Levine BD, Stray-Gundersen J.
"Living high-training low": effect of moderate-altitude acclimatization with low-altitude training on performance.
J Appl Physiol. 83(1):102-112, 1997

Abstract
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 (VO2 max), anaerobic capacity (accumulated O2 deficit), maximal steady state (MSS; ventilatory threshold), running economy, velocity at VO2 max, and blood compartment volumes. **Both altitude groups significantly increased VO2 max (5%) in direct proportion to an increase in red cell mass volume (9%; 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 VO2 max (r = 0.65, $P < 0.01$). **Velocity at VO2 max 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 VO2 max) and maintenance of sea-level training velocities, most likely accounting for the increase in velocity at VO2 max and MSS.**

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Stray-Gundersen J, Chapman RF, Levine BD.
Living high-training low" altitude training improves sea level performance in male and female elite runners.
J Appl Physiol. 91(3):1113-1120, 2001

Abstract
Acclimatization to moderate high altitude accompanied by training at low altitude (living high-training low) has been shown to improve sea level endurance performance in accomplished, but not elite, runners. Whether elite athletes, who may be closer to the maximal structural and functional adaptive capacity of the respiratory (i.e., oxygen transport from environment to mitochondria) system, may achieve similar performance gains is unclear. To answer this question, we studied 14 elite men and 8 elite women before and after 27 days of living at 2,500 m while performing high-intensity training at 1,250 m. The altitude sojourn began 1 wk after the USA Track and Field National Championships, when the athletes were close to their season's fitness peak. Sea level 3,000-m time trial performance was significantly improved by 1.1% (95% confidence limits 0.3-1.9%). **One-third of the athletes achieved personal best times for the distance after the altitude training camp.** The improvement in running performance was accompanied by a **3% improvement in maximal oxygen uptake** (72.1 +/- 1.5 to 74.4 +/- 1.5 ml x kg(-1) x min(-1)). Circulating erythropoietin levels were near double initial sea level values 20 h after ascent (8.5 +/- 0.5 to 16.2 +/- 1.0 IU/ml). **Soluble transferrin receptor levels were significantly elevated on the 19th day at altitude, confirming a stimulation of erythropoiesis** (2.1 +/- 0.7 to 2.5 +/- 0.6 microg/ml). **Hb concentration measured at sea level increased 1 g/dl over the course of the camp** (13.3 +/- 0.2 to 14.3 +/- 0.2 g/dl). **We conclude that 4 wk of acclimatization to moderate altitude, accompanied by high-intensity training at low altitude, improves sea level endurance performance even in elite runners.** Both the mechanism and magnitude of the effect appear similar to that observed in less accomplished runners, even for athletes who may have achieved near maximal oxygen transport capacity for humans.

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Meeuwsen T, Hendriksen IJ, Holewijn M.
Training-induced increases in sea-level performance are enhanced by acute intermittent hypobaric hypoxia.
Eur J Appl Physiol. 2001 Apr;84(4):283-90.

Abstract
The goal of this study was to investigate to what extent intermittent exposure to altitude in a hypobaric chamber can improve performance at sea-level. Over a 10-day period, elite male

triathletes trained for 2 h each day on a cycle ergometer placed in a hypobaric chamber. Training intensity was 60-70% of the heart rate reserve. Eight subjects trained at a simulated altitude of 2.500 m (hypoxia group), the other eight remained at sea-level (sea-level group). Baseline measurements were done on a cycle ergometer at sea-level, which included an incremental test until exhaustion and a Wingate Anaerobic Test. Nine days after training in hypoxia, significant increases were seen in all important parameters of the maximal aerobic as well as the anaerobic test. **A significant increase of 7.0% was seen in the mean maximal oxygen uptake per kilogram body weight (VO2max), and the mean maximal power output per kilogram body weight (Wmax) increased significantly by 7.4%. The mean values of both mean power per kilogram body weight and peak power per kilogram body weight increased significantly by 5.0%, and the time-to-peak decreased significantly by 37.7%.** In the sea-level group, no significant changes were seen in the abovementioned parameters of both the maximal aerobic and the maximal anaerobic test at the second post-test. **The results of this study indicate that intermittent hypobaric training can improve both the aerobic and the anaerobic energy-supply systems.**

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Clark SA, Aughey RJ, Gore CJ, Hahn AG, Townsend NE, Kinsman TA, Chow CM, McKenna MJ, Hawley JA.
Effects of live-high, train-low hypoxic exposure on lactate metabolism in trained humans.
Eur J Appl Physiol. 2001 Apr;84(4):283-90.

Abstract
We determined the effect of 20 nights of live-high, train-low (LHTL) hypoxic exposure on lactate kinetics, monocarboxylate lactate transporter proteins (MCT1 and MCT4) and muscle in-vitro buffering capacity (betam) in well-trained athletes. 29 trained cyclists/triathletes were divided into one of three groups: 20 consecutive nights of hypoxic exposure (LHTLc), 20 nights of intermittent hypoxic exposure (four 5-night blocks of hypoxia, each interspersed with 2 nights of normoxia, (LHTLi), or control (CON). Rates of lactate appearance (Ra), and disappearance (Rd) were determined from a primed, continuous infusion of L-[U-(14)C]-lactic acid tracer during 90 minutes of steady-state exercise (60 min at 65% VO2peak followed by 30 min at 85% VO2peak). A resting muscle biopsy was taken pre and post 20 nights of LHTL for the determination of betam and MCT1 and MCT4 protein abundance. Ra during the first 60 min of exercise was not different between groups. During the last 25 min of exercise at 85% VO2peak Ra was higher compared with exercise at 65% of VO2peak, and was decreased in LHTLc ($P<0.05$) compared with the other groups. Rd followed a similar pattern to Ra. Although Rox was significantly increased during exercise at 85% compared to 65% of VO2peak, there were no differences between the three groups or across trials. There was no effect of hypoxic exposure on betam or MCT1 and MCT4 protein abundance. **We conclude that 20 nights of continuous hypoxia exposure decreased whole-body Ra during intense exercise in well-trained athletes.** However, muscle markers of lactate metabolism and pH regulation. Were unchanged by the LHTL intervention.

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Levine BD.
Intermittent hypoxic training: fact and fancy.
High Alt Med Biol. 3(2):177-193, 2002

Abstract
Intermittent hypoxic training (IHT) refers to the discontinuous use of normobaric or hypobaric hypoxia, in an attempt to reproduce some of the key features of altitude acclimatization, with the ultimate goal to improve sea-level athletic performance. In general, IHT can be divided into two different strategies: (1) providing hypoxia at rest with the primary goal being to stimulate altitude acclimatization or (2) providing hypoxia during exercise, with the primary goal being to enhance the training stimulus. Each approach has many different possible application strategies, with the essential variable among them being the "dose" of hypoxia necessary to achieve the desired effect. **One approach, called living high-training low, has been shown to improve sea-level endurance performance.** This strategy combines altitude acclimatization (2500 m) with low altitude training to ensure high-quality training. The opposite strategy, living low-training high, has also been proposed by some investigators. The primacy of the altitude acclimatization effect in IHT is demonstrated by the following facts: (1) **living high-training low clearly improves performance in athletes of all abilities,** (2) the mechanism of this improvement is primarily an increase in erythropoietin, leading to increased red cell mass, V(O2max), and running performance, and (3) **rather than intensifying the training stimulus, training at altitude or under hypoxia leads to the opposite effect - reduced speeds, reduced power output, reduced oxygen flux - and therefore is not likely to provide any advantage for a well-trained**

athlete.

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Schmidt W.
Effects of intermittent exposure to high altitude on blood volume and erythropoietic activity.
High Alt Med Biol. 3(2):167-76, 2002

Abstract
The purpose of this review is to describe changes in blood volume and erythropoietic activity occurring under different types of intermittent exposure to hypoxia. These hypoxic episodes can vary from a few seconds or minutes to hours, days, or even weeks. Short hypoxic episodes like sleep apnea only lead to a small increase in hemoglobin concentration, which is mainly due to a hormonal-mediated decrease in plasma volume. In most of these cases the cumulative time spent under hypoxia does not exceed the critical threshold of about 90 min. **Endurance athletes and mountaineers who voluntarily expose themselves to hypoxia for some hours or during the night while spending the day at normoxia ("sleep high-train low" concept) do improve their physical performance**. Despite raising erythropoietic activity, indicated by elevated plasma concentrations of EPO and the transferrin receptor, the postulated increase in red cell volume has not satisfactorily been proved. Frequent changes between low and high altitudes, which are usual in some South American and Asian countries, provoke similar adaptations in red cell mass as occur in high altitude residents. However, the plasma volume decreases at altitude and increases again when staying at sea level. Even after more than 20 yr of regular moving between low and high altitude, the total blood volume, hemoglobin concentration and hematocrit, as well as the plasma EPO concentration, noticeably oscillate during every hypoxic-normoxic cycle. We assume these changes to be an **optimal rapid adaptation of the oxygen transport system to the prevailing hypoxic or normoxic environment.**

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Levine BD, Stray-Gundersen J.
The effects of altitude training are mediated primarily by acclimatization, rather than by hypoxic exercise.
Adv Exp Med Biol. 2001;502:75-88.

Abstract
For training at altitude to be effective, it must provide some advantage above and beyond similar training at sea level. This advantage could be provided by: 1) acclimatization to altitude which improves oxygen transport and/or utilization; 2) hypoxic exercise which "intensifies" the training stimulus; or 3) some combination of both. **Controlled studies of "typical" altitude training, involving both altitude acclimatization and hypoxic exercise have never been shown to improve sea level performance.** This failure has been attributed to reduced training loads at altitude. One approach developed by Levine and Stray-Gundersen, called **"living high-training low" has been shown to improve sea level performance** over events lasting 8-20 minutes. This strategy combines altitude acclimatization (2,500 m) with low altitude training to get the optimal effect. The opposite strategy, "living low-training high" is proposed by Dr. Hoppeler in this debate. In defense of the primacy of the altitude acclimatization effect, data will be presented to support the following: 1). **Living high-training low clearly improves performance in athletes of all abilities**; 2). The mechanism of this improvement is primarily an increase in erythropoietin leading to increased red cell mass, VO2max, and running performance; 3). **Rather than intensifying the training stimulus, training at altitude leads to the opposite effect--reduced speeds, reduced power output, reduced oxygen flux--and, following the principal of symmorphosis, is not likely to provide any advantage for a well trained athlete**; 4). At the moderate altitudes used by most athletes, resting oxygen delivery to skeletal muscle is well preserved, arguing against any detrimental effect on "protein synthesis"; 5). It is possible however, that at significantly higher altitudes, acclimatization leads to appetite suppression, inhibition of protein synthesis, muscle wasting, excessive ventilatory work, and metabolic compensation that is NOT advantageous for a competitive athlete.

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Powell FL, Garcia N.
Physiological Effects of Intermittent Hypoxia.
High Alt Med Biol. 1(2):125-136, 2000.

Abstract
Intermittent hypoxia (IH), or periodic exposure to hypoxia interrupted by return to normoxia or less hypoxic conditions, occurs in many circumstances. In high altitude mountaineering, IH is used to optimize acclimatization although laboratory studies have not generally revealed physiologically significant benefits. **IH enhances athletic performance at sea level if blood oxygen capacity increases and the usual level of training is not decreased significantly**. IH for high altitude workers who commute from low altitude homes is of considerable practical interest and the ideal commuting schedule for physical and mental performance is being studied. The effect of oxygen enrichment at altitude (i.e., intermittent normoxia on a background of chronic hypoxia) on human performance is under study also. Physiological mechanisms of IH, and specifically the differences between effects of IH and acute or chronic continuous hypoxia remains to be determined. Biomedical researchers are defining the molecular and cellular mechanisms for effects of hypoxia on the body in health and disease. A comparative approach may provide additional insight about the biological significance of these effects.

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Gore CJ, Hahn AG, Aughey RJ, Martin DT, Ashenden MJ, Clark SA, Garnham AP, Roberts AD, Slater GJ, McKenna MJ
Live high:train low increases muscle buffer capacity and submaximal cycling efficiency.
Acta Physiol Scand. 173(3):275-286, 2001

Abstract
This study investigated whether hypoxic exposure increased muscle buffer capacity (beta(m)) and mechanical efficiency during exercise in male athletes. A control (CON, n=7) and a live high:train low group (LHTL, n=6) trained at near sea level (600 m), with the LHTL group sleeping for 23 nights in simulated moderate altitude (3000 m). Whole body oxygen consumption (VO2) was measured under normoxia before, during and after 23 nights of sleeping in hypoxia, during cycle ergometry comprising 4 x 4-min submaximal stages, 2-min at 5.6 +/- 0.4 W kg(-1), and 2-min 'all-out' to determine total work and VO(2peak). A vastus lateralis muscle biopsy was taken at rest and after a standardized 2-min 5.6 +/- 0.4 W kg(-1) bout, before and after LHTL, and analysed for beta(m) and metabolites. After LHTL, beta(m) was increased (18%, P < 0.05). Although work was maintained, VO(2peak) fell after LHTL (7%, P < 0.05). **Submaximal VO2 was reduced (4.4%, P < 0.05) and efficiency improved (0.8%, P < 0.05) after LHTL probably because of a shift in fuel utilization. This is the first study to show that hypoxic exposure, per se, increases muscle buffer capacity. Further, reduced VO2 during normoxic exercise after LHTL suggests that improved exercise efficiency is a fundamental adaptation to LHTL.**

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Nummela A, Rusko H
Acclimatization to altitude and normoxic training improve 400-m running performance at sea level.
J Sports Sci. 18(6):411-419, 2000

Abstract
To investigate the benefits of 'living high and training low' on anaerobic performance at sea level, eight 400-m runners lived for 10 days in normobaric hypoxia in an altitude house (oxygen content = 15.8%) and trained outdoors in ambient normoxia at sea level. A maximal anaerobic running test and 400-m race were performed before and within 1 week of living in the altitude house to determine the maximum speed and the speeds at different submaximal blood lactate concentrations (3, 5, 7, 10 and 13 mmol x l(-1)) and 400-m race time. At the same time, ten 400-m runners lived and trained at sea level and were subjected to identical test procedures. **Multivariate analysis of variance indicated that the altitude house group but not the sea-level group improved their 400-m race time during the experimental period (P < 0.05). The speeds at blood lactate concentrations of 5-13 mmol x l(-1) tended to increase in the altitude house group but the response was significant only at 5 and 7 mmol x l(-1) (P < 0.05)**. Furthermore, resting blood pH was increased in six of the eight altitude house athletes from 0.003 to 0.067 pH unit (P < 0.05). **The results of this study demonstrate improved 400-m performance after 10 days of living in normobaric hypoxia and training at sea level. Furthermore, the present study provides evidence that changes in the acid-base balance and lactate metabolism might be responsible for the improvement in sprint performance.**

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Katayama K; Matsuo H; Ishida K; Mori; Miyamura M

Intermittent Hypoxia Improves Endurance Performance and Submaximal Exercise Efficiency.
High Alt Med Biol 4(3):291-304, 2003

Abstract
The purpose of the present study was to elucidate the influence of intermittent hypobaric hypoxia at rest on endurance performance and cardiorespiratory and hematological adaptations in trained endurance athletes. Twelve trained male endurance runners were assigned to either a hypoxic group (n = 6) or a control group (n = 6). The subjects in the hypoxic group were exposed to a simulated altitude of 4500 m for 90 min, three times a week for 3 weeks. The measurements of 3000 m running time, running time to exhaustion, and cardiorespiratory parameters during maximal exercise test and resting hematological status were performed before (Pre) and after 3 weeks of intermittent hypoxic exposure (Post). These measurements were repeated after the cessation of intermittent hypoxia for 3 weeks (Re). In the control group, the same parameters were determined at Pre, Post, and Re for the subjects not exposed to intermittent hypoxia. The athletes in both groups continued their normal training together at sea level throughout the experiment. **In the hypoxic group, the 3000 m running time and running time to exhaustion during maximal exercise test improved.** Neither cardiorespiratory parameters to maximal exercise nor resting hematological parameters were changed in either group at Post, whereas **oxygen uptake (VO2) during submaximal exercise decreased significantly in the hypoxic group**. After cessation of intermittent hypoxia for 3 weeks, the improved 3000 m running time and running time to exhaustion tended to decline, and the decreased VO2 during submaximal exercise returned to Pre level. **These results suggest that intermittent hypoxia at rest could improve endurance performance and submaximal exercise efficiency at sea level in trained endurance athletes**, but these improvements are not maintained after the cessation of intermittent hypoxia for 3 weeks.

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Saunders PU, Telford RD, Pyne DB, Cunningham RB, Gore CJ, Hahn AG, Hawley JA.
Improved running economy in elite runners after 20 days of moderate simulated altitude exposure
J Appl Physiol. 2003 Nov [Epub ahead of print].

Abstract
To investigate the effect of altitude exposure on running economy (RE), 22 elite distance runners (VO2max 72.8 +/- 4.4 ml.min(-1).kg(-1); training volume 125 +/- 27 km.wk(-1)) homogenous for VO2max and training volume were assigned to one of three groups; live-high (simulated altitude 2000-3100 m) train-low (natural altitude 600 m; LHTL, n=10), live-moderate train-moderate (natural altitude 1500-2000 m; LMTM, n=10) or live-low train-low (natural altitude 600 m; LLTL, n=13) for a period of 20 d. RE was assessed during three sub-maximal treadmill runs at 14, 16 and 18 km.h(-1) prior to and at the completion of each intervention. O2 consumption (VO2), ventilation (VE), respiratory exchange ratio (RER), heart rate (HR) and blood lactate concentration [La] were determined during the final 60 s of each run, while haemoglobin mass (Hbmass) was measured on a separate occasion. **VO2 (L.min(-1)) averaged across the three sub-maximal running speeds was 3.3% lower** (p=0.005), after LHTL compared with either LMTM or LLTL. VE, RER, HR and Hbmass were not significantly different after the three interventions. **There was no evidence of an increase in [La] after the LHTL intervention suggesting that the lower aerobic cost of running was not attributable to an increased anaerobic energy contribution**. Furthermore, the improved RE could not be explained by a decrease in VE, by preferential use of carbohydrate as a metabolic substrate, nor was it related to any change in Hbmass. We conclude that 20 d LHTL at simulated altitude improved the RE of elite distance runners.

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Wilber RL, Holm PL, Morris DM, Dallam GM, Callan SD.
Effect of F(I)O(2) on physiological responses and cycling performance at moderate altitude.

Med Sci Sports Exerc. 35(7):1153-1159, 2003

Abstract
PURPOSE: To evaluate physiological responses and exercise performance during a "live high-train low via supplemental oxygen" (LH + TLO(2)) interval workout in trained endurance athletes. METHODS: Subjects (N = 19) were trained male cyclists who were permanent residents of moderate altitude (1800-1900 m). Testing was conducted at 1860 m (P(B) 610-612 Torr, P(I)O(2) approximately 128 Torr). Subjects completed three randomized, single-blind trials in which they performed a standardized interval workout while inspiring a medical-grade gas with F(I)O(2) 0.21

(P(I)O(2) approximately 128 Torr), F(I)O(2) 0.26 (P(I)O(2) approximately 159 Torr), and F(I)O(2) 0.60 (P(I)O(2) approximately 366 Torr). The standardized interval workout consisted of 6 x 100 kJ performed on a dynamically calibrated cycle ergometer at a self-selected workload and pedaling cadence with a work:recovery ratio of 1:1.5. RESULTS: Compared with the control trial (21% O (2)), average total time (min:s) for the 100-kJ work interval was 5% and 8% (P < 0.05) faster in the 26% O(2) and 60% O(2) trials, respectively. **Consistent with the improvements in total time were increments in power output (W) equivalent to 5% (26% O(2) trial) and 9% (60% O(2) trial; P < 0.05). Whole-body [VO](2) (L.min-1) was higher by 7% and 14% (P < 0.05) in the 26% O(2) and 60% O(2) trials, respectively, and was highly correlated to the improvement in power output (r = 0.85, P < 0.05). Arterial oxyhemoglobin saturation (S(p)O(2)) was significantly higher by 5% (26% O(2)) and 8% (60% O(2)) in the supplemental oxygen trials.** CONCLUSION: **We concluded that a typical LH + TLO(2) training session results in significant increases in arterial oxyhemoglobin saturation, [V02] and average power output contributing to a significant improvement in exercise performance.**