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"Living high-training low": effect of moderate-altitude acclimatization with low-altitude training on performance

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1Institute for Exercise and Environmental Medicine, Presbyterian Hospital of Dallas 75231; and 2Baylor/The University of Texas Southwestern Sports Science Research Center, The University of Texas Southwestern Medical Center, Dallas, Texas 75235

Levine, Benjamin D., and James Stray-Gundersen. “Living high-training low”: effect of moderate-altitude acclimatization with low-altitude training on performance. J. Appl. Physiol. 83(1): 102–112, 1997.—The principal objective of this study was to test the hypothesis that acclimatization to moderate altitude (2,500 m) plus training at low altitude (1,250 m), “living high-training low,” improves sea-level performance in well-trained runners more than an equivalent sea-level or altitude control. Thirty-nine competitive runners (27 men, 12 women) completed 1) a 2-wk lead-in phase, followed by 2) 4 wk of supervised training at sea level; and 3) 4 wk of field training camp randomized to three groups: “high-low” (n = 13), living at moderate altitude (2,500 m) and training at low altitude (1,250 m); “high-high” (n = 13), living and training at moderate altitude (2,500 m); or “low-low” (n = 13), living and training in a mountain environment at sea level (150 m). A 5,000-m time trial was the primary measure of performance; laboratory outcomes included maximal O2 uptake (VO2max), anaerobic capacity (accumulated O2 deficit), maximal steady state (MSS; ventilatory threshold), running economy, velocity at VO2max, and blood compartment volumes. Both altitude groups significantly increased VO2max (5%) in direct proportion to an increase in red cell mass volume (99%; r = 0.37, P < 0.05), neither of which changed in the control. Five-kilometer time was improved by the field training camp only in the high-low group (13.4 ± 10 s), in direct proportion to the increase in VO2max (r = 0.65, P < 0.01). Velocity at VO2max and MSS also improved only in the high-low group. Four weeks of living high-training low improves sea-level running performance in trained runners due to altitude acclimatization (increase in red cell mass volume and VO2max) and maintenance of sea-level training velocities, most likely accounting for the increase in velocity at VO2max and MSS.

METHODS

Subjects

Forty-one distance runners were recruited from collegiate track and cross-country teams, local running clubs, and USA Track and Field development teams, and 39 (27 men, 12 women, aged 18–31 yr) completed all the testing and training sessions. Sample size was estimated from pilot data demonstrating an increase in maximal O2 uptake (VO2max) of 5% (3 ml·kg−1·min−1) with an SD of 3.2 ml·kg−1·min−1, requiring 11 athletes/group (β = 0.80, α = 0.05). Athletes were required to be competitive at a distance between 1,500 m and the marathon and to have a recent personal best 5,000-m time (or equivalent) of <16:30 for men and <18:30 for women. All were sea-level residents and could not have been to altitude above 1,500 m for a period exceeding 1 wk in the previous 10 mo. All subjects gave their voluntary written informed consent to a protocol approved by the Institutional Review Board of the University of Texas Southwestern Medical Center at Dallas.

Study Design

An outline of the study design is shown in Fig. 1; it consists of four major phases.

Sea-level lead-in phase. Athletes were brought to Dallas, Texas (150 m), 2–4 wk after the spring track season for a 2-wk period of supervised training at sea level and familiarization with laboratory testing procedures. We have previously shown that this phase is necessary and sufficient to bring all the athletes to an equivalent level of training readiness, and that...
may account for a substantial portion of the supervised training camp effect observed in many training studies (23, 39). During this phase, serum ferritin was measured for the assessment of bone marrow iron stores, and iron maintenance or replacement therapy was initiated for all subjects (37).

Sea-level training. After the lead-in phase, athletes underwent a period of supervised training at sea level that was designed to provide a longitudinal sea-level control. Training was conducted according to an individualized template based on a 4-wk mesocycle intended to provide increasing volume and intensity over the first 3 wk, with a slight taper during the last week. The first week involved exclusively base running on area trails with a volume equivalent to 80% of their usual base volume. Laboratory testing also occurred during this week and included one 5,000-m time trial. This testing session served as a baseline for the response to sea-level training. In the second week, volume was increased by 20–25% by increasing both the duration and number of base training workouts. Training intensity was increased by adding one intervals session consisting of five to six 1,000-m intervals (110% of race pace) and one 5,000-m road race. During the third week, base volume was increased by an additional 20%, and intensity was increased by adding a hill running/pliometric training session in addition to the 1,000-m intervals. Finally, during the fourth week, base training volume was reduced by 25–30%, and no interval training sessions were performed. Repeat laboratory testing also occurred during this last week at sea level and included a 5,000-m time trial. This testing session served as the comparison for the response to sea-level training and provided the primary baseline for the altitude and sea-level control training camps. All training sessions were directly supervised by either the investigators or staff and carefully monitored as described below.

Altitude training camp. After the last time trial at sea level, athletes were then matched for gender, 5,000-m time trial performance, and training history into groups of three and then randomized (balanced randomization) to 1) “high-low” [living at moderate altitude (2,500 m) and training at low altitude (1,250 m); n = 13; 9 men, 4 women; primary experimental group]; 2) “high-high” [living at moderate altitude (2,500–2,700 m) and training at moderate altitude (2,500–2,700 m); n = 13; 9 men, 4 women; typical altitude-training control group]; or 3) “low-low” [living at sea level (150 m) and training at sea level (150 m); n = 13; 9 men, 4 women; sea-level control group]. Moderate-altitude living occurred in Deer Valley, Utah, with training on trails and roads in the Wasatch and Uinta mountain ranges. Low-altitude training occurred nearby, an ~30-min drive, in Salt Lake City, Utah. The sea-level training camp took place at the US Olympic Training Center in Chula Vista (San Diego), California, in the foothills of the San Ysidro Mountains, which closely matched the terrain and weather conditions of the altitude camps but were at sea level. The training program during the field camp matched the training program at sea level in Dallas, on the basis of the same 4-wk mesocycle. The first week was an easy acclimatization week. The subsequent 2 wk involved increasing volume and intensity, as described above, with a slight taper during the last week before the return to Dallas.

Sea-level testing period. The first week after return from the field training camp was a testing week and included two 5,000-m time trials on the third and seventh days after return from altitude. Plasma and blood volume and submaximal exercise performance were measured on the second day, the incremental test of \( \text{VO}_{2\text{max}} \) was on the fourth day, and the anaerobic capacity test was on the fifth day after return from altitude. This testing session was compared with the last testing session before the training camps, with all testing...
performed in the same order, and served as the primary experimental comparison. Over the subsequent 2 wk, the athletes performed primarily easy base running, supplemented by short, fast runs, with a 5,000-m time trial at the end of each week. The purpose of this phase was to determine the optimal time for competition after return from the altitude training camp or control.

Evaluation of Performance

The primary outcome measure of this study was running performance, as measured both on a track and in the laboratory on a treadmill. An outline of the testing schedule is included in Fig. 1.

Track evaluation. 5,000-M TIME TRIAL. Multiple time trials over 5,000 m were conducted on a 400-m track. Time trials were performed at sea level in Dallas at 7:00–8:00 AM (temperature 22–26°C, humidity 80–100%, wind 0–10 km/h). To avoid racing strategies, all starts were staggered by at least 2 min.

Treadmill evaluation. V˙O₂max. V˙O₂max was measured with a modified Astrand-Saltin protocol (3) involving incremental exercise on a treadmill. After a brief warm-up, subjects ran at 9.0 miles/h (mph) for men and 8.0 mph for women at 0% grade for 2 min. The grade was then increased 2% every 2 min until exhaustion, which usually occurred after 6–8 min. Oxygen uptake (V˙O₂) was measured by using the Douglas bag method, and fractions measured at the mouth by mass spectrometer (Marquette MGA 1100), and ventilatory volume was measured with either a Tissot spirometer or dry-gas meter (Collins). V˙O₂max was defined as the VO₂ measured from at least a 40-s Douglas bag. In nearly all cases, a plateau in V˙O₂ was observed with increasing work rate, confirming the identification of V˙O₂max. However, to verify that V˙O₂max was achieved, on a separate day a supramaximal treadmill run was performed, with the measurement of VO₂, and anaerobic capacity as described below. The highest value of VO₂ achieved on either test was accepted as V˙O₂max.

In addition, heart rate was monitored continuously (Polar CIC, Port Washington, NY), and fingertip capillary blood was measured with either a Tissot spirometer or dry-gas meter (Collins). V˙O₂max was defined as the VO₂ measured from at least a 40-s Douglas bag. In nearly all cases, a plateau in V˙O₂ was observed with increasing work rate, confirming the identification of V˙O₂max. However, to verify that V˙O₂max was achieved, on a separate day a supramaximal treadmill run was performed, with the measurement of VO₂, and anaerobic capacity as described below. The highest value of VO₂ achieved on either test was accepted as V˙O₂max. However, to verify that V˙O₂max was achieved, on a separate day a supramaximal treadmill run was performed, with the measurement of VO₂, and anaerobic capacity as described below. The highest value of VO₂ achieved on either test was accepted as V˙O₂max. However, to verify that V˙O₂max was achieved, on a separate day a supramaximal treadmill run was performed, with the measurement of VO₂, and anaerobic capacity as described below. The highest value of VO₂ achieved on either test was accepted as V˙O₂max. However, to verify that V˙O₂max was achieved, on a separate day a supramaximal treadmill run was performed, with the measurement of VO₂, and anaerobic capacity as described below. The highest value of VO₂ achieved on either test was accepted as V˙O₂max. However, to verify that V˙O₂max was achieved, on a separate day a supramaximal treadmill run was performed, with the measurement of VO₂, and anaerobic capacity as described below. The highest value of VO₂ achieved on either test was accepted as V˙O₂max. However, to verify that V˙O₂max was achieved, on a separate day a supramaximal treadmill run was performed, with the measurement of VO₂, and anaerobic capacity as described below. The highest value of VO₂ achieved on either test was accepted as V˙O₂max. However, to verify that V˙O₂max was achieved, on a separate day a supramaximal treadmill run was performed, with the measurement of VO₂, and anaerobic capacity as described below. The highest value of VO₂ achieved on either test was accepted as V˙O₂max.
RESULTS

Subjects

Subject characteristics for all three groups are shown in Table 1, which includes the 39 subjects who completed all testing and training phases of the study. Only two subjects dropped out during the course of the study. One subject left because of homesickness. One subject suffered from chronic Epstein-Barr virus infection and was unable to complete the training at altitude. No data from these two subjects are included in the analysis. At baseline and after the sea-level control training period, there were no statistically or physiologically significant differences among the three groups in terms of 5,000-m time, VO₂max, or blood compartment volumes.

Training

There was no significant difference in sea-level training by any criteria among the groups (Fig. 2, A-C). During the field training camps, all three groups had small but similar increases in total training duration and total training distance, from sea level in Dallas to the field training camp, with no significant difference among the groups. This increase was predominantly because the first and last weeks of training in Dallas included the laboratory testing. Similar to training at sea level in Dallas, there was no significant difference

Table 1. Subject characteristics and performance indexes

<table>
<thead>
<tr>
<th></th>
<th>Plasma Volume,† ml/kg</th>
<th>Blood Volume,† ml/kg</th>
<th>Red Cell Mass,† ml/kg</th>
<th>Hemoglobin,† mg/dl</th>
<th>MaxLactate, mM</th>
<th>VO₂ at Maximal Steady State,‡ ml·kg⁻¹·min⁻¹</th>
<th>Velocity at VO₂max,† mph</th>
<th>Anaerobic Capacity, ml/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Low-Low 53.1</td>
<td>High-Low 54.0</td>
<td>High-High 52.0</td>
<td>Low-Low 82.7</td>
<td>51.5</td>
<td>13.16</td>
<td>60.5</td>
<td>54.7</td>
</tr>
<tr>
<td></td>
<td>± 1.8</td>
<td>± 2.7</td>
<td>± 1.6</td>
<td>± 2.2</td>
<td>± 1.5</td>
<td>± 1.27</td>
<td>± 3.8</td>
<td>± 4.0</td>
</tr>
<tr>
<td>Sea-level</td>
<td>Low-Low 51.5</td>
<td>High-Low 56.2</td>
<td>High-High 54.2</td>
<td>Low-Low 79.4</td>
<td>52.7</td>
<td>13.24</td>
<td>56.1</td>
<td>52.4</td>
</tr>
<tr>
<td></td>
<td>± 1.8</td>
<td>± 2.1</td>
<td>± 2.0</td>
<td>± 2.5</td>
<td>± 1.8</td>
<td>± 1.30</td>
<td>± 3.0</td>
<td>± 4.2</td>
</tr>
<tr>
<td>Altitude</td>
<td>Low-Low 51.0</td>
<td>High-Low 51.9</td>
<td>High-High 53.3</td>
<td>Low-Low 78.7</td>
<td>51.9</td>
<td>13.07</td>
<td>53.4</td>
<td>48.7</td>
</tr>
<tr>
<td></td>
<td>± 1.8</td>
<td>± 2.0</td>
<td>± 1.6</td>
<td>± 2.5</td>
<td>± 1.8</td>
<td>± 1.27</td>
<td>± 4.2</td>
<td>± 4.7</td>
</tr>
<tr>
<td>5,000-m Time,† min</td>
<td>Low-Low 17.53</td>
<td>High-Low 17.64</td>
<td>High-High 17.44</td>
<td>Low-Low 64.4</td>
<td>193.9</td>
<td>153.2</td>
<td>143.1</td>
<td>148.3</td>
</tr>
<tr>
<td></td>
<td>± 0.48</td>
<td>± 0.39</td>
<td>± 0.46</td>
<td>± 1.8</td>
<td>± 1.9</td>
<td>± 7.6</td>
<td>± 4.8</td>
<td>± 5.5</td>
</tr>
<tr>
<td>Sea-level</td>
<td>Low-Low 17.23</td>
<td>High-Low 17.23</td>
<td>High-High 17.04*</td>
<td>Low-Low 64.7</td>
<td>193.6</td>
<td>146.3</td>
<td>143.3</td>
<td>150.0</td>
</tr>
<tr>
<td></td>
<td>± 0.46</td>
<td>± 0.43</td>
<td>± 0.42</td>
<td>± 1.8</td>
<td>± 1.7</td>
<td>± 7.9</td>
<td>± 6.1</td>
<td>± 5.2</td>
</tr>
<tr>
<td>Altitude</td>
<td>Low-Low 17.67</td>
<td>High-Low 17.04*</td>
<td>High-High 17.10</td>
<td>Low-Low 63.7</td>
<td>193.6</td>
<td>149.5</td>
<td>146.0</td>
<td>150.6</td>
</tr>
<tr>
<td></td>
<td>± 0.62</td>
<td>± 0.53</td>
<td>± 0.43</td>
<td>± 1.8</td>
<td>± 1.9</td>
<td>± 10</td>
<td>± 6.0</td>
<td>± 7.5</td>
</tr>
</tbody>
</table>

Values are means ± SD; n, no. of subjects. Low-Low, group living and training in a mountain environment at sea level (150 m; n = 13); high-low, group living at moderate altitude (2,500 m) and training at low altitude (1,250 m; n = 13); high-high, group living and training at moderate altitude (2,500 m; n = 13); VO₂max, maximal O₂ uptake; HRmax, maximal heart rate; Vémax, maximal ventilation; Max, maximal. *P < 0.05 compared with previous baseline (post hoc test). Significantly different compared across groups (interaction statistic) by 2-way analysis of variance (ANOVA): †P < 0.05; ‡P < 0.15; §P < 0.10.
among groups for training during the training camp for either TRIMPS, training duration, or estimated total mileage, supporting the conclusion that training was closely matched among the groups during both 4-wk mesocycles.

Base training at sea level (Dallas and San Diego) was performed at 82–84% of sea-level 5,000-m race pace, which required 71% of VO2max, 85% of maximal heart rate, and lactate values of 3.5 mmol/l (Table 2). With increasing altitude, there was a trend for base training to be performed at progressively slower speed and at a lower percentage of sea-level VO2max, which reached statistical significance at 2,700 m. However, base training heart rate was similar under all three conditions, suggesting that base training was performed at similar relative work rates, even though the absolute work rates were less (slower speeds). For 1,000-m interval sessions, training at sea level (Dallas and San Diego) was accomplished at 110% of sea-level 5,000-m race pace, 87% of sea-level VO2max, 96% of sea-level maximal heart rate, and lactate values of 10 mmol/l. For unclear reasons, lactate measured after the interval sessions in San Diego was significantly lower than in Dallas. With increasing altitude, running speed, VO2, and heart rate were all lower than at sea level. Despite the relative oxygen lack at moderate altitude, peak lactate was significantly lower at 2,700 m than at either sea level or 1,250 m (33).

Response to Training

Blood compartment volumes (Table 1). Plasma volume tended to increase in the high-low and high-high groups by training at sea level in the heat in Dallas (5%, P = 0.08) and decreased back to baseline after training in the cooler mountain environments. Plasma...
volume was unchanged in the sea-level control group throughout the study. Living at moderate altitude, regardless of training altitude, resulted in a significant increase in red cell mass volume of 9% (P < 0.01), which was not observed in the sea-level control. Blood volume changes paralleled the changes in plasma volume during sea-level training in Dallas, when red cell mass volume did not change. In contrast, after subjects lived at moderate altitude, the reduction in plasma volume was offset by an increase in red cell mass volume, leaving total blood volume unchanged but with an increase in oxygen-carrying capacity (increased hemoglobin concentration).

Laboratory treadmill performance. $V_{O_{2\text{max}}}$ After the 2-wk lead-in phase, an additional 4 wk of training at sea level in Dallas did not increase $V_{O_{2\text{max}}}$ in any group, confirming the fact that the athletes had reached a plateau in aerobic power induced by this training program at sea level (Fig. 3). However, after an additional 4 wk of living at moderate altitude, both high-low and high-high groups increased $V_{O_{2\text{max}}}$ significantly by an additional 5% (P < 0.05 for each). Approximately one-half of the subjects increased $V_{O_{2\text{max}}}$ by achieving a higher work rate (higher grade) on the incremental treadmill test. The other half was able to increase the proportion of work performed aerobically at the highest work rate and therefore had a higher $V_{O_{2\text{max}}}$ at the same peak treadmill grade. In contrast, there was no change in $V_{O_{2\text{max}}}$ in the sea-level control despite an equivalent supervised training program. The change in $V_{O_{2\text{max}}}$ was loosely but significantly correlated with both the change in red cell mass volume during the training camp ($r = 0.37$, $P = 0.02$) and the change in hemoglobin concentration ($r = 0.40$, $P = 0.01$).

MSS. Similar to $V_{O_{2\text{max}}}$, $V_{O_{2\text{max}}}$ at MSS did not change in any group during 4 wk of supervised training at sea level in Dallas (Fig. 4). However, in contrast to $V_{O_{2\text{max}}}$ in MSS increased significantly only in the high-low group after the altitude training camp (P < 0.05).

**Table 2. Training characterization**

<table>
<thead>
<tr>
<th></th>
<th>Base</th>
<th>Interval, 1,000 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Running speed, $%$-km time</td>
<td>$V_{O_{2\text{max}}}$, $%$SL$_{\text{max}}$</td>
</tr>
<tr>
<td>Sea-level training (150 m; n = 39)</td>
<td>83.9 ± 6.2 70.5 ± 8.6</td>
<td>164 ± 10 (85.6 ± 4.6)</td>
</tr>
<tr>
<td>Field training camp</td>
<td>81.5 ± 5.7 71.9 ± 7.5</td>
<td>163 ± 7 (84.4 ± 4.5)</td>
</tr>
<tr>
<td>Sea level (150 m; n = 13)</td>
<td>77.3 ± 9.0* 67.2 ± 5.4</td>
<td>164 ± 6 (86.8 ± 3.3)</td>
</tr>
<tr>
<td>Low altitude (1,250 m; n = 13)</td>
<td>75.9 ± 4.4* 63.5 ± 4.2*</td>
<td>160 ± 9 (85.0 ± 3.9)</td>
</tr>
<tr>
<td>Moderate altitude (2,700 m; n = 13)</td>
<td>75.9 ± 4.4* 63.5 ± 4.2*</td>
<td>160 ± 9 (85.0 ± 3.9)</td>
</tr>
</tbody>
</table>

Values are means ± SD; n = no. of subjects. $V_{O_{2\text{max}}}$, $O_{2}$ uptake; SL$_{\text{max}}$, sea level maximum; HR, heart rate; $V_E$, ventilation. *P < 0.05 compared with sea-level training (post hoc test). Significantly different sea-level values compared with field training values across groups (interaction statistic) by 2-way ANOVA: †P < 0.05; ‡P < 0.10; §P < 0.15.

ANAEROBIC CAPACITY. There were no significant changes in accumulated oxygen deficit in any group after training at either sea level or altitude (Table 1). Uphill treadmill run time did not change in any group after training at sea level in Dallas. After the field training camp, uphill treadmill run time increased only in the high-high group (159 ± 10 to 182 ± 13 s, P < 0.05).

SUBMAXIMAL ECONOMY AND PERFORMANCE. Treadmill running economy was stable throughout the study and did not change in any group from any training stimulus (Table 3). Similarly stable was the relationship be-
Velocity at \( V_{\text{O}2_{\text{max}}} \) increased significantly after the output tended to be lower in both altitude groups (5,000-m time-trial speeds (12 mph for men), cardiac output/\( V_{\text{O}2_{\text{max}}} \)), which was constant in all groups at all times (Table 3) and \( \text{VO}_{2_{\text{max}}} \) (slope of cardiac output Fig. 4). Oxygen uptake (\( \text{V}_{\text{O}2} \)) at maximal steady state, determined from ventilatory threshold, at baseline, after sea-level training in Dallas (sea level), and after altitude training camp or sea-level control (altitude). Group characteristics and figure symbols are defined as in Fig. 2. *\( P < 0.05 \) compared with previous time point.

The principal new observation from this study is that aclimatization to moderate altitude, when combined with training at low altitude, results in an improvement in sea-level running performance over 5,000 m in already well-trained, competitive runners. Such an improvement was not observed when aclimatization was combined with training at moderate altitude, or with an equivalent supervised training camp at sea level. The mechanism of this improvement appears to be twofold: an altitude-acclimatization effect, increase in blood oxygen-carrying capacity and \( \text{VO}_{2_{\text{max}}} \), which was translated into improved performance by low-altitude training, with maintenance of training velocities and oxygen flux, presumably allowing an increase in velocity at \( \text{VO}_{2_{\text{max}}} \) and MSS.

**High-Altitude Acclimatization Effect**

The rationale for this study was based on the assumption that, if altitude training works to improve sea-level endurance performance, then the physiological benefits of altitude training must derive from either the development of aclimatization, an enhancement of the training effect by hypoxic exercise, or both (23). Aclimatization to high altitude includes a number of physiological adaptations that might theoretically improve oxygen transport during exercise. Ventilatory adaptations could improve alveolar oxygenation in some athletes (13) but are likely to be short lived. Structural and biochemical adaptations in skeletal muscle may be more robust and could improve oxygen extraction and substrate utilization (4, 8, 26, 31, 34, 41, 44). All have been reported in animal models and frequently in humans. However, probably the most important adaptation that would improve sea-level performance is an increase in red blood cell mass (43), which increases the oxygen-carrying capacity of the blood and improves aerobic power (9, 16, 20). In the present study, we have demonstrated that 4 wk of living at an altitude of 2,500 m was sufficient to stimulate erythropoietin secretion (37) and increase red blood cell mass volume by \( \sim \)10%. This increase in oxygen-carrying capacity of the blood is on the order of magnitude observed in previous studies of acute erythrocyte infusion that demonstrated a similar improvement in \( \text{VO}_{2_{\text{max}}} \) (9). In this study, the significant, albeit loose, correlation between both the increases in red blood cell mass volume and hemoglobin concentration and the increase in \( \text{VO}_{2_{\text{max}}} \) observed in both groups living at moderate high altitude suggests that this endogenous "erythrocyte infusion" is at least partially responsible for the improvement in maximal aerobic power. Moreover, at running speeds on the treadmill that approximated 5,000-m race velocity, the increase in oxygen-carrying capacity allowed a lower...
Table 3. Submaximal exercise responses

<table>
<thead>
<tr>
<th>Cardiac Output, l/min</th>
<th>( \dot{V}O_2 ), ml-kg(^{-1})-min(^{-1} )</th>
<th>HR, beats/min</th>
<th>Lactate, mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-Low (n = 13)</td>
<td>High-Low (n = 13)</td>
<td>High-High (n = 13)</td>
<td>Low-Low (n = 13)</td>
</tr>
<tr>
<td>Baseline</td>
<td>21.8 ± 4.4</td>
<td>22.2 ± 2.4</td>
<td>22.4 ± 4.6</td>
</tr>
<tr>
<td>SL training</td>
<td>21.1 ± 3.9</td>
<td>21.4 ± 2.1</td>
<td>21.8 ± 4.6</td>
</tr>
<tr>
<td>Altitude training</td>
<td>21.1 ± 3.3</td>
<td>21.5 ± 3.0</td>
<td>20.3 ± 4.3</td>
</tr>
</tbody>
</table>

8 mph (n = 39)

| Baseline | 25.7 ± 5.6 | 23.6 ± 4.0 | 25.6 ± 4.8 | 50.9 ± 4.8 | 49.2 ± 3.4 | 51.1 ± 3.4 | 175 ± 12 | 169 ± 12 | 170 ± 12 | 4.0 ± 1.7 | 3.1 ± 2.0 | 3.5 |
| SL training | 24.5 ± 3.7 | 23.5 ± 4.8 | 24.7 ± 5.7 | 50.8 ± 5.7 | 48.3 ± 2.5 | 48.9 ± 3.4 | 172 ± 11 | 165 ± 11 | 163* ± 12 | 2.6* ± 1.7 | 2.0* ± 2.0 | 2.2 |
| Altitude training | 24.5 ± 5.0 | 24.5 ± 3.3 | 25.6 ± 3.2 | 50.3 ± 3.2 | 48.3 ± 3.5 | 52.5 ± 8.5 | 174 ± 12 | 166 ± 12 | 167 ± 11 | 3.3 ± 1.5 | 2.3 ± 1.4 | 2.7 |

10 mph (n = 39)

| Baseline | 29.1 ± 7.4 | 29.2 ± 5.7 | 31.4 ± 4.0 | 60.3 ± 2.0 | 57.0 ± 3.4 | 59.3 ± 3.0 | 187 ± 7 | 184 ± 7 | 182 ± 7 | 6.6 ± 1.7 | 5.5 ± 2.3 | 6.1 |
| SL training | 29.6 ± 4.5 | 27.7 ± 4.2 | 29.1 ± 6.1 | 58.4 ± 6.7 | 60.0 ± 5.7 | 60.2 ± 3.4 | 185 ± 6 | 184 ± 6 | 178 ± 6 | 5.2* ± 2.1 | 4.7 ± 1.8 | 4.8* |
| Altitude training | 29.6 ± 6.7 | 26.0 ± 2.1 | 27.6* ± 3.5 | 59.4 ± 3.5 | 60.2 ± 3.3 | 4.4 ± 1.6 | 186 ± 6 | 182 ± 6 | 182 ± 6 | 5.7 ± 2.3 | 4.6 ± 2.0 | 5.4 |

12 mph (n = 27 [men only])

| Baseline | 39.1 ± 9.6 | 39.8 ± 6.9 | 31.2 ± 8 | 63.6 ± 8 | 59.9 ± 17 | 60.3 ± 35 | 198 ± 16 | 194 ± 16 | 191 ± 15 | 6.6 ± 1.8 | 5.5 ± 1.8 | 6.1 |
| SL training | 66.7 ± 14 | 66.7 ± 13 | 68.7 ± 13 | 143 ± 36 | 134 ± 33 | 151 ± 4 | 143 ± 14 | 143 ± 14 | 151 ± 14 | 5.2 ± 1.8 | 4.7 ± 1.8 | 4.8* |
| Altitude training | 71.7 ± 71 | 72* ± 73* | 72.3 ± 43 | 146 ± 43 | 140 ± 33 | 136 ± 23 | 146 ± 19 | 140 ± 19 | 136 ± 19 | 1.9 ± 1.9 | 1.9 ± 1.9 | 3.1 |

Values are means ± SD; n = no. of subjects. SL, sea level; (a-v)DO\(_2\), arteriovenous O\(_2\) difference. *P < 0.05 compared with previous baseline (post hoc test). Significantly different compared across groups (interaction statistic) by 2-way ANOVA; †P < 0.05; ‡P < 0.15.

cardiac output and therefore more peripheral diffusion time and oxygen extraction [i.e., increased (a-v)DO\(_2\)], as well as providing for additional cardiac flow reserve. Finally, the close correlation between the increase in \( \dot{V}O_2\)\(_{\text{max}} \) and the improvement in 5,000-m time after the field training camp argues strongly that this is a key adaptation during altitude training and a necessary mechanism for improving sea-level performance.

However, this adaptation, by itself, may be necessary but not sufficient to improve sea-level performance. Thus the high-high group was exposed to exactly the same living conditions at 2,500 m and had similar increases in red cell mass volume and \( \dot{V}O_2\)\(_{\text{max}} \) as the high-low group, yet they did not increase running performance over 5,000 m at sea level. The only difference between these two groups was the training site, which in the high-high group was at moderate altitude.
Low-Altitude Training

Training (as opposed to living) at moderate altitude is associated with relatively severe hypoxemia, with oxyhemoglobin saturations reported to be <80% during typical base training (19). This hypoxia results in a decrease in maximal aerobic power of ~1% for every 100 m above 1,500 m (11). Particularly for well-trained athletes, there are more marked reductions in aerobic power even at lower altitudes (41). Thus, elite athletes are not able to sustain the high work rates at altitude necessary to maintain competitive fitness (35). In the present study, this limitation was manifested most clearly during interval training that was performed nearly 15% slower, and at 20% lower VO₂, than comparable training at sea level. Despite an equivalent effort (VE was 16% greater than at sea level), heart rate and lactate were also significantly lower at 2,700 m, consistent with previous reports of decreased maximal heart rate and maximal lactate after acclimatization to high altitude (33). Such a reduction in interval-training intensity in trained runners has recently been shown to decrease running performance over 5,000 m despite a preservation of VO₂max (27). It thus appears likely that in the high-high group, the increase in red blood cell mass and VO₂max was offset by a reduction in training velocity and oxygen flux, leading to no change in running performance.

In contrast to the training in the high-high group, who performed all interval training at 2,700 m, similar training at 1,250 m in the high-low group was only slightly (6%) slower than at sea level and was accomplished at virtually the same VO₂, heart rate, and lactate concentration. Although the mechanism is not entirely clear, such a maintenance of training velocity and oxygen flux is likely to be critical toward sustaining competitive performance, as has been recently shown in runners who decrease training volume but maintain intensity (6). This difference in training between high-high and high-low groups appeared to be the most important factor that, combined with the increase in VO₂max induced by altitude acclimatization, allowed for both an increase in the VO₂ at MSS and the velocity at VO₂max only in the high-low group.

Whether these characteristics associated with “low-altitude training” are specifically responsible for the improvement in 5,000-m time or simply markers for some other skeletal muscle adaptation is not clear. Adaptations such as increases in MSS would be expected to have a greater impact on longer distance events, during which competition occurs at some fraction below VO₂max than on 5,000-m performance, which is run essentially at VO₂max. One previous study has demonstrated an increase in muscle buffer capacity after a period of “high-high” altitude training (29) associated with an increase in oxygen deficit and an increase in treadmill run time. In the present study, we did observe an increase in uphill treadmill run time in our high-high group, raising the possibility of an in-

![Fig. 5. Time trial (5,000 m) results for all subjects (n = 13/group; 9 men, 4 women, A) and also for men only (n = 9/group; B) at baseline, after sea-level training in Dallas (sea level), and after altitude training camp or sea-level control (altitude). Time trials (5,000 m) were performed 3, 7, 14, and 21 days after leaving training camp. Group characteristics and figure symbols are defined as in Fig. 2. *P < 0.05 compared with previous timepoint. Asterisks next to brackets, interaction statistics for analysis of variance, P < 0.05.](image)

![Fig. 6. Relationship between change in maximal oxygen uptake (ΔVO₂max) and change in 5,000-m time trial performance (Δ5K) after training camp for all subjects. Group characteristics and symbols are defined as in Fig. 2, except for men (squares) and women (circles).](image)
increase in buffer capacity. However, we did not observe any changes in anaerobic capacity, as measured by the accumulated oxygen deficit. The difference between the study of Mizuno et al. (29) and ours may derive from the fact that their athletes changed training modalities, from running to skiing, during their sojourn at altitude. They also did not have any controls doing similar ski training at sea level.

We were concerned with the observation that in the present experiment, the concurrent sea-level control, if anything, tended to have a worse 5,000-m performance after the training camp compared with before, although this did not reach statistical significance. We suspect that, because all time trials were conducted in the heat of the Texas summer, a loss of heat acclimatization in the cooler mountains outside of San Diego, without the benefit of altitude acclimatization, may have been responsible for some of this apparent deterioration. We also considered the possibility that the athletes in the San Diego control might not have been as motivated as the altitude groups on the basis of previously held expectations of a benefit from altitude training. However, the new Olympic training center represents the state of the art in training facilities available to American Olympic athletes and would not be available to the athletes in this study under other circumstances. Virtually all the athletes were therefore very excited about the opportunity to go to San Diego, thus eliminating any sense of disappointment that might occur on the basis of randomization to the sea-level control. Moreover, these athletes are by nature very competitive, and the athletes in San Diego were, if anything, more motivated to perform better on return from the camp to prove that their training experience was every bit as good as their altitude counterparts. Over the course of the training cycle, it was clear that these athletes were receiving an outstanding training experience. They bonded as a group, performed extremely well in the interim races to which they were assigned during the month, and uniformly felt that they had improved significantly. The observed and reported differences are therefore even more remarkable in this regard.

On closer inspection, the majority of this seeming decline was due to unusually poor performances in two of our women athletes. Because we had only four female athletes in each group, which might increase the variability, as an additional check we also examined the 5,000-m performance for all men in the study separately. As can be seen in Fig. 5B, the results for men only were less variable, with no clear change in performance in the low-low or high-high group, and an even greater improvement in the high-low group. We believe that further studies involving larger numbers of female athletes will be necessary to confirm the applicability of this study to all women. However, we speculate that as long as adequate iron is made available through supplementation, the results will be consistent for all athletes, regardless of gender.

In conclusion, well-trained competitive runners living at moderate altitude increased red cell mass and oxygen-carrying capacity of the blood and increased $\dot{V}O_2_{\text{max}}$ after return to sea level. This increase in $\dot{V}O_2_{\text{max}}$ was translated into improved performance by the maintenance of near sea-level training velocities and oxygen flux when interval training was performed at low altitude, resulting in an increase in $V_O_2$ at MSS and velocity at $\dot{V}O_2_{\text{max}}$. Running performance over 5,000 m at sea level therefore improved only in the runners who lived at moderate altitude and trained near sea level (high-low group) but not in those who lived and trained at moderate altitude or lived and trained at sea level, after equivalent training programs.

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