Training High - Living Low: Changes of Aerobic Performance and Muscle Structure with Training at Simulated Altitude

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This study was undertaken to test the hypothesis that endurance training in hypoxia is superior to training of the same intensity in normoxia. To avoid adaptation to hypoxia, the subjects lived under normoxic conditions when not training. A secondary objective of this study was to compare the effect of high- vs. moderate-intensity training on aerobic performance variables. Thirty-three men without prior endurance training underwent a cycle ergometer training of 6 weeks, 5 days/week, 30 minutes/d. The subjects were assigned to 4 groups: Nhigh, Nlow, H-high and H-low based on the training criteria normoxia (N; corresponding to a training altitude of 600 m), vs. hypoxia (H; training altitude 3850 m) and intensity (high; corresponding to 80% and low: corresponding to 67% of VO2max). VO2max measured in normoxia increased between 8.5 to 11.1%, independent of training altitude or intensity. VO2max measured in hypoxia increased between 2.9 and 7.2%. Hypoxia training resulted in significantly larger increases than normoxia training. Maximal power that subjects could maintain over a thirty-minute period (measured in normoxia or hypoxia) increased from 12.3 – 26.8% independent of training altitude. However, subjects training at high intensity increased performance more than subjects training at a low intensity. Muscle volume of the knee-extensors as measured by magnetic resonance imaging increased significantly in the H-high group only (+ 5.0%). Mitochondrial volume density measured by EM-morphometry in biopsy samples of m. vastus lat. increased significantly in all groups with the highest increase seen in the H-high group (+ 59%). Capillary length density increased significantly in the H-high group only (+ 17.2%). The main finding of this study is that in previously untrained people, training in hypoxia while living at low altitude increases performance in normoxia to the same extent as training in normoxia, but leads to larger increases of aerobic performance variables when measured under hypoxic conditions. Training intensity had no effect on the gain of VO2max. On the level of skeletal muscle tissue, the combination of hypoxia with high training intensity constitutes the most effective stimulus for increasing muscle oxidative capacity.

Key words: Hypoxia, training intensity, endurance, VO2max, biopsy, human, mitochondrial density, capillary length density.

Introduction

The aim of this experiment was to investigate the effects of low ambient PO2 (PpO2 = 89 mmHg corresponding to an altitude of approx. 3850 m) during training on aerobic performance variables determined in normoxia and hypoxia as well as on skeletal muscle structure. Training periods at altitude are used by many athletes with the hope to improve performance after return to sea level [9]. However, the scientific rationale of this practice is not well-established [2]. Investigations with appropriate controls often report no additional benefit of altitude training [1,3,26]. Mellerowicz et al. [19] measured faster 3000 m times and a larger increase of VO2max in middle and long distance runners trained at an altitude of 1800 m compared to a sea level group. Similarly, Levine et al. [17] found an increase of VO2max on the treadmill and faster running times over 5 km after 28 days of living at 2500 m and training at 1200 m. Living and training at altitude increased VO2max but not the 5 km running time. Burtscher et al. [7] tested sports students after a 12 day running training at 2315 m. VO2max on the cycle ergometer increased when measured on day 16 after return but not on day 3. A control group trained with the same protocol at sea level showed no improvement. It thus appears that training at altitude might have a positive effect that surpasses that of equivalent sea level training under some conditions. However, the mechanisms remain debated. Most importantly, performance could be increased due to the increase in hematocrit observed after high-altitude exposure [12]. Additionally, an increased lung ventilation persisting upon return to sea level [18] could be beneficial to athletes who show desaturation of arterial blood during maximal performance at sea level.

It is presently not established whether training in hypoxia has effects on global performance variables and on muscle tissue that are not seen with training of similar intensity in normoxia.
The literature reports some evidence that such might be the case. Desplanches et al. [8] showed a larger increase in VO₂max (measured in hypoxia) for subjects trained in hypoxia whereas Terrados et al. [28] showed larger increase in endurance times as well as muscle myoglobin and oxidative capacity with hypoxia than with normoxia training. In order to test this hypothesis, we designed a study in which untrained subjects were exposed, at two training intensities, to a hypoxic environment during training only. An altitude of 3850 m was simulated in the laboratory with hypoxic gas mixtures.

**Methods**

**Subjects**

Thirty-three healthy untrained male volunteers gave their written consent to participate in the study. The experiments were approved by the ethics committee of the University of Bern. Candidates were excluded from the study if they had a record of previous endurance training, the limit being set at 30 minutes of continuous exercise per week at an intensity where lactate formation increases steeply. Anthropometric characteristics are given in Table 1. Body fat was estimated from the sum of skinfold measurements over the m. biceps brachii, m. triceps brachii, subcapular and suprailiacal, according to Durnin and Womersley [10].

**Training protocol**

Two variables, hypoxia and intensity, characterized the training, hence four groups were constituted, 1) high intensity, normoxia (n = 8, N-high), 2) high intensity, hypoxia (n = 10, H-high), 3) low intensity, normoxia (n = 7, N-low), and 4) low intensity and hypoxia (n = 8, H-low). The low intensity normoxia group trained at the same absolute load as the high intensity hypoxia group.

All subjects trained on an electrically braked cycle ergometer (Ergoline, Bitz, Germany) at a constant load during 30 minutes per day, 5 days per week for a total of 6 weeks. Initial load in the high intensity group was adjusted to elicit a heart rate of 85% of HRmax after 10 minutes of exercise. This corresponded to a VO₂ during training of approximately 80% of VO₂max and a blood lactate concentration in the domain of steep increase, i.e. 4 to 6 mmol/l in both the normoxia and hypoxia high intensity groups. This was a load that most subjects could tolerate for 40 to 45 minutes at most. During the 6 weeks of training the load was adjusted to the increasing aerobic capacity by maintaining training HR always approximately at the same level as well as the subjective feeling of exercise load. The low intensity group was trained at a lactate level of 2 to 3 mmol/l at around 77% of HRmax, which corresponds to 68% of VO₂max. The load was around 55% of maximal power. Training load was adjusted when necessary, generally once or twice a week in order to keep HR and lactate at the initially chosen level. The normoxia corresponded to air breathing at 600 m and the hypoxia was achieved through addition of N₂ to the inspired air resulting in the PIO₂ that prevails at an altitude of 3850 m. A summary of the experimental conditions can be found in Table 1.

**Measurements**

The functional measurements comprised the following: Before and after the training period, a venous blood sample was drawn and analyzed for hemoglobin, hematocrit, reticulocytes, iron, transferrin and ferritin.

Maximal oxygen uptake (VO₂max) was measured in hypoxia and in normoxia in each subject before and after the training period. The initial load was 100 Watt in normoxia and 70 Watt in hypoxia. Every two minutes the load was increased by 30 Watt until the subject could no longer continue despite verbal encouragement. We judged the test valid when the respiratory exchange ratio at the termination of the test exceeded 1.1 and/or a plateau of VO₂ was reached. The criterion for reaching a plateau was less than a 100 ml/min increase in VO₂ in the last minute. Measurements of heart rate, lactate and respiratory exchange rate reached at the termination of the test are listed in Table 2. Mean values for each group, before and after training are given. Heart rate was measured with the Sport Tester (Polar OY, Kempele, Finland). Initial testing in hypoxia was done un-

**Table 1** Subject characteristics and training conditions

<table>
<thead>
<tr>
<th>Group</th>
<th>N-high</th>
<th>N-low</th>
<th>H-High</th>
<th>H-low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>8</td>
<td>7</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Age</td>
<td>25 ± 3</td>
<td>29 ± 13</td>
<td>23 ± 2</td>
<td>23 ± 3</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>180 ± 5</td>
<td>181 ± 6</td>
<td>178 ± 5</td>
<td>180 ± 6</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>76.5 ± 8.2</td>
<td>75.5 ± 13.5</td>
<td>75.8 ± 10.0</td>
<td>77.7 ± 13.3</td>
</tr>
<tr>
<td>Body fat (percent)</td>
<td>13.1 ± 3.2</td>
<td>16.5 ± 8.4</td>
<td>15.7 ± 4.3</td>
<td>15.6 ± 4.7</td>
</tr>
<tr>
<td>VO₂max (ml/min/kg)</td>
<td>51.0 ± 4.7</td>
<td>48.8 ± 8.0</td>
<td>51.1 ± 6.0</td>
<td>48.5 ± 5.1</td>
</tr>
<tr>
<td>Equivalent altitude (m)</td>
<td>600</td>
<td>600</td>
<td>3850</td>
<td>3850</td>
</tr>
<tr>
<td>Training intensity</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Lactate (mmol/L)</td>
<td>4–6</td>
<td>2–3</td>
<td>4–6</td>
<td>2–3</td>
</tr>
<tr>
<td>PIO₂ (mmHg)</td>
<td>138</td>
<td>138</td>
<td>89</td>
<td>89</td>
</tr>
</tbody>
</table>

Mean values ± SD. N stands for normoxic conditions. H for hypoxia. PIO₂ and equivalent altitude are given without SD. Daily changes in barometric pressure are in the range of 2 mmHg. Gas mixtures in hypoxia were hand regulated. We achieved a precision corresponding in ±100 m around the mean value of 3850 m. Lactate values are from capillary blood samples after 20 minutes of cycling.
<table>
<thead>
<tr>
<th>Group</th>
<th>N-high</th>
<th>N-low</th>
<th>H-high</th>
<th>H-low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test altitude (m)</td>
<td>600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lactate (mmol/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before training</td>
<td>8.9 ± 1.6</td>
<td>8.0 ± 2.0</td>
<td>8.2 ± 1.7</td>
<td>9.1 ± 1.6</td>
</tr>
<tr>
<td>after training</td>
<td>8.3 ± 2.7</td>
<td>9.3 ± 1.6</td>
<td>8.6 ± 1.6</td>
<td>10.0 ± 1.0</td>
</tr>
<tr>
<td>Heart rate (min⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before training</td>
<td>192 ± 5</td>
<td>188 ± 11</td>
<td>189 ± 7</td>
<td>194 ± 7</td>
</tr>
<tr>
<td>after training</td>
<td>188 ± 7</td>
<td>184 ± 9</td>
<td>184 ± 5</td>
<td>187 ± 9</td>
</tr>
<tr>
<td>Respiratory exchange ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before training</td>
<td>1.16 ± 0.01</td>
<td>1.18 ± 0.08</td>
<td>1.17 ± 0.06</td>
<td>1.16 ± 0.03</td>
</tr>
<tr>
<td>after training</td>
<td>1.17 ± 0.01</td>
<td>1.17 ± 0.08</td>
<td>1.18 ± 0.05</td>
<td>1.19 ± 0.08</td>
</tr>
<tr>
<td>Test altitude (m)</td>
<td>3850</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lactate (mmol/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before training</td>
<td>8.5 ± 2.9</td>
<td>7.7 ± 0.6</td>
<td>9.4 ± 2.0</td>
<td>8.7 ± 1.7</td>
</tr>
<tr>
<td>after training</td>
<td>9.7 ± 23</td>
<td>8.9 ± 1.7</td>
<td>9.7 ± 1.8</td>
<td>9.7 ± 2.9</td>
</tr>
<tr>
<td>Heart rate (min⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before training</td>
<td>181 ± 9</td>
<td>182 ± 10</td>
<td>184 ± 7</td>
<td>185 ± 9</td>
</tr>
<tr>
<td>after training</td>
<td>180 ± 8</td>
<td>180 ± 9</td>
<td>179 ± 7</td>
<td>184 ± 10</td>
</tr>
<tr>
<td>Respiratory exchange ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before training</td>
<td>1.27 ± 0.06</td>
<td>1.29 ± 0.06</td>
<td>1.29 ± 0.08</td>
<td>1.29 ± 0.13</td>
</tr>
<tr>
<td>after training</td>
<td>1.35 ± 0.09</td>
<td>1.32 ± 0.11</td>
<td>1.32 ± 0.08</td>
<td>1.34 ± 0.11</td>
</tr>
</tbody>
</table>

Mean values ± SD. N stands for normoxic conditions, H for hypoxia. High and low pertain to relative training effort. Pre- and post-training values as well as group means are not statistically different.

der surveillance by a 12-lead ECG. Capillary blood from the fingertip was taken every 2 minutes for lactate analysis (YSI model 23L, Yellow Springs, Ohio). The respiratory gases were analyzed by an open circuit method in the Oxycon Champion (Jaeger, Würzburg, Germany), which allows continuous, breath by breath measurement of ventilation, $\text{VO}_2$ and $\text{VCO}_2$.

Power sustained during 30 minutes at approximately 85% of $\text{HR}_{\text{max}}$ was measured in normoxia and hypoxia before and after the training period.

Morphological measurements: In each subject muscle mass of the thigh was determined on the basis of magnetic resonance images. Computed images of cross-sections of the thigh (distance between slices 23 mm) were printed on X-ray film. The individual muscles were identified and marked by pencil. The cross-sectional area of the muscles in each slice was indirectly determined by counting the crossing points of a randomly applied grid laid on a particular muscle. Muscle volume was reconstituted by application of the principle of Cavalieri [21]. The method is valid when for a muscle the sum of crossing points in all slices is >100. The mesh of the grid was chosen in accordance with this requirement.

Two muscle biopsies in the vastus lateralis were taken in each subject, one before and one after the training period, using the technique of Bergström [6]. During the 24 h preceding the biopsy the subjects refrained from physical exercise. The samples served for a complete morphometric analysis including the volume of central and subsarcolemmal mitochondria and capillary length density. Details about sample processing and analysis can be found in previous publications [15].

Statistical analysis

To test the effect of the 6-week training on each measured variable, a two-tailed t-test was performed on the ratios after training/baseline value. The significance level was set at $p = 0.05$. The influence of the factors $\text{FIO}_2$ and training intensity on training effects was assessed from an unbalanced factorial analysis of variance. When significant effects were detected, a post hoc Scheffé test was employed. A $p$ value of 0.05 or less was considered statistically significant.

Results

Hematology

Hematologic data were measured before and after 6 weeks of training. Daily exposure to hypoxia during 30 minutes was not sufficient to elicit increased erythropoiesis. Hemoglobin before training was (mean ± SD) 151 ± 12 g/L (normal range 140–180) in the N group and 154 ± 8 in the H group. After training the values were 149 ± 11 (N) and 155 ± 6 (H). Increased concentration of red cells would be preceded by an increase in the reticulocyte count. No such observation was made. In the N group there were 15.4 ± 8.8 reticulocytes per 1000 red cells before training (normal value < 20) and 16.2 ± 5.6 after training. In the H group we measured 18.2 ± 7.1 before and 16.9 ± 6.4 after training. This does not exclude that the reticulocyte count may have increased sometime during the 6-week training period. The absence of a reaction of the hematopoietic system to hypoxia over the entire training period can likely be attributed to the shortness of the exposure and not to an iron deficiency as sometimes observed [25]. Ferritin, which reflects iron reserves, was in the normal range (30–300 μg/L). It amounted to 97 ± 56 in group N before training and 79 ± 36 afterwards and in group H 86 ± 52 and 82 ± 54, respectively. None of these differences were statistically significant.

Training-induced functional changes

Training effects on $\text{VO}_2\text{max}$ maximum power and sustained power are shown in Table 3. $\text{VO}_2\text{max}$ measured in normoxic conditions increased by 8.5 to 11.1% after 6 weeks of training, there were no differences due to intensity or the level of inspired $\text{PO}_2$ during the training. When $\text{VO}_2\text{max}$ was measured in hypoxia, there was again no different improvement for high
Table 3  Training effects on aerobic functions

<table>
<thead>
<tr>
<th>Group</th>
<th>N-high</th>
<th>N-low</th>
<th>H-high</th>
<th>H-low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test altitude (m)</td>
<td>600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \dot{V}O_2 \max ) (L/min), before training</td>
<td>3.88±0.37</td>
<td>3.56±0.29</td>
<td>3.85±0.32</td>
<td>3.64±0.42</td>
</tr>
<tr>
<td>Percent increase after training</td>
<td>8.5±4.2*</td>
<td>9.5±5.6*</td>
<td>10.4±5.8*</td>
<td>11.1±6.2*</td>
</tr>
<tr>
<td>Peak power (Watt), before training</td>
<td>300±41</td>
<td>301±17</td>
<td>305±32</td>
<td>299±28</td>
</tr>
<tr>
<td>Percent increase after training</td>
<td>15.4±8.0*§</td>
<td>13.2±4.4*</td>
<td>18.0±6.8*§</td>
<td>11.3±3.9*</td>
</tr>
<tr>
<td>Sustained power during 30 minutes, before training</td>
<td>194±19</td>
<td>211±12</td>
<td>211±28</td>
<td>200±23</td>
</tr>
<tr>
<td>Percent increase after training</td>
<td>21.9±6.1*§</td>
<td>15.8±4.2*</td>
<td>19.1±9.2*§</td>
<td>15.6±6.6*</td>
</tr>
<tr>
<td>Test altitude (m)</td>
<td>3850</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \dot{V}O_2 \max ) (L/min), before training</td>
<td>3.03±0.26</td>
<td>2.94±0.24</td>
<td>3.12±0.32</td>
<td>2.81±0.12</td>
</tr>
<tr>
<td>Percent increase after training</td>
<td>2.9±5.2</td>
<td>3.4±3.9</td>
<td>7.2±6.8* &amp;</td>
<td>7.2±2.9* &amp;</td>
</tr>
<tr>
<td>Peak power (Watt), before training</td>
<td>237±37</td>
<td>255±18</td>
<td>253±27</td>
<td>241±22</td>
</tr>
<tr>
<td>Percent increase after training</td>
<td>12.5±4.3*</td>
<td>9.5±7.1*</td>
<td>16.1±7.3*</td>
<td>14.3±6.83*</td>
</tr>
<tr>
<td>Sustained power during 30 minutes, before training</td>
<td>155±15</td>
<td>171±10</td>
<td>159±19</td>
<td>163±21</td>
</tr>
<tr>
<td>Percent increase after training</td>
<td>20.1±6.4*§</td>
<td>13.9±4.4*</td>
<td>26.8±7.6*§</td>
<td>12.3±8.6*</td>
</tr>
</tbody>
</table>

Mean values ± SD. N stands for normoxic conditions, H for hypoxia. The level for statistical significance of differences was set at p<0.05. Symbols: * denotes pre- and postraining differences. & means that hypoxia trained subjects performed better than normoxia trained, and § denotes better performance after intense vs. moderate training.

or low intensity training groups. However, the hypoxia trained groups performed better in hypoxia than the normoxia trained groups (+7.2 vs +3.1%).

Peak power developed in the \( \dot{V}O_2 \max \) test increased more than \( \dot{V}O_2 \max \). After training peak power measured in normoxia increased between 11.3 and 18.0% in the four groups. Training altitude had no effect but in the more intensely trained subjects peak power increased more (+16.8 vs. +12.2%). Interestingly the training effect on peak power measured in hypoxia was the same for the two training intensities. However, as with \( \dot{V}O_2 \max \), the hypoxia trained subjects fared better, although only marginally (+15.3 vs. +11.0%, p = 0.08).

Endurance was characterized by sustained power. The power sustained during 30 minutes at 85% of HRmax increased markedly more than \( \dot{V}O_2 \max \). Overall increase after training, lumping together values measured during normoxic and hypoxic work in the four groups was 19.0±8.8%. Training altitude did not affect the outcome neither for performance under normoxia nor under hypoxia. Intensively trained subjects performed better (tested in normoxia +20.3 vs. +15.7% and tested in hypoxia +23.8 vs. +13.0%).

Training induced structural changes

Changes in muscle volume with training are reported in Table 4. We observed generally a small increase in muscle volume. There don’t seem to be any particularities due to the training conditions. A comparison on the entire collective of 33 subjects yields a mean increase of 2.8% (p < 0.01). The largest increase was observed in the H-high group. Subcutaneous fat did not change. Bone volume remained constant proving that no systematic errors were made in the evaluation process. Group means for structural variables measured by morphome-

Hypoxia training and endurance performance

If an additional benefit from altitude training exists, this could be the result of adaptations to altitude. The increase of oxygen carrying capacity is generally considered to be the most important factor. Measurements in venous blood samples show that the exposure to hypoxia during half an hour per day did not elicit a change in hemoglobin concentration over the entire training period. Our results are therefore not due to a change in oxygen carrying capacity of the blood. This is in accordance
with current knowledge and merely corroborates results published in the past [8].

The increase of sea level VO\textsubscript{2max} after training was 3 to 11 % in all settings. There was no difference whether the subjects had trained in normoxia or in hypoxia. The increase is rather low but in the expected range. In contrast, when VO\textsubscript{2max} was measured in hypoxia, the hypoxia trained subjects showed a more important progression than those trained in normoxia.

Endurance was determined from the power that could be maintained at a heart rate of 85 % of HR\textsubscript{max} during 30 min. This work intensity was the training load in both high intensity groups. Corresponding blood lactate concentrations were 4 to 6 mmol/L. Lactate in hypoxia was not systematically lower as could have been expected from the literature on the lactate paradox [16]. However, the study was not designed to address this problem specifically. The result of our study was an approximately 20 % increase of sustained power at the same HR and same lactate, again hypoxia training was not better nor worse than training in normoxia. The increase in endurance however was larger in the more intensely trained subjects. Measured in hypoxia the most efficient training condition appeared to be the combination of high intensity and hypoxia, although this could not be proved statistically. The conclusions from these results are that sea level performance is not enhanced by hypoxia applied only during training and that a specificity of the training exists in that best performances in hypoxia can be expected after hypoxic training. This result is in accordance with findings by Desplaches et al. [8] and others [4,5].

There are only few studies with a similar design to ours, i.e. hypoxia during training only. Most of them found no additional effect of hypoxia training on sea level performance. Vallier et al. [29] have submitted trained triathletes to a three-week training in a hypobaric chamber (4000 m). VO\textsubscript{2max} did not change, neither measured in hypoxia nor in normoxia. Engfred et al. [11] did a 5-week cycle ergometer training in the hypobaric chamber (2500 m) with previously untrained subjects. VO\textsubscript{2max} increased by 12 %, without any difference between the hypoxia-trained group and the normoxia control. In contrast with the above studies that agree well with our results from testing in normoxia, is the paper by Roskamm et al. [23]. They found a larger increase in VO\textsubscript{2max} in the altitude-trained groups (2250 and 3450 m) than in the sea-level group. We have no explanation for this discrepancy. One difficulty in Roskamms's study was that VO\textsubscript{2max} was measured by sampling of expired air during the last minute of the incremental VO\textsubscript{2max} test, subsequently analyzed by the Scholander technique. While the measurement itself is very reliable, it may be difficult to make coincide the sampling period exactly with the last minute of exercise, and additionally a plateau during this last minute is assumed, a condition that seldom exists. Terrados et al. [27] studied trained cyclists. Three to 4 weeks of training in a hypobaric chamber at 2300 m did not change VO\textsubscript{2max}. They measured, however, an increase in work capacity. Work capacity was defined as the cumulated work in an exhaustive test with 50 W increases every 2 minutes. In the altitude group this increase seemed larger than in the sea level group but it didn't reach statistical significance. This endurance test lasted only for 10 to 12 minutes of which only few minutes were above the anaerobic threshold. Interestingly, when performance in hypoxia was tested, the altitude group did better than the sea level group. Benoit [5] found similar results. After 3 weeks of training the hypoxia trained group increased VO\textsubscript{2max} at altitude by 5 % while the normoxia-trained group increased only VO\textsubscript{2max} in normoxia. The general bias of the available studies with similar design to ours is therefore towards an advantage of hypoxia training but only when performance is estimated in hypoxia.

### Training intensity

Our study was designed to compare training of equal relative intensity (N-high vs. H-high) and also of equal absolute substrate turnover (H-high vs. N-low). The addition of an H-low group permitted an analysis of training effects on aerobic functions depending on training intensity. While subjectively and based on lactate levels the two intensities were quite different, training effects on VO\textsubscript{2max} did not differ and the increases in endurance performance were only slightly better after intense training. Intuitively a larger difference between the two training intensities would be expected but in fact the result is comparable to those of a training study by Gaesser and Rich [13] who found the same increase in VO\textsubscript{2max} after 18 weeks of training either at a load of 45 % or 80 % of VO\textsubscript{2max}.  

### Table 4  Morphological measurements in M. vastus lateralis. Comparisons after 6 weeks of training

<table>
<thead>
<tr>
<th>Group</th>
<th>N-high</th>
<th>N-low</th>
<th>H-high</th>
<th>H-low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase of knee extensor volume (%)</td>
<td>1.36 ± 0.74</td>
<td>3.24 ± 1.65</td>
<td>4.96 ± 1.01*</td>
<td>1.09 ± 1.03</td>
</tr>
<tr>
<td>Volume density of total mitochondria (%)</td>
<td>before training 6.01 ± 0.48</td>
<td>5.53 ± 0.39</td>
<td>5.25 ± 0.38</td>
<td>5.22 ± 0.45</td>
</tr>
<tr>
<td>Volume density of subsarcolemmal mitochondria (%)</td>
<td>before training 1.42 ± 0.25</td>
<td>1.01 ± 0.16</td>
<td>1.00 ± 0.17</td>
<td>0.80 ± 0.22</td>
</tr>
<tr>
<td>Capillary length density (mm\textsuperscript{-2})</td>
<td>after training 1.61 ± 0.24</td>
<td>0.88 ± 0.18</td>
<td>2.05 ± 0.37* &amp;</td>
<td>1.54 ± 0.35 &amp;</td>
</tr>
<tr>
<td>Capillary length density (mm\textsuperscript{-2})</td>
<td>before training 762 ± 35</td>
<td>729 ± 31</td>
<td>735 ± 44</td>
<td>644 ± 42</td>
</tr>
<tr>
<td>Capillary length density (mm\textsuperscript{-2})</td>
<td>after training 760 ± 37</td>
<td>655 ± 52</td>
<td>821 ± 35* &amp;</td>
<td>658 ± 23</td>
</tr>
</tbody>
</table>

Mean values ± SE. N stands for normoxic conditions. H for hypoxia. Volume density of mitochondria is volume/fiber volume in %. Total mitochondria are the sum of central and subsarcolemmal mitochondria. Symbols as in Table 3.
**Morphology**

Muscle mass increased slightly, but significantly. The biological significance of this increase is not quite obvious. First, we cannot entirely exclude that this difference has to do with training related increases of water content of the muscle. If it really represents an increase in contractile elements, we could conclude that in untrained persons endurance training has also a slight training effect on muscle cross section area.

Endurance training is known to increase the total mitochondrial volume [14]. Our study confirms this observation and, in addition, reveals an additional effect of hypoxia during training. After endurance training in normoxia volume adaptations are primarily observed in the subsarcommaal mitochondria [14]. Not so in the present study where the increase in volume density was much more pronounced in intrafibrillary mitochondria. The hypoxia-trained subjects increased both volume densities of subsarcommaal and intrafibrillary mitochondria. This latter result is also at variance with the study by Desplanches et al. [8]. Their findings were the absence of any enlargement of mitochondria volume after normoxia training and a preferential volume increase of intrafibrillar mitochondria when training under hypoxia. The difference with our study was essentially the much longer duration of training, 2 hours a day, and the equivalent altitude, which started at 4100 m and ended at 5700 m after 3 weeks. It is unclear, however, how these differences could cause such dissimilar effects on mitochondria. A common conclusion from all those rather conflicting results seems to be that hypoxia and normoxia training has not the same effects on subsarcommaal and intrafibrillary mitochondria. The exact response pattern however probably depends on a combination of factors like the level of hypoxia during training and duration and intensity of training. A larger sample and a more focussed design of the experiment would be needed to define the conditions for the increase of one or the other of the two mitochondrial compartments.

One important effect of endurance training is an increase in capillary length density [8, 15, 20, 22]. It rather astonishes that only in the H-high group a significant increase was observed. An analysis of variance showed that hypoxia was the main contributing factor. Perhaps the total duration of the training sessions was not sufficient to elicit measurable increases in capillary length density, except when hypoxia was combined with exercise of high intensity. The present data are further evidence for the dichotomy between local and global changes of aerobic capacity with training [24]. However, the noise in the data does not allow us to draw firm conclusions or even to put forward a reasonable hypothesis. This is likely due to the limited number of subjects. Moreover, the study was not designed to reveal these differences in particular.

In conclusion, untrained subjects living at low altitude and training in hypoxia increase VO₂max and peak power in the VO₂max test in hypoxia more than subjects trained in normoxia. For the test in low altitude, the altitude during training did not influence the outcome. We also found that hypoxia during training enhances training effects on the mitochondrial and capillary density and thus on oxidative mechanisms on the cellular level. Training intensity had no effect on VO₂max but seemed to influence positively peak power (at normoxia), sustained power and muscle oxidative capacity.

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**References**


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