



## INFLUENCE OF HYPOXIA TRAINING ON THE AEROBIC CAPACITY OF AN ELITE RACE WALKER

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### ABSTRACT

**Purpose.** The aim of the study was to evaluate the influence of a combination of two different hypoxic training models (“live high-train high” and “live high-train low” with the use of a hypoxic tent) on the aerobic capacity of a elite race walker preparing for the 2009 IAAF World Championships. **Methods.** Evaluation of  $VO_2$ max and the second ventilatory threshold was performed three times: 1) after four weeks training without hypoxic conditions, 2) after 28 days training in normoxia and sleeping for 8 h/day in a hypoxic tent (normobaric hypoxia, simulated hypoxia at 2133 m above sea level) and 3) after 26 days of classical altitude training at a moderate altitude of about 1800 m ASL (hypobaric hypoxia). The hematological parameters of the athlete’s blood (hematocrit, hemoglobin concentration, and erythrocytes and reticulocytes counts) were also measured after each stage. **Results.** After training in normoxia and sleeping in a hypoxic tent the ventilatory threshold was noted at a higher work intensity and featured an improvement in his hematological parameters, although  $VO_2$ max was unchanged (compared to training without hypoxia). After classical altitude training a higher level of  $VO_2$ max was observed (with a ventilatory threshold level similar to the level after training in normobaric hypoxia), but the hematological indices were lower than the levels observed before starting hypoxic training. **Conclusions.** The combination of two methods of hypoxic training improved the aerobic capacity of the test subject, but an improvement in the analyzed hematological indicators was observed only after LH + TL training. After training in LH + TH these indicators were lower in comparison to the levels prior hypoxic training. The changes in the hematological indices after hypoxic training did not seem to have a significant influence on aerobic capacity; the observed improvements in physical performance may result from other factors.

**Key words:** hypoxia, aerobic capacity, ventilatory threshold, training

### Introduction

The aerobic capacity is determined by several factors, most commonly referred to as the mechanisms of oxygen supply. These include, inter alia, maximal minute ventilation ( $VE_{max}$ ), the efficient diffusion of gases in the lungs and tissues, maximal cardiac output, blood oxygen capacity and muscle capillarization. Of these factors, it appears that the most limiting aerobic capacity is blood oxygen capacity, which is mainly determined by the number of erythrocytes and hemoglobin in the blood. For this reason, modern training techniques primarily focus on improving blood hematological indices, thus increasing the oxygen capacity of the blood. The most commonly used method in sports is to have individuals train in conditions with low oxygen partial pressure (hypoxia). This requires taking advantage of the natural environmental conditions that exist when training at high altitudes, where reduced oxygen partial pressure results in hypoxia (hypobaric hypoxia). Another

more frequently method used in competitive sport is the use of hypoxic tents that artificially change the environmental conditions in it, reducing the pressure of oxygen to simulate high-altitude conditions (normobaric hypoxia).

Hypoxia causes the body to synthesize erythropoietin in the kidneys, which is a hormone which stimulates erythropoiesis. This leads to increased levels of erythrocytes and hemoglobin and, thus, increases the oxygen capacity of the blood. The effectiveness of using different models of hypoxic training (hypobaric hypoxia, normobaric hypoxia) is not clear. Some authors observed improvements in hematological indices and physical performance, while others have found no change in the level of physical endurance and/or a reduction in blood hematological indices; in some studies it was even observed that training under hypoxic conditions resulted in detraining [1–5]. The reasons behind an eventual improvement in physical performance are still not clear, caused in some part by the different effects observed by hypoxia [2, 6, 7].

The aim of this paper was to present the impact of a combination of two hypoxic training methods on the aerobic performance of a highly trained athlete practicing race walking.

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## Material and methods

The test subject represented the country of Poland numerous times over his career, placing seventh in the Olympic Games in Athens (2004), ninth in the Olympic Games in Beijing (2008), fourth in the World Championships in Athletics in Berlin (2009), second in the European Championships (2010) as well as being a multiple Champion of Poland in race walking. The test subject was competitor in the 50 km race walk and is considered an elite race walker at the international level. At the time of testing the subject was aged 30.5 years, with a 16-year-long career in race walking.

The study was conducted during the subject's preparatory training phase prior to the competitive season, in which the goal was to complete in the World Championships in Athletics in Berlin (2009). The study was based on the subject's training schedule and divided into three stages: Stage I consisted of a preliminary examination carried out after the subject completed a four-week training period without hypoxic conditioning, Stage II consisted of training with the use of a hypoxic tent, whereas Stage III consisted of training conducted at high altitudes. During Stages I and II, the athlete trained in Kraków (Poland) at an altitude of about 230 m above sea level (ASL). The second stage lasted 28 days and was supplemented by sleeping in a hypoxic tent, the Altitude Tent System (WAT 14000, Wallace, USA) to simulate atmospheric conditions at an altitude of 2133 m ASL. After awakening, the subject measured his oxygen saturation using a pulse oximeter and recorded the total time (sleep) spent in the tent. After this stage, the subject began training in South Africa for a total of 26 days at an altitude of about 1800 m ASL (stage III); upon completion of his training he flew back to Kraków.

Immediately after each stage the somatic characteristics and aerobic capacity of the subject were measured, as well as a basic blood test was performed for hematocrit, hemoglobin, erythrocyte and reticulocyte counts.

Anthropometric measurements were conducted with a Tanita TBF-300 body analyzer (Tanita, USA), which estimated body composition based on bioelectrical impedance analysis (BIA). Measurements included: body mass (BM), body mass index (BMI), body fat percentage (% FAT), fat mass (FM) and lean body mass (LBM). The first test also included measuring the subject's body height (BH) using an anthropometer.

Aerobic capacity was assessed by maximal oxygen uptake ( $\text{VO}_{2\text{max}}$ ) and the second ventilatory threshold, defined as the point when the load from high-intensity exercise is so great that the anaerobic metabolism's production of lactate leads to the onset of fatigue, in a test in which a steadily increasing workload was performed till exhaustion. This would determine both the size of  $\text{VO}_{2\text{max}}$  as well as the exercise intensity that would correspond to the second ventilatory threshold. This test was

performed on a treadmill (Saturn, HP Cosmos, Germany), where the subject was to race walk at an increasing speed. After a number of baseline factors were analyzed, the subject began a warm-up (4 min) at a speed of  $3.2 \text{ m} \cdot \text{s}^{-1}$  ( $11.5 \text{ km} \cdot \text{h}^{-1}$ ) with the treadmill inclined to  $1^\circ$ . The speed was then increased to  $3.3 \text{ m} \cdot \text{s}^{-1}$ , which then after two minutes of exercise was systematically increased by  $0.3 \text{ m} \cdot \text{s}^{-1}$  every two minutes. After reaching a gait speed of  $4.2 \text{ m} \cdot \text{s}^{-1}$ , the workload was further increased by raising the treadmill at an angle of  $1^\circ$  every minute.

The subject's respiratory metabolism was analyzed using an ergospirometer (Medikro 919, Medikro Oy, Finland), which continuously measured the respiratory rate (FR), tidal volume (TV), maximal minute ventilation (VE), oxygen uptake ( $\text{VO}_2$ ) and the ratio of oxygen and carbon dioxide of exhaled gas as a respiratory quotient (RQ). This test was also used to determine  $\text{VO}_{2\text{max}}$ . Based on the changes in the respiratory rates that were observed during the study, the level of the ventilatory thresholds were defined as per Reinhard et al. [8] and Bhambhani and Singh [9], in which the second ventilation threshold corresponded to the threshold of decompensated metabolic acidosis (TDMA). In addition, the heart rate (HR) of the subject was continuously recorded throughout the test using a Polar S610i heart rate monitor (Polar, Finland).

Blood samples were taken from the fingertip before, and then three and 20 minutes, after the test was completed. The concentration of lactate (La) was determined by a colorimetric method using the Lactate PAP enzyme test (Biomerieux, France).

Based on the subject's training diary, the amount of physical exertion performed at a certain intensity (metabolic training zones) was defined: exercise below the lactate threshold (LT), above the lactate threshold or at the lactate threshold ( $\text{HR}_{\text{LT}} \pm 3 \text{ bpm}^{-1}$ ) as well as a recovery zone (heart rate below  $140 \text{ bpm}^{-1}$ ). Training intensity was monitored by the subject with a heart rate monitor (RS 800, Polar, Finland).

The body height of the participant was 175 cm, while body mass was found to steadily decrease from 61.9 kg measured in the first test to 59.9 kg in the third test (subject's starting weight). This change was mainly due to a decreased amount of body fat: fat mass decreased from 3.7 kg in the first test to 2.0 kg in the last one. Body fat content was found to be very low in each test and steadily decreased in each subsequent test, reaching 3.4% of body mass by the third test. Lean body mass in each test was relatively stable at around 58 kg (Tab. 1).

When analyzing the entire training period, each of the stages were found to be very similar to each other: nearly 80–90% of the subject's training was performed with work intensity below the lactate threshold, 7–17% at the lactate threshold, and only 3–5% of the training volume was done at an intensity above the lactate threshold. It is worth noting that in the second stage the sub-

Table 1. The somatic characteristics of the studied athlete after each stage

Variable	Stage I	Stage II	Stage III
BH (cm)		175	
BM (kg)	61.9	60.7	59.9
BMI	20.2	19.8	19.3
LBM (kg)	58.2	58.4	57.9
FAT (%)	6	3.8	3.4
FM (kg)	3.7	2.3	2.0

BH – body height; BM – body mass; BMI – body mass index; LBM – lean body mass; FAT – body fat percentage; FM – fat mass

ject had the smallest training volume (approx. 15–16 h) than in the other stages.

In the first stage of the study, during the four-week training period without the use of hypoxic conditioning, the subject completed 39 training units with a total training time of 40 h 40 min in which he covered a distance of 493 km. Exercise performed with intensity below LT was 87% of the total or about 33 h 44 min, of which 19 h was part of the recovery phase (46% of the total training time). Exercise at the lactate threshold was found to be 4 h 5 min (10% of total training time), while time spent in exercise zone above the LT accounted for 3% (49 min) of total training time.

In the second stage of the study, the 28-day training period that saw the use of the hypoxic tent, the subject completed 29 training units. Total training time was 24 h 50 min in which the subject covered a distance of 284 km. Exercise completed with intensity below LT amounted to 90% of the total training volume, or 22 h 24 min, of which 12 h 46 min was part of the subject's recovery phase (51% of total time). Exercise completed at an average intensity amounted to 1 h 41 min, which accounted for 7% of total training time. In this stage the subject spent a total of 221.5 h in the hypoxic tent, which averaged to 9 h 20 min per day (28 days). The average blood oxygen saturation level measured after waking up was 89.5%.

In the third stage of the study, lasting 26 days in which training was conducted at a high altitude, the subject completed 42 training units. Total training time was 41 h 30 min and the distance run was 510 km. Exercise intensity below LT amounted to 78% of the total training volume (32 h 34 min), with 14 h as part of a recovery phase (33% of the total training time). Exercise per-

formed at the lactate threshold was 7 h or 17% of the total training time. Training intensity above the LT accounted for 5% (2 h 12 min) of the training volume. The reason for the larger distances covered in the I and III stage was the result of attending a training camp and being able to complete more training units.

## Results

The subject presented a high level of aerobic capacity, which were confirmed by the high values of maximum oxygen consumption (approx.  $70 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ ) presented in each of the tests. The highest value, at  $75.3 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ , was recorded after the subject returned from high-altitude training (an increase of approx. 8.7%) when compared to the other two tests, both of which were a similar level of  $68\text{--}69 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ . The increased value of the relative value of  $\text{VO}_{2\text{max}}$  was in part due to the subject's loss in body mass. Similar changes were noted in the overall level of maximal oxygen uptake: the highest rate was also recorded in the third test ( $4.51 \text{ L} \cdot \text{min}^{-1}$ ), which was almost 5% higher than the values recorded in the first test. A slight decrease (compared to the first test) in overall  $\text{VO}_{2\text{max}}$  values (by  $0.17 \text{ L} \cdot \text{min}^{-1}$ ) was found after being subjugated to the hypoxic tent. The subject's maximum heart rate in each test was around  $184\text{--}189 \text{ bpm}^{-1}$ , while the maximal minute ventilation ranged from  $138.6 \text{ L} \cdot \text{min}^{-1}$  (second test) to  $144.6 \text{ L} \cdot \text{min}^{-1}$  (third test).

The results of the three tests conducted after each stage are presented in Table 3. Here, the longest time trial (14.12 min) as well as the longest distance (3055 m) was recorded after the high-altitude training stage. The results after the second stage were marginally smaller when compared to the first test in terms of the distance covered and test time, by 80 m and 15 s, respectively. In addition, higher concentrations of blood lactate in the third minute post-test after training in hypoxic conditions (stage II using the hypoxic tent and stage III in high-altitude conditions) were found when compared to training in normoxia conditions. However, the rate of lactate removal from the blood was considerably improved after training in hypoxemic conditions by about 150% after use of the hypoxic tent and by about 100% after high-altitude training (Tab. 3).

The effects of hypoxia training on the analyzed physiological parameters at the TDMA were significant. Both training stages in hypoxic conditions, whether with

Table 2. Characteristics of completed training loads for each stage

Stage	Number of training units	Total training time (h:min)	Distance covered (km)	Below LT (%)	At LT (%)	Above LT (%)
Stage I	39	40:40	493	87	10	3
Stage II	29	24:50	284	90	7	3
Stage III	42	41:48	510	78	17	5

LT – lactate threshold

Table 3. Distance, time, maximum values for the analyzed parameters and changes in blood lactate concentration measured in each test

Parameter	Test I	Test II	Test III
Distance (m)	2902	2820	3055
t (min)	13.50	13.25	14.12
HRmax (bpm <sup>-1</sup> )	184	188	189
VEmax (L · min <sup>-1</sup> )	143.20	138.60	144.60
VO <sub>2</sub> max (L · min <sup>-1</sup> )	4.31	4.14	4.51
VO <sub>2</sub> max (mL · min <sup>-1</sup> · kg <sup>-1</sup> )	69.30	67.90	75.30
La <sub>bt</sub> (mmol · L <sup>-1</sup> )	1.44	1.10	0.80
La <sub>3'</sub> (mmol · L <sup>-1</sup> )	8.40	10.70	10.10
La <sub>20'</sub> (mmol · L <sup>-1</sup> )	6.14	5.00	5.4
Δ La	2.26	5.70	4.70

t – time to finish the aerobic capacity test; HRmax – maximum heart rate; VEmax – maximal minute ventilation; VO<sub>2</sub>max – maximum oxygen uptake; La – blood lactate concentration: bt – before the test; 3' – in the third minute after completing the test; 20' – twenty minutes after completing the test; Δ – difference La<sub>3'</sub>–La<sub>20'</sub>

Table 4. Time to reach the TDMA, velocity and the values of parameters at the decompensated metabolic acidosis threshold

Parameter	Test I	Test II	Test III
t (min)	6	8	8
v (m · s <sup>-1</sup> )	3.30	3.63	3.63
VE (L · min <sup>-1</sup> )	75.10	80.40	79.00
HR (bpm <sup>-1</sup> )	161	170	167
% HRmax	87.50	90.40	88.40
VO <sub>2</sub> (L · min <sup>-1</sup> )	3.17	3.31	3.26
VO <sub>2</sub> (mL · min <sup>-1</sup> · kg <sup>-1</sup> )	51.30	54.30	54.40
%VO <sub>2</sub> max	73.55	79.95	72.30

t – time to finish the aerobic capacity test; v – velocity threshold; VE – minute ventilation; HR – heart rate; %HRmax – percentage maximum heart rate; VO<sub>2</sub> – oxygen uptake; %VO<sub>2</sub>max – percentage of maximal oxygen uptake

Table 5. Morphological blood parameters for each test

Parameter	Test I	Test II	Test III
RBC (mln/μL)	5.0	5.4	4.8
HGB (g/dL)	15.4	16.9	14.6
HCT (%)	45	48	42
Reticulocytes (‰)	12	11	11

RBC – erythrocytes; HGB – hemoglobin; HCT – hematocrit

the use of the hypoxic tent or at a high-altitude, found an increased exercise intensity corresponding to the TDMA. In both cases, the time needed to reach the TDMA (about two minutes) as well as the speed at which the threshold was reached were found to be increased. Exercise intensity, expressed as %VO<sub>2</sub>max and %HRmax, at which the TDMA was reached, also increased, especially in the second stage (hypoxic tent). The results demonstrate an improvement in aerobic performance.

The reticulocyte level for all tests was found to be at a similar level (Tab. 5). The highest level of erythrocytes, hemoglobin and hematocrit was found after training with the hypoxic tent (Stage II). Compared to the test performed before hypoxic training (Stage I), the level of erythrocytes in the blood increased by 8%, hemo-

globin concentration increased by nearly 10%, while the change in hematocrit was 3%. The morphological characteristics were found to be lower when comparing the first test (Stage I) to the test performed after high-altitude training (Stage III) (Tab. 5). This is interesting as this type of training had the highest values of maximal oxygen uptake (Tab. 2). This could lead to the assumption that the cause for such an improvement in efficiency was not the result of increased blood oxygen capacity but from other mechanisms that improve oxygen supply. It can also be assumed the training carried out at an altitude of 1800 m ASL was too low to stimulate erythropoiesis.

## Discussion

Improving exercise capacity by use of hypoxic training is mainly done by improving oxygen transport [6] or by having the muscle tissue adapt to hypoxic conditions [7]. An improved oxygen transport system is achieved mainly by increasing hematocrit and blood volume. Hypoxia has been found to stimulate the kidneys towards increasing the production of erythropoietin, which in turn enhances erythropoiesis. Levine and Stray-Gundresen [10] and Stray-Gundresen et al. [11]

found that the increases in hematopoiesis, erythrocyte and hemoglobin concentrations in the blood are correlated with an increase to  $VO_2\max$ .

Although many studies have indicated similar changes brought on by hypoxic conditioning, some authors have found that despite the increase in erythropoietin levels by high-altitude training, this was not accompanied by an increase in the number of reticulocytes [12]. This was similar in the case of the athlete in this study. Lofredo and Glazer [1] stated that the effects of hypoxia on changes in the blood depend more on the altitude and the time spent in hypoxia. One study found that the concentration of hemoglobin in the blood increased by about 1% per week while in high altitudes [13], while other studies have shown no improvement in hematological indices after hypoxic training [14, 15].

Modern training techniques currently use different models when including hypoxic conditions, with the three most common being: “Live high and train high” (LH + TH), “Live high and train low” (LH + TL) and “Live low and train high” (LL + TH). The second model (LH + TL) itself has three variants, the first of which is taking advantage of the high-altitude environmental conditions the athlete resides in while training at a lower altitude. This variant poses a number of logistical problems. In order to shorten the amount of time needed to travel between different altitudes, a training method was developed to simulate high-altitude conditions by thinning the air with nitrogen (LH + TL via nitrogen dilution) to increase the concentration of nitrogen while at the same time reducing the percent amount of oxygen. This is frequently done by constructing a special nitrogen apartment or by directly reducing the concentration of oxygen in the air (LH + TL via oxygen filtration) in a room or tent. This option uses normobaric hypoxia, where the subject lives in hypoxic conditions at a low altitude while training is conducted outside in conditions sans hypoxia. The third variant of LH + TL training makes use of natural conditions (high-altitude) in hypobaric hypoxia, where training takes place in a room which simulates the atmospheric conditions prevailing at sea level by increasing the concentration of oxygen (LH + TH via supplemental oxygen). LL + TH training also has two commonly used variants. The subject lives in normobaric normoxic conditions, but is placed for a short period of time (5–180 min) in hypoxic conditions (either normobaric or hypobaric). While in hypoxia, the subject can rest (intermittent hypoxic exposure – IHE) or exercise (intermittent hypoxic training – IHT) [5].

The main goal of each form of training, regardless of which hypoxic variant is used, is to increase the subject’s physical fitness. Some studies have pointed to the fact that a combination of hypoxic training with classical aerobic exercise provides better physical fitness than the use of aerobic exercise alone [16, 17]. Nonetheless other authors [18, 19] have indicated that classical altitude training (LH + TH) can have a negative impact (or

reveal no improvement) on physical endurance. Only LH + TL training has been fairly well-documented to have a positive effect on physical performance.

The use of simulated hypoxia (IHE) is a promising field of study that still requires further analysis [1]. The beneficial effects of LH + TL training (increasing  $VO_2\max$ , improving running economy) were observed by Brugniaux et al. [20], Robach et al. [21] and Cornolo et al. [22]. A shortcoming of LH + TH training that was noted was the reduction of training intensity, as was observed in athletes residing and training at a high altitude. When compared to conditions at sea level, the athletes were not able to perform similar amounts of physical work such as the ability to maintain a running speed similar to the one performed at a lower altitude. For this reason, LH + TL training is more commonly used, where the athlete resides at an altitude of 2000–3000 m ASL while training at an altitude less than 1500 m ASL. This has two goals, it allows the athlete to maintain a high exercise intensity while also permitting the beneficial effects caused from becoming acclimatized to hypoxia. Richalet and Gore [2] showed that the effects of hypoxic training (LH + TL) depend on two factors, the time spent in hypoxia and at what altitude above sea level: the shorter the time spent in hypoxia the higher the required altitude. They stated that if the maximum amount of time that could be spent in hypoxic conditions reached only 3–4 hours a day, then the subject would need to be at 4000 m ASL. Usually, LH + TL training is conducted at an altitude of 2000–3500 m. The authors suggested that training at a height of approx. 2500 meters ASL best stimulates erythropoiesis and increases the oxygen capacity of the blood, while at the same time requires only a minimum training time of 18 days, where 12 hour per day ought to be spent in hypoxic conditions. Similar results were obtained in this study, where positive changes in the blood morphological parameters were observed only after training mode LH + TL, which simulated conditions at an altitude of approx. 2100–2200 m ASL; LH + TH training at an altitude of about 1800 m ASL featured no similar changes. In the classical hypoxic training model (LH + TH), it has been recommended to train at an altitude  $\geq 2000$  m ASL for a period of 3–4 weeks [4].

However, the basic goal of LL + TH training, when an athlete resides (or trains) for only a short period of time in hypoxic conditions, is to bring about favorable hematological and metabolic changes (e.g., increasing erythropoietin levels or increasing mitochondrial density). The results of the effectiveness of this training model are still not clear – Bärtsch et al. [3] did not recommend this type of training method in preparation for competition held at sea level.

In this study, the athlete used a combination of LH + TL and LH + TH training, which was similar to the training model analyzed by Saunders et al. [23]. Both this study and Saunders et al. found physical exercise

performed with the use of two variants of hypoxic training resulted in an improvement in the aerobic capacity. However, this study found that favorable changes in the blood were only noted after training in normobaric hypoxia (LH + TL). High-altitude training (LH + TH) led to a decrease in the hematological indices in the blood. It can therefore be assumed that the changes observed in these indicators did not have a significant impact on the physical ability of the subject. It can also be inferred that the improvement in physical fitness in hypoxic conditions could be caused by factors that instead affect muscle performance. The muscles' adaptation to hypoxic conditions could have resulted in improved muscle metabolism by an increase in mitochondrial density or by an increase in muscle capillarization [24]. Thus, different forms of hypoxic training may produce different metabolic effects, and therefore have different effects on physical fitness.

### Conclusions

1. Similar race walking training methods conducted in different atmospheric conditions (normoxia and hypoxia) found that training combined with hypoxic conditioning had a positive effect on the test subject's aerobic performance.

2. Training combined with the use of a hypoxic tent, despite the lower training volume, contributed to increasing the TDMA which was achieved at a higher intensity of physical exertion. In addition, improvements in the hematological indices of the blood were observed after this type of training.

3. Training conducted in high-altitude conditions contributed to the increase in maximal oxygen uptake, but did not affect the TDMA level. No improvements in the morphological parameters of blood were also observed.

4. Physical performance tests conducted after hypoxic training found a greater amount of lactate in the blood as well as a higher utilization rate during the recovery phase.

### References

- Loffredo B.M., Glazer J.L., The ergogenics of hypoxia training in athletes. *Curr Sports Med Rep*, 2006, 5 (4), 203–209, doi: 10.1097/01/CSMR.0000306508.63482.f8.
- Richalet J.P., Gore C.J., Live and/or sleep high: train low, using normobaric hypoxia. *Scand J Med Sci Sports*, 2008, 18, Suppl. 1, 29–37, doi: 10.1111/j.1600-0838.2008.00830.x.
- Bärtsch P., Dehnert C., Friedmann-Bette B., Tadibi V., Intermittent hypoxia at rest for improvement of athletic performance. *Scand J Med Sci Sports*, 2008, 18, Suppl. 1, 50–56, doi: 10.1111/j.1600-0838.2008.00832.x.
- Friedmann-Bette B., Classical altitude training. *Scand J Med Sci Sports*, 2008, 18, Suppl. 1, 11–20, doi: 10.1111/j.1600-0838.2008.00828.x.
- Wilber R.L., Application of altitude/hypoxic training by elite athletes. *J Hum Sport Exerc*, 2011, 6 (2), 271–286, doi: 10.4100/jhse.2011.62.07.
- Levine B.D., Stray-Gundersen J., Point: positive effects of intermittent hypoxia (live high:train low) on exercise performance are mediated primarily by augment red cell volume. *J Appl Physiol*, 2005, 99 (5), 2053–2055, doi: 10.1152/jappphysiol.00877.2005.
- Gore C.J., Hopkins W.G., Counterpoint: positive effects of intermittent hypoxia (live high:train low) on exercise performance are not mediated primarily by augment red cell volume. *J Appl Physiol*, 2005, 99 (5), 2055–2057, doi: 10.1152/jappphysiol.00820.2005.
- Reinhard U., Müller P.H., Schmölling R.M., Determination of anaerobic threshold by ventilatory equivalent in normal individuals. *Respiration*, 1979, 38 (1), 36–42, doi: 10.1159/000194056.
- Bhambhani Y., Singh M., Ventilatory thresholds during a graded exercise test. *Respiration*, 1985, 47 (2), 120–128, doi: 10.1159/000194758.
- Levine B.D., Stray-Gundersen J., Living high-training low: effects of moderate-altitude acclimatization with low-altitude training on performance. *J Appl Physiol*, 1997, 83 (1), 101–112.
- Stray-Gundersen J., Chapman R.F., Levine B.D., Living high-training low altitude training improves sea level performance in male and female elite runners. *J Appl Physiol*, 2001, 91 (3), 1113–1120.
- Ashenden M.J., Gore C.J., Dobson G.P., Boston T.T., Parisotto R., Emslie K.R. et al., Simulated moderate altitude elevates serum erythropoietin but does not increase reticulocyte production in well-trained runners. *Eur J Appl Physiol*, 2000, 81 (5), 428–435, doi: 10.1007/s004210050064.
- Berglund B., High-altitude training. Aspects of haematological adaptation. *Sports Med*, 1992, 14 (5), 289–303.
- Hahn A.G., Gore C.J., Martin D.T., Ashenden M.J., Roberts A.D., Logan P.A., An evaluation of the concept of living at moderate altitude and training near sea level. *Comp Biochem Physiol A Mol Integr Physiol*, 2001, 128 (4), 777–789, doi: 10.1016/s1095-6433(01)00283-5.
- Saunders P.U., Telford R.D., Pyne D.R., Cunningham R.B., Gore C.J., Hahn A.G. et al., Improved running economy in elite runners after 20 days of simulated moderate altitude exposure. *J Appl Physiol*, 2004, 96 (3), 931–937, doi: 10.1152/jappphysiol.00725.2003.
- Rusko H.K., Tikkanen H.O., Peltonen J.E., Altitude and endurance training. *J Sports Sci*, 2004, 22 (10), 928–944, doi: 10.1080/02640410400005933.
- Sawka M.N., Convertino V.A., Eicher E.R., Schneider S.M., Young A.J., Blood volume: importance and adaptations to exercise training, environmental stresses, and trauma/sickness. *Med Sci Sports Exerc*, 2000, 32 (2), 332–348.
- Böning D., Altitude and hypoxia training – a short review. *Int J Sports Med*, 1997, 18 (8), 565–570, doi: 10.1055/s-2007-972682.
- Gore C.J., Hahn A., Rice A., Bourdon P., Lawrence S., Walsh C. et al., Altitude training at 2690 m does not increase total haemoglobin mass or sea level VO<sub>2</sub>max in world champion track cyclists. *J Sci Med Sport*, 1998, 1 (3), 156–170, doi: 10.1016/s1440-2440(98)80011-x.
- Brugniaux J.V., Schmitt L., Robach P., Nicolet G., Fouillot J.P., Moutereau S. et al., Eighteen days of “living high, training low” stimulate erythropoiesis and enhance aerobic performance in elite middle-distance runners. *J Appl Physiol*, 2006, 100 (1), 203–211, doi: 10.1152/jappphysiol.00808.2005.

21. Robach P., Schmitt L., Brugniaux J.V., Duvallat A., Fouillot J.P., Moutereau S. et al., Living high – training low: effects on erythropoiesis and maximal aerobic performance in elite Nordic skiers. *Eur J Appl Physiol*, 2006, 97 (6), 695–705, doi: 10.1007/s00421-006-0240-7.
22. Cornolo J., Fouillot J.P., Schmitt L., Povea C., Robach P., Richalet J.P., Interactions between exposure to hypoxia and training-induced autonomic adaptations in “live high and train low” session. *Eur J Appl Physiol*, 2006, 96 (4), 389–396, doi: 10.1007/s00421-005-0083-7.
23. Saunders P.U., Telford R.D., Pyne D.B., Gore C.J., Hahn A.G., Improved race performance in elite middle-distance runners after cumulative altitude exposure. *Int J Sport Perform*, 2009, 4 (1), 134–138.
24. Vogt M., Puntschart A., Geiser J., Zuleger C., Billeter R., Hoppeler H., Molecular adaptations in human skeletal muscle in endurance training under simulated hypoxic conditions. *J Appl Physiol*, 2001, 91 (1), 173–182.

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