase in erythrocyte volume, while simultaneously enabling them to “train low” for the purpose of replicating sea-level training intensity and oxygen flux, thereby inducing beneficial metabolic and neuromuscular adaptations. In addition to natural/terrestrial LH+TL, several simulated LH+TL devices have been developed including nitrogen apartments, hypoxic tents, and hypoxicator devices. One of the key issues regarding the practical application of LH+TL is what the optimal hypoxic dose is that is needed to facilitate altitude acclimatization and produce the expected beneficial physiological responses and sea-level performance effects. The purpose of this review is to examine this issue from a research-based and applied perspective by addressing the following questions: What is the optimal altitude at which to live, how many days are required at altitude, and how many hours per day are required? It appears that for athletes to derive the hematological benefits of LH+TL while using natural/terrestrial altitude, they need to live at an elevation of 2000 to 2500 m for ≥4 wk for ≥22 h/d. For athletes using LH+TL in a simulated altitude environment, fewer hours (12–16 h) of hypoxic exposure might be necessary, but a higher elevation (2500 to 3000 m) is required to achieve similar physiological responses.

Key Words: erythropoietin, intermittent hypoxic training, nitrogen dilution, normobaric hypoxia

Altitude training has been used by endurance athletes for many years based on the belief that it serves to enhance sea-level performance. The original model of altitude training was one in which athletes lived and trained in a natural/terrestrial hypobaric hypoxic environment at moderate altitude (1500 to 3000 m). This method of altitude training came to be known as “live high–train high” (LH+TH) altitude training and is still used today by many athletes. Although LH+TH altitude training has been studied extensively over several decades, it remains unclear whether it has an enhancing effect on sea-level performance. Whereas some investigations have demonstrated significant improvements in erythrocyte parameters, maximal
oxygen uptake (VO\textsubscript{2}max), or sea-level endurance performance after LH+TH altitude training, others have failed to do so.\textsuperscript{1-6}

One of the potential limitations of LH+TH altitude training is that many athletes are unable to produce the level of training intensity (eg, running velocity) and oxygen flux necessary to bring about or preserve the physiological changes that have a positive impact on performance. It is not uncommon to hear athletes remark that they seem to lose “speed” or “turnover” as a result of LH+TH altitude training, which ultimately has a negative impact on their sea-level performance. In response to this potential limitation of LH+TH altitude training, the live high–train low (LH+TL) altitude-training model was developed in the early 1990s by Drs Benjamin Levine and James Stray-Gundersen of the United States. The essence of LH+TL is that it allows athletes to “live high” for the purpose of facilitating altitude acclimatization (eg, an increase in endogenous erythropoietin [EPO] and resultant increase in erythrocyte volume and other nonerythropoietic adaptations) while simultaneously enabling them to “train low” to induce beneficial metabolic and neuromuscular adaptations. Based on the promising findings of the initial investigations of natural/terrestrial LH+TL\textsuperscript{7-9}, several modifications of LH+TL were developed in the 1990s. These include

- Nitrogen apartment: a normobaric hypoxic (2500 to 3000 m) living and sleeping environment created via nitrogen dilution.\textsuperscript{10-12}
- Hypoxic tent: a normobaric hypoxic (2000 to 4000 m) sleeping environment based on oxygen-filtration technology.\textsuperscript{11-12}
- Supplemental oxygen: a temporary (1- to 3-hour) normoxic training environment created by inhaling a medical-grade gas with the appropriate fraction of inspired oxygen to simulate sea-level conditions (partial pressure of inspired oxygen ~159 Torr).\textsuperscript{13-16}

Figure 1 outlines the different methods of altitude/hypoxic training currently used by endurance athletes, and a detailed review of literature regarding these methods is provided elsewhere.\textsuperscript{17}

![Altitude/Hypoxic Training Diagram](image)

**Figure 1** — Contemporary altitude training models. LH+TH indicates live high–train high; LH+TL, live high–train low; LL+TH, live low–train high; IHE, intermittent hypoxic exposure; and IHT, intermittent hypoxic training.
Research findings regarding the various modifications of LH+TL are equivocal. Whereas some investigations have demonstrated significant increases in erythrocyte volume and improvements in sea-level endurance performance, others have been unable to replicate those results. One possible explanation for the inconsistent results might be relatively small sample sizes, resulting in lack of statistical power and increased potential for type II error. A more likely explanation, however, is that a variety of protocols have been used to administer the hypoxic “dose.” There has been great disparity in the altitude—natural or simulated—at which athletes were exposed, the number of days of altitude/hypoxic exposure, and the number of hours per day of altitude/hypoxic exposure. This has led researchers to focus on the question, in using LH+TL, what is the optimal hypoxic dose needed to produce the expected beneficial physiological responses and sea-level performance effects in most individuals? Accordingly, the purpose of this review is to examine the concept of optimal hypoxic dose from a research-based and applied perspective by focusing on the following key questions:

- What is the optimal altitude at which to live?
- How many days are required at altitude?
- How many hours per day are required?

There is controversy regarding the primary physiological mechanism that influences sea-level endurance performance after altitude/hypoxic training. Whereas some have argued that the performance-enhancing effects of altitude/hypoxic training result from accelerated erythropoiesis, others think that the benefits are related to changes in running economy, skeletal-muscle buffering capacity, hypoxic ventilatory response, or skeletal-muscle Na\(^+\)-K\(^+\)-ATPase activity. Nevertheless, because most research on altitude/hypoxic training among endurance athletes has included direct and/or indirect markers of accelerated erythropoiesis, this article will focus primarily on optimal hypoxic dosage related to changes in serum EPO and erythrocyte volume.

**Dose–Response Concept Applied to Altitude/Hypoxic Training**

The analogy of a dose–response curve can be used to define the optimal hypoxic dose. In a medical scenario, the physician’s goal is to administer a pharmacological therapy that lies within the “therapeutic range.” In other words, the dose must be sufficient to induce the desired effect on at least 50% of the patients (“effective dose 50”) without exceeding the critical level that proves lethal to 50% or more of the patients (“lethal dose 50”). Any dose below the therapeutic range will be extremely safe but essentially ineffective in curing the illness or disease in most individuals. In contrast, any dose above the therapeutic range might be effective in curing the illness or disease but is likely to “kill the patient in the process.”

In an altitude/hypoxic-training scenario, the athlete’s goal is to live and sleep at an altitude—natural or simulated—within the beneficial range. This range should be high enough (and the exposure long enough) to induce the desired acclimatization effect in at least 50% of athletes (effective dose 50) via an acute and sustained increase in EPO and subsequent accelerated erythropoiesis (or other performance-enhancing physiological responses), without being so high that more
than 50% of athletes (lethal dose 50) are unable to recover from daily training or experience symptoms of acute mountain sickness or more debilitating high-altitude afflictions. This leads us to examine how coaches and athletes can design LH+TL altitude-training programs within the “beneficial range” for enhancing sports performance.

Practical Application of LH+TL: Optimal Hypoxic Dose

We now address the practical application of LH+TL altitude training and provide recommendations for the optimal hypoxic dose needed to induce the desired physiological responses and sea-level performance effects in most individuals. In defining the optimal hypoxic dose, the pertinent questions are how high and how long in terms of days and hours per day.

What Is the Optimal Altitude at Which to Live?

The question of optimal altitude range has been previously investigated in the laboratory and in the field. Forty-eight competitive runners were initially evaluated for serum EPO response after a 24-hour exposure to each of 4 elevations (1780, 2085, 2454, and 2800 m) via simulated hypobaric hypoxia. Subjects were then randomly assigned to live for 4 weeks at one of 4 natural/terrestrial altitudes (1780, 2085, 2454, 2800 m) after being matched for gender, prealtitude running performance, and the percentage increase in serum EPO at a simulated altitude of 2454 m. All 4 groups trained together at 1250 to 1780 m (high-intensity training) or 1700 to 3000 m (moderate-intensity training).

Hematological results indicated that serum EPO increased significantly after 6 hours at all 4 simulated altitudes and then remained at the same level after 24 hours at the 2 lowest elevations, 1780 m and 2085 m. In contrast, serum EPO continued to increase significantly after 24 hours at the 2 highest elevations, 2454 m and 2800 m, although there was no difference between 2454 m and 2800 m. Substantial individual variability in serum EPO response was demonstrated across the range of the 4 simulated altitudes, with some individuals exhibiting ~400% increments in serum EPO levels, whereas others did not increase serum EPO levels in response to 2800 m. After 4 weeks of LH+TL, VO\textsubscript{2} max increased in the runners who lived at the 3 highest elevations (2085, 2454, and 2800 m). The runners who lived at the 2 middle elevations, 2085 m and 2454 m, improved their postaltitude sea-level 3000-m-run performance by 2.8% (15.7 seconds) and 2.7% (16.6 seconds), respectively. In contrast, the runners who lived at the lowest altitude (1780 m) had only modest improvements in their postaltitude sea-level 3000-m-run time (6.3 seconds = 1.1%), as did the runners who lived at the highest altitude (2800 m; 7.1 seconds = 1.4%).

Collectively, these results suggest that the optimal altitude range for LH+TL altitude training is approximately 2000 to 2500 m. Elevations ≤1780 m might be too low for effective acclimatization and stimulation of a significant and sustained erythropoietic response in most individuals. Because serum EPO response at 2800 m was similar to that at 2454 m, and postaltitude sea-level running performance
was enhanced after living for 4 weeks at 2085 m and 2454 m, but not at 2800 m, elevations ≥2800 m do not appear to provide an additional erythropoietic effect (vs ~2500 m). In fact these elevations might be too high and could potentially induce some negative acclimatization effects that ultimately compromise sea-level endurance performance. Thus, based on these data, it appears that the optimal altitude range (beneficial range) for the LH+TL model is approximately 2000 to 2500 m for most athletes, keeping in mind that there is considerable individual variability in the altitude-acclimatization response.

Many investigators think that postaltitude sea-level endurance performance might be enhanced because of nonhematological changes, including running economy, skeletal-muscle buffering capacity, hypoxic ventilatory response (HVR), and skeletal-muscle Na⁺-K⁺-ATPase activity. These studies employed a LH+TL protocol with well-trained endurance athletes who lived/slept at an elevation of 2000 to 3100 m in normobaric hypoxia (nitrogen house), for 8 to 12 h/d for 20 to 23 days. The athletes trained and lived for the balance of the day at 600 m in normobaric normoxia. It appears that the minimal elevation at which athletes should live and sleep to bring about potentially beneficial physiological changes in running economy, skeletal-muscle buffering capacity, HVR, and skeletal-muscle Na⁺-K⁺-ATPase activity is similar to that recommended for accelerated erythropoiesis—approximately 2000 m. It also appears, however, that elevations up to 3100 m, which is relatively higher than the 2500-m recommended upper limit for inducing accelerated erythropoiesis without compromising recovery, are effective (and potentially necessary) to bring about performance-affecting changes in nonhematological physiological parameters.

How Many Days Are Required at Altitude?

Several LH+TL investigations, as well as altitude training “camps,” have employed an altitude exposure of 28 consecutive days at moderate altitude (2500 m), based in large part on previous studies of exogenous EPO supplementation and its effect on erythropoiesis. Even after recombinant human EPO is injected directly 3 times per week, there is little change in hemoglobin concentration or hematocrit for the first 7 to 10 days, and then only a minimal increase after 2 weeks. There is, however, accelerated erythropoiesis during weeks 3 and 4 post-EPO injection, as evidenced by significant increments in hemoglobin concentration and hematocrit. Hypoxic exposure ≤2 weeks in duration will probably not increase erythrocyte volume; rather, a minimum of 3 to 4 weeks appears necessary for accelerated erythropoiesis to occur.

This “4-week minimum” guideline for inducing accelerated erythropoiesis is supported by a number of published and unpublished studies. Levine and Stray-Gundersen reported a minimal increase (≤2.2%) in erythrocyte volume resulting from less than 2 weeks of natural or simulated (normobaric hypoxia via nitrogen dilution) altitude exposure. With an increase in altitude exposure beyond 2 weeks, however, there was a prominent increase in the magnitude of the erythropoietic response, particularly as the hypoxic exposure increased to 4 weeks (7.1% to 7.9%). This effect appears to be substantial whether the altitude is natural/terrestrial or simulated via nitrogen-dilution technology.
Studies that have reported significant nonhematological changes resulting from LH+TL have used either continuous or intermittent protocols of 20 to 23 days (8 to 12 h/d, 2000 to 3100 m) of exposure to normobaric hypoxia (nitrogen apartment). Thus, it appears that 3 weeks, but not necessarily 4 weeks, are required to elicit potentially beneficial changes in running economy, skeletal-muscle buffering capacity, HVR, and skeletal-muscle Na\(^+\)-K\(^+\)-ATPase activity.

How Many Hours per Day Are Required?

Natural/terrestrial altitude of 2000 m to 2500 m with hypoxic exposure ≥22 h/d should be sufficient to stimulate an accelerated erythropoiesis and enhance postaltitude sea-level endurance performance. Using simulated altitude (normobaric hypoxia via nitrogen dilution or oxygen filtration), hypoxic exposure of 12 to 16 h/d might have similar erythropoietic effects, provided athletes are exposed to higher altitudes (2500 to 3000 m). It appears, however, that there is an additive effect as hypoxic exposure increases beyond 12 to 16 h/d, as illustrated in Figure 2.

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which shows the effect of 3 different hypoxic-exposure protocols on erythrocyte volume. The data shown on the left side of Figure 2 from the initial LH+TL study of Levine and Stray-Gundersen. That study employed a hypoxic exposure of approximately 22 h/d for 4 weeks at a natural altitude of 2500 m and resulted in significant prealtitude versus postaltitude increases in erythrocyte volume (8%), treadmill VO\textsubscript{2}max (4%), and 5000-m-run performance (1.3%) at sea level. The middle set of data in Figure 2 (nitrogen house, 16 h/d) is taken from the investigation of Rusko et al that evaluated the efficacy of LH+TL altitude training in Finnish endurance athletes using a nitrogen house. The hypoxic exposure was 12 to 16 h/d for 25 days at a simulated altitude of 2500 m, resulting in substantial prealtitude versus postaltitude increases in erythrocyte volume (5%) and treadmill VO\textsubscript{2}max (3%), which were slightly lower than the increments seen in the 22-h/d protocol used by Levine and Stray-Gundersen. Finally, the data shown on the right side of Figure 2 (nitrogen house, 8 to 10 h/d) come from the study of Ashenden et al that evaluated the efficacy of LH+TL altitude training in Australian national-team cyclists using a nitrogen house. The athletes completed a daily hypoxic exposure of 8 to 10 hours for 12 days at a simulated altitude of 2650 m, which did not significantly alter hemoglobin mass (VO\textsubscript{2}max not measured or reported). Collectively, the data from these 3 representative investigations suggest that (1) a daily hypoxic exposure of \(\leq 8\) to 10 hours is inadequate to stimulate erythropoiesis; (2) a daily hypoxic exposure to simulated altitude of 12 to 16 hours appears to be sufficient to stimulate erythropoiesis in most individuals, provided the simulated altitude is 2500 to 3000 m; and (3) a daily hypoxic exposure \(\geq 22\) h/d at a natural altitude of 2000 to 2500 m should accelerate erythropoiesis and enhance postaltitude sea-level performance in most individuals. These observations were confirmed in recent investigations of elite endurance athletes in France and Switzerland. In terms of nonhematological changes, it appears that a daily hypoxic exposure to simulated altitude (normobaric hypoxia via nitrogen dilution) of 8 to 12 h/d (2000 to 3100 m, 20 to 23 days) is sufficient to induce potentially beneficial changes in running economy, skeletal-muscle buffering capacity, HVR, and skeletal-muscle Na\textsuperscript{+}–K\textsuperscript{+}–ATPase activity.

In the past decade, intermittent hypoxic exposure (IHE) and intermittent hypoxic training (IHT) have become viable altitude-training options for athletes because they can be undertaken with minimal travel or inconvenience. In using IHE, athletes live in a natural, normobaric normoxic environment and are exposed in a resting state to short intervals (5 to 180 minutes) of simulated normobaric hypoxia or hypobaric hypoxia. In other words, IHE allows athletes to live low–train high (LL+TH). Normobaric hypoxia can be simulated via nitrogen dilution (e.g., Altitrainer 200 hypoxicator), oxygen filtration (e.g., Go2Altitude hypoxicator), or inspiration of hypoxic gas. IHT is essentially IHE undertaken in conjunction with an exercise or training session. It is purported that IHE/IHT can enhance athletic performance by stimulating an increase in serum EPO and erythrocyte volume. IHT is purported to augment skeletal-muscle mitochondrial density, capillary-to-fiber ratio, and fiber cross-sectional area via up-regulation of HIF-1\(\alpha\). The key research findings regarding the efficacy of IHE/IHT can be reviewed in detail elsewhere. However, the empirical evidence regarding the efficacy of IHE/IHT on erythropoietic response and sea-level endurance performance is not exceptionally
compelling. Only a few well-designed, well-controlled studies on trained or elite athletes have reported increments in hemoglobin concentration,\textsuperscript{45,46} and to my knowledge none have evaluated or reported any increases in robust erythropoietic markers such as soluble transferrin receptor, erythrocyte volume, or hemoglobin mass. Furthermore, no IHE/IHT study has demonstrated improvements in VO\textsubscript{2}max, and only 25\% have reported that sea-level athletic performance was enhanced after IHE/IHT.\textsuperscript{45,47-49} In contrast, several studies have failed to demonstrate significant alterations in erythropoietic acceleration, VO\textsubscript{2}max, or post-IHE/IHT performance at sea level.\textsuperscript{50-61} Finally, to my knowledge, the effect of IHE/IHT on nonhematological mechanisms in well-trained endurance athletes has only been examined in a few studies.\textsuperscript{48,49,55,58} This lack of investigation is surprising considering the underlying premise that nonhematological mechanisms are responsible in part or in whole for the purported enhancement of athletic performance after IHE and, particularly, IHT.

A final note regarding IHE/IHT: A number of studies have found that IHE/IHT is an effective method of preacclimatization before ascending to high altitude (>4000 m),\textsuperscript{62-65} and those findings are presented in detail elsewhere.\textsuperscript{66} Although this series of IHE/IHT studies was conducted on mountaineers and soldiers, the findings have implications for athletes who include altitude-training camps in their seasonal training programs. Based on the current literature,\textsuperscript{62-65} it appears that IHE/IHT can be used effectively by athletes to preacclimatize, either before competition at altitude (eg, Mexico City, 2300 m, Salt Lake City, 1250 m) or before undertaking an extended altitude-training block.

In summary, hypoxic exposure of approximately 22 hours at a natural altitude of 2000 to 2500 m should be sufficient to stimulate the erythropoietic pathway and enhance postaltitude sea-level endurance performance. When using simulated altitude (normobaric hypoxia via nitrogen dilution or oxygen filtration), hypoxic exposure of 12 to 16 h/d should have similar erythropoietic effects, as well as some performance-affecting nonhematological effects, provided that athletes are exposed to higher altitudes (2500 to 3000 m). Daily hypoxic exposures of ≤8 to 10 hours appear to be ineffective in terms of enhancing erythropoietic response and sea-level endurance performance. Finally, there is minimal evidence that IHE/IHT—either alternate hypoxia/normoxia short-interval (5-minute) sessions, or longer (1- to 3-hour) continuous sessions—provides the necessary acclimatization and physiological stimuli to produce beneficial changes in erythrocyte volume, VO\textsubscript{2}max, and sea-level performance. IHE/IHT might, however, be a viable preacclimatization strategy for athletes to use before training or competing at altitude.

**Integration of LH+TL in Elite Sport**

The US Olympic team in long-track speed skating represents an example of the successful integration of several LH+TL altitude-training methods. This team initially used LH+TL in preparation for the 2002 Salt Lake City Winter Olympics. Three years before the Salt Lake City Olympics, the speed skaters began living in the Deer Valley/Park City area of the western US state of Utah (~2500 m) to enhance erythrocyte volume and acclimatize at an elevation markedly higher than the altitude of their competition venue (Utah Olympic Oval ~1425 m). The athletes continue to use Deer Valley/Park City as their base of operation and use different LH+TL methods depending on the specific phase of the competitive season.
During the base phase of the season (~4 months), the speed skaters focus almost exclusively on moderate-intensity, high-volume, dry-land training at 2000 to 2500 m. There is minimal emphasis on high-intensity training during this phase, so essentially the athletes adhere to the traditional LH+TH model at this time. There are also some sea-level training blocks during the base phase, but the training intensity remains moderate. During the precompetition phase of the season (~3 months), the speed skaters use a LH+TL regimen in which they continue moderate-intensity, dry-land training at 2000 to 2500 m. They complement this with high-intensity off-ice interval training using in-line skates on an oversized treadmill while breathing supplemental oxygen, which allows them to temporarily and conveniently train at “sea level.” They also spend significant time on ice during the precompetition phase, with emphasis on technical refinement, as well as continued advancement of their conditioning. During the competition phase of the season (~5 months), the emphasis is on high-intensity, race-pace training, and the speed skaters use the Utah Olympic Oval (1425 m) to train low. In addition, they use supplemental oxygen (portable backpack unit) in conjunction with select high-intensity on-ice training sessions at the Utah Olympic Oval during the competition phase. Approximately 4 weeks before a major competition such as the World Championships, the speed skaters abandon use of supplemental oxygen.

The US national-team speed skaters compete internationally and therefore spend several weeks away from their natural/terrestrial altitude-training base in Park City. In an effort to maintain altitude/hypoxia acclimatization, they have frequently relied on simulated altitude devices. Initially, they experimented with using hypoxic tents while traveling to Europe but found them difficult to transport and relatively uncomfortable to sleep in, thereby compromising recovery from training and competition. In recent years, however, the US speed skaters have worked out an agreement with several of the Scandinavian speed-skating teams to use nitrogen apartments and dormitories located in those countries. In addition, they make use of several hypoxic apartments at the Petit National Ice Center during select sea-level training blocks in Milwaukee, Wis (176 m).

The US long-track speed skaters enjoyed unprecedented success in the 2002 Salt Lake City Winter Olympics, with 6 athletes winning 8 medals, including 3 gold medals and 2 world records. The athletes continued to use LH+TL methods in the quadrennium before the 2006 Torino Winter Olympics, during which time they established themselves as one of the best and most consistent speed-skating teams in the world based on World Cup and World Championship performances. Similar to the 2002 Salt Lake City Olympics, US long-track speed skaters performed very well in the 2006 Torino Olympics, capturing 3 gold, 3 silver, and 1 bronze medal.

In summary, the US Olympic team in long-track speed skating has been a leader in the use of LH+TL altitude training to enhance elite performance. The US speed skaters have credited LH+TL as an important part of their success over the past 10 years and have served as a model for other US national-team athletes to integrate LH+TL into their training programs. Included in this group are the US Olympic marathon runners, who enjoyed unprecedented success at the 2004 Athens Olympics (Deena Kastor, bronze; Meb Keflezighi, silver) after using natural/terrestrial LH+TL altitude training. A summary and cost–benefit analysis of the different methods of LH+TL are provided in Table 1.
Table 1  Summary of Methods Used for Live High–Train Low (LH+TL) and Live Low–Train High (LL+TH) Altitude Training*

<table>
<thead>
<tr>
<th>Method</th>
<th>Application</th>
<th>Cost vs benefit</th>
</tr>
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<tbody>
<tr>
<td>LH+TL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>natural/terrestrial</td>
<td>Live and sleep in a natural/terrestrial hypoxic environment.</td>
<td>Locations that have close proximity of high vs low sites might be difficult to find or travel to. No simulated altitude equipment required. Living and training in a mountain environment.</td>
</tr>
<tr>
<td></td>
<td>Train in a natural/terrestrial normobaric normoxic environment at or near sea level.</td>
<td></td>
</tr>
<tr>
<td>nitrogen</td>
<td>Live and sleep in a normobaric hypoxic environment simulated via nitrogen dilution ($\downarrow F_1O_2$).</td>
<td>Potential additional expense of construction, maintenance, and use of equipment. Number of hours of living and sleeping required for physiological benefits might interfere with lifestyle and multiple training sessions. Convenient in terms of proximity of high vs low sites.</td>
</tr>
<tr>
<td>apartment</td>
<td>Train in a natural/terrestrial normobaric normoxic environment at or near sea level.</td>
<td></td>
</tr>
<tr>
<td>hypoxic tent</td>
<td>Live and sleep in a normobaric hypoxic environment simulated via oxygen filtration ($\downarrow F_1O_2$).</td>
<td>Potential additional expense of purchase and maintenance of equipment. Number of hours of living and sleeping required for physiological benefits might interfere with lifestyle and multiple training sessions. Convenient in terms of proximity of high vs low sites.</td>
</tr>
<tr>
<td></td>
<td>Train in a natural/terrestrial normobaric normoxic environment at or near sea level.</td>
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supplemental oxygen
Live and sleep in a natural/terrestrial hypobaric hypoxic environment.
Train in a simulated normoxic environment via use of supplemental oxygen (↑ \( F_iO_2 \)).
Potential added expense of construction, maintenance, and use of equipment.
Convenient in terms of proximity of high vs low sites. Living in a mountain environment.

LL+TH
intermittent hypoxic exposure
Live and sleep in a natural/terrestrial normobaric normoxic environment.
Brief exposure to simulated hypobaric hypoxia (↓ \( PO_2 \)) or normobaric hypoxia (↓ \( F_iO_2 \)).
Potential additional expense of purchase and maintenance of equipment. Scientific support less extensive vs LH+TL.
Convenient in terms of proximity of low vs high sites. Potential use for preacclimatization to altitude.

intermittent hypoxic training
Live and sleep in a natural/terrestrial normobaric normoxic environment.
Train in simulated hypobaric hypoxia (↓ \( PO_2 \)) or normobaric hypoxia (↓ \( F_iO_2 \)).
Potential additional expense of purchase and maintenance of equipment. Scientific support less extensive vs LH+TL.
Convenient in terms of proximity of low vs high sites. Potential for use in preacclimatization to altitude.

*↑ indicates increase; ↓, decrease; \( F_iO_2 \), fraction of inspired oxygen; and \( PO_2 \), partial pressure of oxygen.
Simulated Altitude:
Update on Ethical and Legal Issues

Athletes and coaches need to be aware of the fact that some of the LH+TL methods described in this article have recently come under review by the World Anti-Doping Agency (WADA). The rationale behind the WADA review is related to the fact that WADA officials are concerned that some athletes who are exploiting illegal erythropoietic agents are making use of “utilization of simulated altitude” as a false explanation for their abnormally elevated hemoglobin and hematocrit levels, thereby circumventing WADA’s list of prohibited substances and methods. WADA currently considers artificially induced hypoxic conditions to include hypobaric hypoxia (barometric pressure chamber), normobaric hypoxia via nitrogen dilution (nitrogen apartment; Altitrainer 200 hypoxicator), or normobaric hypoxia via oxygen filtration (hypoxic apartment or tent; Go2Altitude hypoxicator).

After extensive review of the relevant research and consultation with scientific experts in the area of altitude/hypoxic training, the WADA executive committee reached a final decision regarding artificially induced hypoxic conditions in September 2006. The decision was announced by WADA Chairman Richard Pound as follows:

In response to our stakeholders who requested that there be full consideration of hypoxic conditions in the context of the Prohibited List, WADA performed a scientific and ethical review of the matter, and engaged in a thorough consultation with experts and stakeholders. While we do not deem this method appropriate for inclusion on the List at this time, we still wish to express the concern that, in addition to the results varying individually from case to case, use of this method may pose health risks if not properly implemented and under medical supervision. http://altitudeforall.info/index.html

This statement indicated that WADA does not prohibit the use of “artificially induced hypoxic conditions” by elite athletes, at least through 2007. It should be noted, however, that in Italy all hypobaric or hypoxic practices are currently prohibited, as mandated by the Italian Health Ministry in June 2005 (Decree of the Italian Ministry of Health 13.04.2005. Section 5, Subsection M.1, June 3, 2005) in response to an incident involving professional cyclists competing in the 2005 Giro d’Italia (stage 10; May 18, 2005). The Italian law regarding simulated altitude is totally independent of any current and future WADA rulings and presently has judicial precedence over any WADA rulings in areas of Italian jurisdiction. Finally, the International Olympic Committee has prohibited the use of simulated altitude devices within the boundaries of the Olympic Village since the 2000 Sydney Olympics, and this mandate is expected to apply to all future summer and winter Olympic Games.

Conclusion

The purpose of this review was to objectively evaluate the important issue of, when using LH+TL, what the optimal hypoxic dose is that is needed to facilitate altitude acclimatization and produce the expected beneficial physiological responses and
sea-level performance effects in most individuals. In attempting to define the optimal hypoxic dose, 3 key questions have been addressed: What is the optimal altitude at which to live, how many days are required at altitude, and how many hours per day are required? Based on the current literature, it appears that for most athletes to effectively acclimatize and achieve an increase in erythrocyte volume significant enough to enhance postaltitude endurance performance, they need to live at a natural/terrestrial altitude of 2000 to 2500 m for a minimum of 4 weeks to include a daily hypoxic exposure of ≥22 hours. Based on investigations of LH+TL using simulated altitude (normobaric hypoxia via nitrogen dilution or oxygen filtration), fewer hours of hypoxic exposure appear necessary (12 to 16 hours), but a higher elevation (2500 to 3000 m) is required to achieve similar erythropoietic effects.

Evidence regarding the effects of LH+TL on nonhematological mechanisms is less extensive. Based on the current literature, however, it appears that exposure to simulated altitude (normobaric hypoxia via nitrogen dilution) of 2000 to 3100 m for 8 to 12 h/d for 20 to 23 days can elicit beneficial physiological changes in running economy, skeletal-muscle buffering capacity, HVR, and skeletal-muscle Na$^+$-K$^+$-ATPase activity.

There is considerable individual variation in the physiological responses of athletes using altitude/hypoxic training, and differentiation between “responders” and “nonresponders” is probably based in part on genetic predisposition. Future research should be directed toward identifying the specific genetic factors that influence the observed individual variation in the altitude/hypoxic-acclimatization response. Ultimately, a clearer understanding of the key factors (genetic or otherwise) affecting an athlete’s individual acclimatization response at altitude will enable sport scientists and coaches to better determine an optimal hypoxic dose for each athlete.

References


