Living altitude influences endurance exercise performance change over time at altitude

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Department of Kinesiology, Indiana University, Bloomington, Indiana; K. G. Jebsen Center of Exercise in Medicine, Department of Circulation and Medical Imaging, Norwegian University of Science and Technology, Trondheim, Norway; Research Center for High Altitude Medicine, Qinghai University, Qinghai, China; US Ski and Snowboard Association, Park City, Utah; and Institute for Exercise and Environmental Medicine, Texas Health Presbyterian Dallas, The University of Texas Southwestern Medical Center, Dallas, Texas

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Chapman RF, Karlsen T, Ge RL, Stray-Gundersen J, Levine BD. Living altitude influences endurance exercise performance change over time at altitude. J Appl Physiol 120: 1151–1158, 2016. First published March 10, 2016; doi:10.1152/japplphysiol.00909.2015.—For sea level based endurance athletes who compete at low and moderate altitudes, adequate time for acclimatization to altitude can mitigate performance declines. We asked whether it is better for the acclimatizing athlete to live at the specific altitude of competition or at a higher altitude, perhaps for an increased rate of physiological adaptation. After 4 wk of supervised sea level training and testing, 48 collegiate distance runners (32 men, 16 women) were randomly assigned to one of four groups. Subjects completed 3,000-m performance trials on the track at sea level, 28 and 6 days before departure, and at 1,780 m on days 5, 12, 19, and 26 of the altitude camp. Groups living at 2,454 and 2,800 m had a significantly larger slowing of performance vs. the 1,780-m group on day 5 at altitude. The 1,780-m group showed no significant change in performance across the 26 days at altitude, while the groups living at 2,085, 2,454, and 2,800 m showed improvements in performance from day 5 to day 19 at altitude but no further improvement at day 26. The data suggest that an endurance athlete competing acutely at 1,780 m should live at the altitude of the competition and not higher. Living ~300-1,000 m higher than the competition altitude, acute altitude performance may be significantly worse and may require up to 19 days of acclimatization to minimize performance decrements.

NEW & NOTEWORTHY

This study adds new practical information for endurance athletes, coaches, and sport physiologists on the best living altitude and acclimatization time for altitude training before an endurance competition taking place at altitude. We recommend that endurance athletes competing acutely at a low altitude (1,780 m) acclimatize by living at that altitude and not higher. Athletes choosing to live at a higher altitude may need longer acclimatization time to minimize performance decrements at altitude.

IT IS WELL ESTABLISHED THAT endurance exercise performance in select events (e.g., running, cycling, swimming) is impaired with acute exposure to altitude, will improve over time with chronic acclimatization, but will not reach the same level of performance that would normally be obtained at sea level (20, 36). Knowing this outcome, sea level based athletes who engage in competitive endurance exercise events at altitude will commonly plan for some period of time in residence at altitude before the competition to minimize the altitude-mediated performance declines. From a practical and logistical standpoint, two variables that must be selected by the athlete related to altitude acclimatization are 1) how long to arrive at altitude before the event, and 2) at what altitude to reside, relative to the altitude of the event.

The question of when to arrive at altitude before an endurance exercise competition at moderate altitude has been explored, and the data suggest that performance improves significantly over the first 14 days of living at the same altitude as the performance trial, with a minimal rate of improvement afterwards (41). However, the altitude at which it is best to reside for altitude performance remains unclear. Most studies that have examined altitude performance with chronic exposure have utilized either the same living and performance altitudes (2, 17, 39) or have used a lower, moderate-altitude living exposure as a preacclimatization period before high-altitude exposure (5, 8, 18, 37, 42). Whether living at an altitude higher than the altitude of the competition is more advantageous than living at the competition altitude is not known. For many physiological responses associated with altitude acclimatization, the magnitude of the response is dependent on the living altitude (16). Therefore, living at a higher altitude may augment the magnitude or accelerate the rate of positive adaptive responses (e.g., ventilatory acclimatization), which could theoretically reduce the number of acclimatization days needed to minimize performance decline. However, higher living altitudes may also enhance acclimatization responses, which are potentially negative to endurance exercise performance (e.g., poor sleep quality, increased plasma volume). This which would suggest the alternate possibility that living at the competition altitude, and not higher, would be the preferred strategy.

The purpose of this study was to examine the decline in competitive distance running performance between sea level and a low altitude (1,780 m), as a function of 1) differing strata of living altitudes equal to and higher than the altitude of the competition, and 2) days in residence at altitude. We hypothesized that athletes living at progressively higher altitudes than the altitude of the competition would have progressively smaller declines in performance with acute exposure to altitude.

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MATERIALS AND METHODS

Subjects

Forty-eight collegiate track and cross country runners (32 men and 16 women, 21 ± 2 yr, 64.0 ± 8.4 kg, and 174 ± 9 cm) volunteered to participate in the study and gave their informed consent after receiving information of the study protocol. Data from this cohort on responses to physiological and performance changes at sea level after altitude training (12), acute hypobaric hypoxia (22, 23), and submaximal exercise (35) have been published elsewhere. Exclusion criteria included altitude residence (>1,500 m) longer than 7 days in the previous 10 mo, permanent altitude residence of >3 mo during their lifetimes, or injury or illness that impaired normal training and racing before the study. All subjects gave written informed consent to a protocol approved by the Institutional Review Board of the University of Texas Southwestern Medical Center at Dallas and Presbyterian Hospital of Dallas.

Study Protocol

The study protocol was a modified version of previous protocols developed by the authors (34, 43) and is described in detail in Ref. 11. The study protocol is visually displayed in Fig. 1. Briefly, in the first phase of the study, 4 wk of supervised sea level training in Dallas, TX was performed, during which exercise testing, simulated altitude exposure, blood testing, and iron maintenance or replacement therapy was initiated. In the second phase of the study, subjects were transported by airplane to Salt Lake City, UT. Subjects were randomly assigned to one of four groups, and each group of subjects was housed in the Wasatch mountain area for a 28-day altitude training camp. In Utah, subjects in each altitude group were housed in comparable vacation residences, typical of a ski resort area. Subjects slept one or two to a bedroom. Although food intake was not controlled, weekly grocery shopping trips were supervised by research staffs to ensure healthy food choices were purchased.

Altitude Training Camp

Subjects were matched by sex, training history, $V_{O_2\ max}$, and 3,000-m performance time in groups of four and assigned in a balanced randomization to housing at four different altitudes in the Wasatch mountain region near Salt Lake City. Four women and eight men constituted each of the four altitude groups. Subjects lived at Heber City (1,780 m), Park City (2,085 m), Deer Valley (2,454 m), or Guardsman’s Pass (2,800 m). During the training camp, subjects were instructed to spend the majority of time at their assigned living altitude and were supervised by a staff member to ensure compliance. With some exceptions, subjects gathered daily for supervised training at the same altitude and location (between 1,250 and 3,000 m), regardless of the subjects’ assigned living altitude. This effectively standardized the training altitude across all subjects for each day of the altitude exposure. Group training at a common altitude was also necessary to control for and maintain the group training dynamic established during the 4-wk prealtitude training period. Training followed the “HiHiLo” model of live high-train low-altitude training (i.e., moderate-altitude living, moderate-altitude low-intensity base training, and high-intensity training at low altitude) (43). Low-intensity and moderate “base” training took place at mild to moderate altitudes (1,780–3,000 m), while higher intensity runs and aerobic interval training sessions were performed at the lowest possible altitude in Salt Lake City (1,250 m). All subjects received daily liquid iron supplementation (Feo-Sol, 9 mg elemental iron/ml) during both the 4-wk sea level and 4-wk altitude training camps in doses based on prealtitude ferritin concentration (5–45 ng/ml). In testing the week before altitude exposure, all men had serum ferritin levels >30 ng/ml, and all women were >20 ng/ml.

Training Quantification and Standardization

Subjects kept daily training logs, which included training volume (recorded in units of miles run per day) and the number of “high-intensity” workout sessions (e.g., interval training or tempo runs performed at a pace, subjectively determined by the athlete, as being faster than lactate threshold pace). Before the study, each athlete and his or her coach were given a global training template, previously used by the researchers in altitude training studies (34, 43), to design their individual training plan. This template has previously been successful in matching training impulse across multiple groups living and/or training at different altitudes. Athletes were asked to complete common workouts (e.g., interval sessions, long runs, tempo efforts) on the same day of the week, so that an overall group training milieu could be established and recovery before the time trials could be standardized.

Assessments

Performance assessments. Performance at both sea level and altitude was assessed by 3,000-m time trial races on 400-m outdoor tracks. Subjects were instructed to achieve the best time possible in each race. Experienced pace setters (athletes not involved in the study) were utilized to set a fast, competitive pace for the first 1,600 m of the 3,000-m race to ensure physiological rather than tactical performance.

Fig. 1. Study timeline. Subjects completed 4 wk of sea level training, followed by 4 wk of HiHiLo altitude training (i.e., moderate-altitude living, moderate-altitude low-intensity base training, and high-intensity training at low altitude), with groups assigned to 1 of 4 different living altitudes. Testing was completed at various time points throughout the experiment (see MATERIALS AND METHODS).

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The pace setter or “rabbit” ran the same preselected race pace in all time trials. Time was recorded for each athlete to the nearest 0.1 s.

Sea level time trials took place in Dallas and were performed at study initiation and after 4 wk of group sea level training, 6 days before departure for altitude. The sea level time trial races were held between 0700 and 0800 in the morning and were run in separate women’s and men’s heats. Altitude time trials took place weekly in Heber City (1,780 m) on days 5, 12, 19, and 26 after arrival at altitude, the frequency of which matches the protocol previously used by Schuler et al. (41). The altitude time trials were held between 0730 and 0830 in the morning and were run in separate women’s and men’s heats.

Procedures and outcomes of the assessments listed below have been reported previously (12) and are described in brief here.

Treadmill assessment. Submaximal and maximal oxygen uptake (VO2max) were tested at sea level (Dallas) on two occasions before departure for altitude. Test one was performed upon initial athlete arrival for the study and test two after 4 wk of sea level training in Dallas. In the submaximal protocol, after a 15-min warm-up on the treadmill, subjects ran at a constant velocity of 14.4 km/h (9 miles/h). Metabolic variables (minute ventilation, VO2, heart rate) were recorded from the 4 min of this exercise bout. For the maximal exercise protocol, subjects ran to volitional exhaustion following a modified Astrand/Saltin protocol (4). Subjects ran at a constant velocity of 14.4 km/h (9 miles/h) for men and 12.8 km/h (8 miles/h) for women at a 0% grade for 2 min, with the grade increasing 2% every 2 min until exhaustion. VO2 was measured via the Douglas bag method, with fractional gas concentrations determined by mass spectroscopy (Marquette MGA 1100, Milwaukee, WI) and ventilatory volumes by a dry gas meter (Collins, Boston, MA). Maximal heart rate was measured from telemetry (Polar, Finland).

Hematology assessment. Plasma volume, blood volume, and erythrocyte volume (blood volume – plasma volume) were measured once at sea level before and after the altitude training camp. Plasma volume was measured by using the Evans blue dye indicator-dilution technique (38). Subjects rested quietly for at least 30 min in the supine position; a known quantity of Evans blue dye was injected through a catheter placed in a peripheral vein, and venous blood was drawn at 10, 20, and 30 min after injection for the measurements of absorbance at 620 and 740 nm via spectrophotometry (Model DU 600 Beckman, Brea, CA). Hematocrit was measured via microcentrifuge and blood volume was estimated by dividing plasma volume by 1 minus hematocrit, using appropriate corrections for trapped plasma and peripheral sampling (6). Total red cell volume was defined as blood volume minus plasma volume. This method has been compared recently in a different group of athletes against the carbon monoxide rebreathing technique with excellent agreement for the assessment of blood compartment volumes (r2 = 0.85; 3% difference between methods) (26).

Oxygenation during sleep

Arterial oxyhemoglobin saturation (Sao2) during sleep was determined by pulse oximetry (Ohmeda 3700, Louisville, CO). Measures were taken between 0400 and 0600 on the mornings corresponding to 24-h, 48-h, 72-h, 1-wk, 2-wk, and 3-wk time points after arrival at altitude. These measures were utilized to document the desaturation differences between groups, as a potential marker affecting the quality of sleep and recovery.

Statistical analysis

Data were analyzed using IBM SPSS version 20 statistical software. All data values are reported as mean ± SD, except where noted. A Shapiro-Wilk test was utilized and all dependent variables were determined to be normally distributed. Therefore, parametric statistics were used in all further analyses. Least squares regression was used to determine the slope of the change in 3,000-m performance as a function of time at altitude. Two-way split plot repeated-measures ANOVAs with a priori tests of simple main effects (and Fisher’s least significant difference post hoc analysis) were used to determine differences in dependent measures at different time points within altitude groups. The same procedure was also used to determine differences in dependent measures between altitude groups at the same time point. One-way ANOVAs were used to determine differences in baseline subject characteristics and performance vs. time regression slopes between altitude groups. The α-level for significance was set at P < 0.05.

RESULTS

Subjects

A total of 43 athletes (28 men and 15 women) successfully completed the full altitude racing protocol. One athlete dropped out before travel to altitude for personal reasons; one was in a car accident in Utah and was unable to complete the altitude exposure; and three did not complete one or more of the altitude time trials due to injury or sickness (2 men from the 1,780-m group, 1 man from the 2,085-m group, and 1 man and 1 woman from the 2,800-m group). Subject characteristics are displayed in Table 1. No differences in physical characteristics, VO2max or hematological measures were detected between the different living altitude groups at inclusion in the study.

Training

Training volume during the altitude training camp was not different among the four altitude living groups and neither was the number of self-classified high-intensity workouts. The total volume of miles (1 mile = 1.609 km) run per person was

### Table 1. Subject characteristics

<table>
<thead>
<tr>
<th>Living Altitude</th>
<th>1,780 m</th>
<th>2,085 m</th>
<th>2,454 m</th>
<th>2,800 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men/women, number of subjects</td>
<td>6/4</td>
<td>7/4</td>
<td>8/4</td>
<td>7/3</td>
</tr>
<tr>
<td>Age, yr</td>
<td>21.4 ± 3.1</td>
<td>20.1 ± 1.5</td>
<td>20.7 ± 1.6</td>
<td>21.0 ± 2.0</td>
</tr>
<tr>
<td>Height, cm</td>
<td>175.5 ± 10.1</td>
<td>174.7 ± 7.9</td>
<td>171.8 ± 8.6</td>
<td>176.8 ± 10.0</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>64.7 ± 9.3</td>
<td>64.2 ± 8.4</td>
<td>62.6 ± 8.0</td>
<td>66.4 ± 9.0</td>
</tr>
<tr>
<td>VO2max, ml·kg⁻¹·min⁻¹</td>
<td>63.9 ± 4.8</td>
<td>61.9 ± 6.7</td>
<td>61.3 ± 7.2</td>
<td>61.6 ± 7.7</td>
</tr>
<tr>
<td>Serum ferritin, ng/ml</td>
<td>33 ± 15</td>
<td>27 ± 7</td>
<td>34 ± 15</td>
<td>36 ± 15</td>
</tr>
<tr>
<td>Red cell mass, ml/kg</td>
<td>36.3 ± 4.0</td>
<td>36.1 ± 5.6</td>
<td>35.8 ± 5.3</td>
<td>35.4 ± 5.3</td>
</tr>
<tr>
<td>ΔEPO after 24-h chamber exposure at 2,454 m, %</td>
<td>110 ± 73</td>
<td>116 ± 74</td>
<td>106 ± 88</td>
<td>107 ± 98</td>
</tr>
</tbody>
</table>

Values are mean ± SD. VO2max, maximal oxygen uptake; EPO, serum erythropoietin concentration.

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Table 2. 3,000-m performance times

<table>
<thead>
<tr>
<th>Living Altitude</th>
<th>Sea Level Day 5</th>
<th>Altitude Day 5</th>
<th>Altitude Day 12</th>
<th>Altitude Day 19</th>
<th>Altitude Day 26</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,780 m s</td>
<td>584.3 ± 48.7*</td>
<td>610.9 ± 51.6</td>
<td>603.0 ± 49.1</td>
<td>606.4 ± 55.0</td>
<td>603.0 ± 51.2</td>
</tr>
<tr>
<td>Δ%</td>
<td>104.5 ± 0.4</td>
<td>103.2 ± 0.6</td>
<td>103.7 ± 0.7</td>
<td>103.2 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>2,085 m s</td>
<td>582.3 ± 37.3*</td>
<td>617.8 ± 49.6</td>
<td>609.2 ± 45.1</td>
<td>598.0 ± 45.0a</td>
<td>595.6 ± 45.6ab</td>
</tr>
<tr>
<td>Δ%</td>
<td>106.0 ± 1.0</td>
<td>104.6 ± 1.1</td>
<td>102.7 ± 1.3</td>
<td>102.3 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>2,454 m s</td>
<td>593.4 ± 64.0*</td>
<td>638.8 ± 68.3</td>
<td>637.6 ± 79.4</td>
<td>611.6 ± 61.0ab</td>
<td>619.1 ± 55.6s</td>
</tr>
<tr>
<td>Δ%</td>
<td>107.7 ± 1.1s</td>
<td>107.4 ± 1.6s</td>
<td>103.2 ± 0.9</td>
<td>104.6 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>2,800 m s</td>
<td>591.5 ± 66.8*</td>
<td>640.0 ± 73.4</td>
<td>622.4 ± 68.7a</td>
<td>615.4 ± 65.0ab</td>
<td>607.1 ± 63.5s</td>
</tr>
<tr>
<td>Δ%</td>
<td>107.8 ± 1.1s</td>
<td>105.1 ± 0.9</td>
<td>102.5 ± 1.1</td>
<td>102.1 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>All (n = 43)</td>
<td>588.2 ± 54.4*</td>
<td>627.8 ± 61.4</td>
<td>618.9 ± 62.4a</td>
<td>608.0 ± 55.5ab</td>
<td>606.6 ± 53.0ab</td>
</tr>
<tr>
<td>Δ%</td>
<td>106.6 ± 3.2</td>
<td>105.2 ± 3.9</td>
<td>103.0 ± 3.1</td>
<td>103.1 ± 3.3</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SD. Values are time in seconds and percentage of sea level time for 3,000-m time trials. Altitude time trials all took place at 1,780 m of altitude. *Significantly different from Altitude at all time points. aSignificantly different from Altitude Day 5. bSignificantly different from Altitude Day 12.

cSignificantly different from 1,780 m.

dSignificantly different from 1,780 m.

227 ± 48, 219 ± 57, 215 ± 54, and 214 ± 53 in the athletes living at 1,780, 2,085, 2,454, and 2,800 m, respectively. The number of athlete reported high-intensity workouts per week was 3.8 ± 1.5, 3.8 ± 0.8, 3.1 ± 1.1, and 4.0 ± 1.6 workouts in the athletes living at 1,780, 2,085, 2,454, and 2,800 m, respectively.

Three-Thousand-Meter Time Trial Performance: Acute Altitude Exposure

Mean 3,000-m performance times for all altitude living groups at each time point are displayed in Table 2. As expected, compared with sea level, 3,000-m race performance was significantly slower with acute exposure to altitude (day 5) across all subjects (587.0 ± 54.4 vs. 625.9 ± 62.0 s or a 6.7 ± 3.4% increase in time; P < 0.001) as well as within each altitude living group compared with sea level (P < 0.001 within each altitude group). However, the groups at 2,454 m (P < 0.05) and 2,800 m (P < 0.01) had a significantly larger decline in race performance at day 5 vs. sea level compared with the 1,780-m group.

Three-Thousand-Meter Time Trial Performance: Rate of Change with Chronic Altitude Exposure

The magnitude and rate of improvement in 3,000-m performance over time at altitude was dependent on the living altitude (Fig. 2). The group living at 1,780 m showed no improvement in performance time from day 5 to altitude to any subsequent altitude time point (Table 2). Both the 2,085- and 2,454-m groups showed no improvement in performance time from day 5 to day 12 at altitude but showed significant performance improvement at day 19 at altitude (P < 0.01). Only the 2,800-m group showed a significant improvement in performance from day 5 to day 12 at altitude (P < 0.01). None of the four living altitude groups demonstrated a significant change in 3,000-m performance from day 19 to day 26 at altitude.

Table 3 shows the change in 3,000-m performance time per week as a percentage improvement from the first altitude time trial on day 5 to the final altitude time trial on day 26. The 1,780-m group had a significantly smaller rate of performance change per week than all other altitude groups (P < 0.05 for all comparisons). The rate of change in 3,000-m performance time per week at altitude in the 2,800-m group approached significance compared with the 2,085-m (P = 0.07) and 2,454-m (P = 0.08) groups.

Oxygenation During Sleep

SaO2, values obtained during sleep over the course of the altitude camp are displayed in Fig. 3. Subjects displayed a consistent difference in SaO2 across most time points between the two lowest and two highest altitude groups.

Treadmill and Hematological Assessment

VO2 max, when expressed as ml·kg⁻¹·min⁻¹, was significantly increased from the pre- to postaltitude time points in the 2,085- and 2,454-m group (P < 0.05) but was not different in the 1,780- or 2,800-m groups (ΔVO2 max 0.1 ± 3.1, 1.1 ± 2.2,
SaO2 during exercise (11, 24, 33). Previously, we demonstrated that exercise SaO2 has been linked in numerous studies to the ability to maintain V˙O2 max during exercise (11, 24, 33). Now, we show that a higher altitude results in a significant decrease in SaO2 during exercise (11, 24, 33). This decrease is likely due to the lower oxygen partial pressure at higher altitudes (11, 24, 33). We also show that the decrease in SaO2 during exercise is significantly more pronounced in the two highest altitude groups (1, 780- and 2,085-m groups, respectively). Erythrocyte volume, whether expressed in absolute (liters) or relative (ml/kg) terms, was significantly increased (P < 0.05) in all four altitude groups from pre- to postaltitude (Δerythrocyte volume 7.0 ± 9.7, 6.1 ± 8.1, 5.9 ± 8.5, and 6.2 ± 7.8% for the 1,780-, 2,085-, 2,454-, and 2,800-m groups, respectively).

DISCUSSION

Sea level based endurance athletes who compete at altitude will commonly relocate to altitude for some extended period of time before the competition to gain positive effects of acclimatization and mitigate performance decline at altitude. The primary finding of this investigation is that the altitude at which an athlete chooses to reside affects both the acute worsening of race performance at a low altitude compared with sea level, as well as the rate of improvement in performance over time in residence at altitude. The data suggest that a distance runner competing at a low altitude of 1,780 m should live at the altitude of the competition, and not higher, if the competition altitude of 1,780 m to enhance acclimatization responses over a longer period of time, acute altitude performance will likely be significantly worse than if they lived at the competition altitude. The data suggest that a distance runner competing at a low altitude of 1,780 m should live at the altitude of the competition, and not higher, if the competition altitude of 1,780 m to enhance acclimatization responses over a longer period of time, acute altitude performance will likely be significantly worse than if they lived at the competition altitude. The data suggest that a distance runner competing at a low altitude of 1,780 m should live at the altitude of the competition, and not higher, if the competition altitude of 1,780 m to enhance acclimatization responses over a longer period of time, acute altitude performance will likely be significantly worse than if they lived at the competition altitude.

Response to Acute Altitude Exposure

Within cohorts of highly trained endurance athletes, the decline in maximal oxygen uptake with acute altitude exposure has been linked in numerous studies to the ability to maintain SaO2 during exercise (11, 24, 33). Previously, we demonstrated that this link between exercise SaO2 and V˙O2max decline with acute exposure to simulated altitude extends to actual measures of performance decline in elite distance runners at 2,100 m, after 48 h living at 2,500 m (14). Although we did not measure exercise SaO2 in this study, we would expect individual differences in exercise SaO2 maintenance to be randomly distributed across all four groups. Rather, we posit that the difference in acute performance decline between altitude groups is a function of disparate acclimatization responses to the altitude of residence.

For example, we observed significant differences in sleeping SaO2 between the two lowest and the two highest altitude groups that persisted over the first week at altitude, which corresponds with the reductions in 3,000-m performance on day 5. With acute exposure to altitude, a reduction in SaO2 during sleep may increase the number of episodes of periodic breathing, as well as significantly reducing sleep quality (30, 40). While poor sleep quality may affect recovery, overall perception of well-being, and exercise performance (3), any negative effect of this acclimatization response should be most evident early in the altitude exposure, subsiding with chronic residence. In fact, sleeping SaO2 stayed essentially unchanged over the entire altitude camp in the two lowest altitude groups, while in the two highest altitude groups, sleeping SaO2 significantly rose from the 24-h measure to the 2-wk measure (Fig. 2), again, corresponding to the responses seen in 3,000-m performance in the 2,454- and 2,800-m groups from day 5 to day 26 at altitude.

Additionally, a number of well-known and well-characterized physiological responses occur within the first few days at altitude that, independently or in sum, can be negative for performance with acute altitude exposure. Perhaps one of the quickest and most consistent initial physiological responses to hypoxia is a peripheral chemoreceptor-mediated increase in ventilation, both at rest and during exercise (9). The ensuing respiratory alkalosis causes a renal compensation, resulting in significant diuresis (45). This acute ventilatory and renal response to hypoxia has three consequences that can be negative for endurance exercise performance: 1) a significant reduction in plasma volume (28), affecting both cardiac function (via the Frank-Starling mechanism) (4, 27) and thermoregulatory capacity (46); 2) an acute reduction in buffering capacity (44); and 3) an increase in ventilatory work and dyspnea during heavy exercise (1, 32). The ventilatory response to hypoxia has been shown to increase with ascending altitude, as well as with duration of residence at altitude (47), even within the endurance athlete population who, as a group, are known to demonstrate blunted measures of peripheral chemosensitivity to hypoxia (10). The hypoxic ventilatory response has been theorized to be a positive component of altitude acclimation, by helping to mitigate the decline alveolar Po2 and subsequently

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**Table 3. Rate of change in 3,000-m performance time**

<table>
<thead>
<tr>
<th>Living Altitude</th>
<th>Δ3,000-m Time per Week, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,780 m</td>
<td>-0.35 ± 0.91</td>
</tr>
<tr>
<td>2,085 m</td>
<td>-1.33 ± 0.59*</td>
</tr>
<tr>
<td>2,454 m</td>
<td>-1.36 ± 0.96*</td>
</tr>
<tr>
<td>2,800 m</td>
<td>-1.98 ± 0.95*b,c</td>
</tr>
<tr>
<td>All (n = 43)</td>
<td>-1.29 ± 1.02</td>
</tr>
</tbody>
</table>

Values are means ± SD. Values are change in 3,000-m performance time per week, as a percent change from the first altitude time trial on day 5. Values determined from the individual regression slopes of all four altitude time trials from day 5 to day 26 at altitude for each group and all subjects. *Significantly different from 1,780-m group. bP = 0.07 vs. 2,085-m group. cP = 0.08 vs. 2,454-m group.

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**Fig. 3. Arterial oxyhemoglobin saturation (SaO2) measured during sleep.** Values are means ± SE. Letters indicate significant differences at the same time point at the P < 0.05 level. *1.780 m different from 2,454 m; **1.780 m different from 2,800 m; *2.085 m different from 2,454 m; ***2.085 m different from 2,800 m.
arterial \textit{PO}_2) in the face of a reduced atmospheric pressure. However, the high ventilatory work rates achieved during an all-out 3,000-m running time trial (which typically elicits \(\sim 90–110\% \text{ of } V\text{O}_2\text{max}\); Ref. 21) have been shown in cyclists to result in a decrease in blood flow to exercising leg muscles, presumably to divert a greater portion of cardiac output to the respiratory musculature (i.e., the respiratory muscle metaboflex) (29). Although we do not have direct measures of acute ventilatory changes at altitude in our cohort, previously, we published the pre- to postaltitude change in the ventilatory response to submaximal steady state exercise at sea level in this cohort, showing increases in minute ventilation in the two highest altitude groups (12). Taken together, we believe it is reasonable to speculate judiciously that a heightened ventilatory response to heavy exercise in the higher altitude groups, secondary to larger gains in peripheral chemoreceptor sensitivity over the first 5 days of altitude residence, was likely a strong enough stimuli to be one factor influencing a conscious or unconscious selection of a slower pace when racing on \textit{day 5} at altitude.

\textbf{Response to Chronic Altitude Exposure}

In classic altitude training studies from the 1960s and 1970s (2, 17), where swimmers or runners lived, trained, and competed at a common moderate or high altitude, interestingly none demonstrated significant improvements in altitude performance after durations of 2–3 wk of altitude residence. However, these studies generally suffer from experimental design issues and/or lack of controls that are now known to affect performance measures, i.e., iron storage levels and supplementation, training camp and group training effects, and/or training levels before the altitude camp (15). In studies where these controls are considered (31, 41), altitude performance is significantly improved after time periods of between 2 and 3 wk at altitude. Perhaps the best comparable data set to our own on performance changes at altitude over time come from Schuler et al. (41). In their study, eight elite cyclists lived for 3 wk at 2,340 m, trained at altitudes below 1,100 m (i.e., Live High-Train Low), and completed weekly tests at 2,340 m of \textit{V}\text{O}_2\text{max} and time to exhaustion at 80% of sea level maximal power output. Although not directly comparable to our data using a fixed distance performance test where speed could vary, time to exhaustion decreased by 25.8% on \textit{day 1} at altitude. By \textit{day 14} at altitude, time to exhaustion improved significantly to \(\sim 17\%\) less than sea level baseline time, an improvement of \(\sim 4.5\%\) per week over the first 2 wk at altitude. However, by \textit{day 21}, time to exhaustion at 2,340 m was not significantly improved over \textit{day 14}. Compared with these data of Schuler et al., our 1,780-m cohort also lived and completed performance trials at a common altitude but in contrast did not demonstrate an improvement in performance over 26 days at altitude. Whether this disparate response between these data sets is due to differing modes of exercise (running vs. cycling), different living/performance altitudes (1,780 vs. 2,340 m), or different performance measures (fixed distance for time lasting \(\sim 8–9\) min vs. fixed intensity time to exhaustion lasting 30–45 min) is not clear. Even our most rapidly improving group in terms of performance, that being the group living at 2,800 m, still showed an improvement rate per week that was less than half of that seen by the cohort of Schuler et al. (2.0 vs. 4.5%). We also cannot say whether small differences in performance altitude within the low-altitude range (\(>500–2,000\) m; Ref. 7) would alter the outcome of runners, cyclists, swimmers, rowers, or other athletes using different combinations of muscle mass activation using this paradigm.

Another differing outcome from our data and that of Schuler et al. is the timing of maximal performance improvement with residence at altitude. Whereas Schuler et al. demonstrated no significant improvement in performance (or maximal power or maximal oxygen uptake) from \textit{day 14} to \textit{day 21} at altitude, our two highest living groups (2,454 and 2,800 m) both showed significant performance improvements from \textit{day 12} to \textit{day 19} at altitude, as did the overall study sample of 43 athletes. Again, it is important to note that these two groups were living at a higher altitude than that of the performance trial (1,780 m). Interestingly, our data from \textit{day 19} showed what could be described as a convergence in 3,000-m performance among groups, with just a 1.0% difference in 3,000-m time (range of 2.7–3.7% slower than sea level performance time) across all four living altitude groups. No groups demonstrated a significant improvement in performance from \textit{day 19} to \textit{day 26} at altitude, which leads us to conclude that performance gains may be maximized at 19 days at altitude, slightly longer, but within the same range as suggested by Schuler et al.

We hypothesized that athletes living at higher altitudes would see an accelerated rate of improvement in 3,000-m time trial performance at altitude. The most likely mechanism would be a greater increase in Hb mass over time in the groups living at the highest altitudes. However, as we published previously (12), we saw no difference between altitude groups in the change in Hb mass from prealtitude to after 4 wk of altitude exposure (all altitude groups, \(\Delta\text{Hb mass range } 5.9–7.0\%\)).

While some period of altitude acclimatization is normally utilized by athletes before an altitude competition, a strategy that is gaining in popularity among coaches and athletes is to try and arrive at altitude with as minimal time as possible (as short as 2 h) before competing (13). This strategy, termed “fly-in-fly out” within the football/soccer community, is believed to lessen the performance decline at altitude by eliminating or shortening the time that select negative physiological responses to altitude (e.g., poor sleep, plasma volume loss) have to affect performance (25, 48). Currently, there are little direct data to support this short-term arrival strategy, and most data examining shorter term serial measures of performance at altitude typically utilize more extreme altitudes (e.g., 4,300 m; Ref. 19).

In conclusion, acute exposure of 5 days of living at 1,780 m resulted in the smallest decrement in distance running performance at 1,780 m, compared with athletes who lived at higher altitudes up to 2,800 m. Therefore, we recommend that sea level based athletes, who must compete at or near this altitude, live at the same altitude as the competition for a minimum of 5 days, with longer exposures resulting in small performance improvements (<0.4% per week), which may hold practical but not statistical significance. Living at higher altitudes of up to 2,800 m did not result in an improved altitude performance at any time out to 26 days of altitude residence, compared with the group who lived at the competition altitude of 1,780 m. However, should circumstance or strategy (i.e., attempting to enhance the erythropoietic effect of chronic altitude exposure)
require the athlete to live higher than the competition altitude, our data suggest that 19 days of altitude residence or more is recommended to minimize the altitude mediated performance decrement.

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REFERENCES


