PHYSIOLOGY AND PERIODIZATION OF ALTITUDE TRAINING

Iñigo Mujika

PHYSIOLOGY & TRAINING

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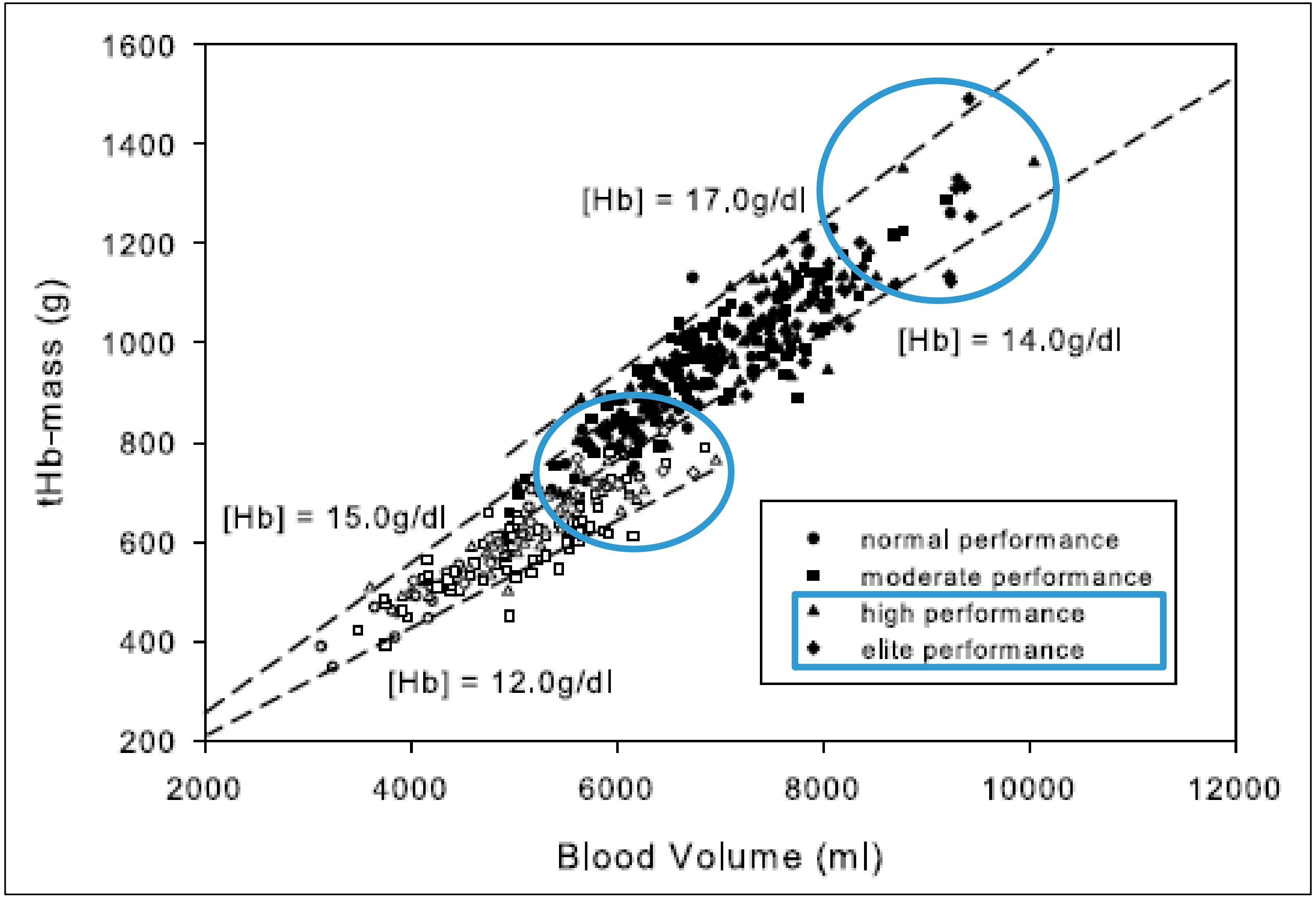

Schmidt & Prommer *Exerc. Sport Sci. Rev.* 38: 68-75, 2010

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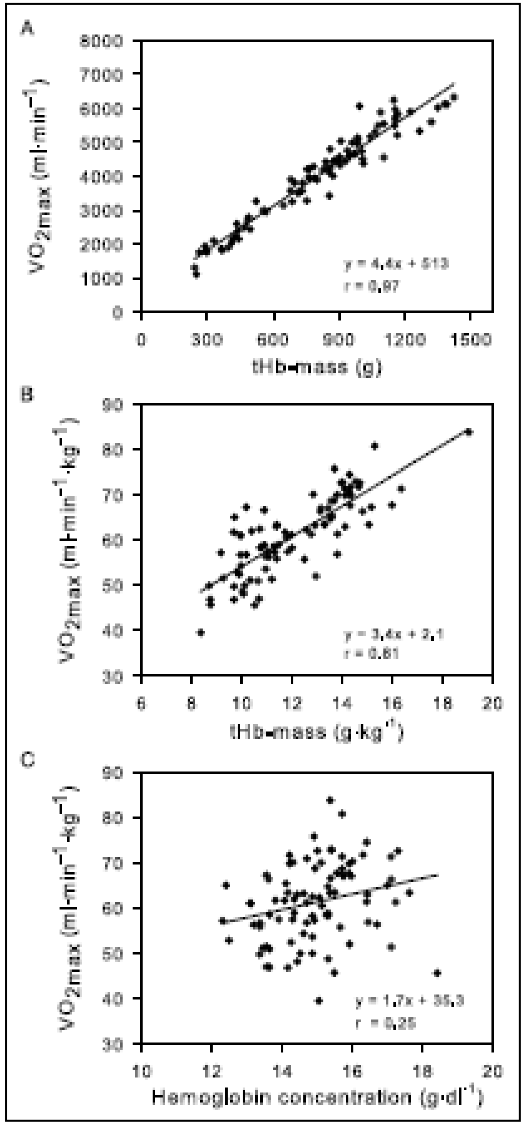

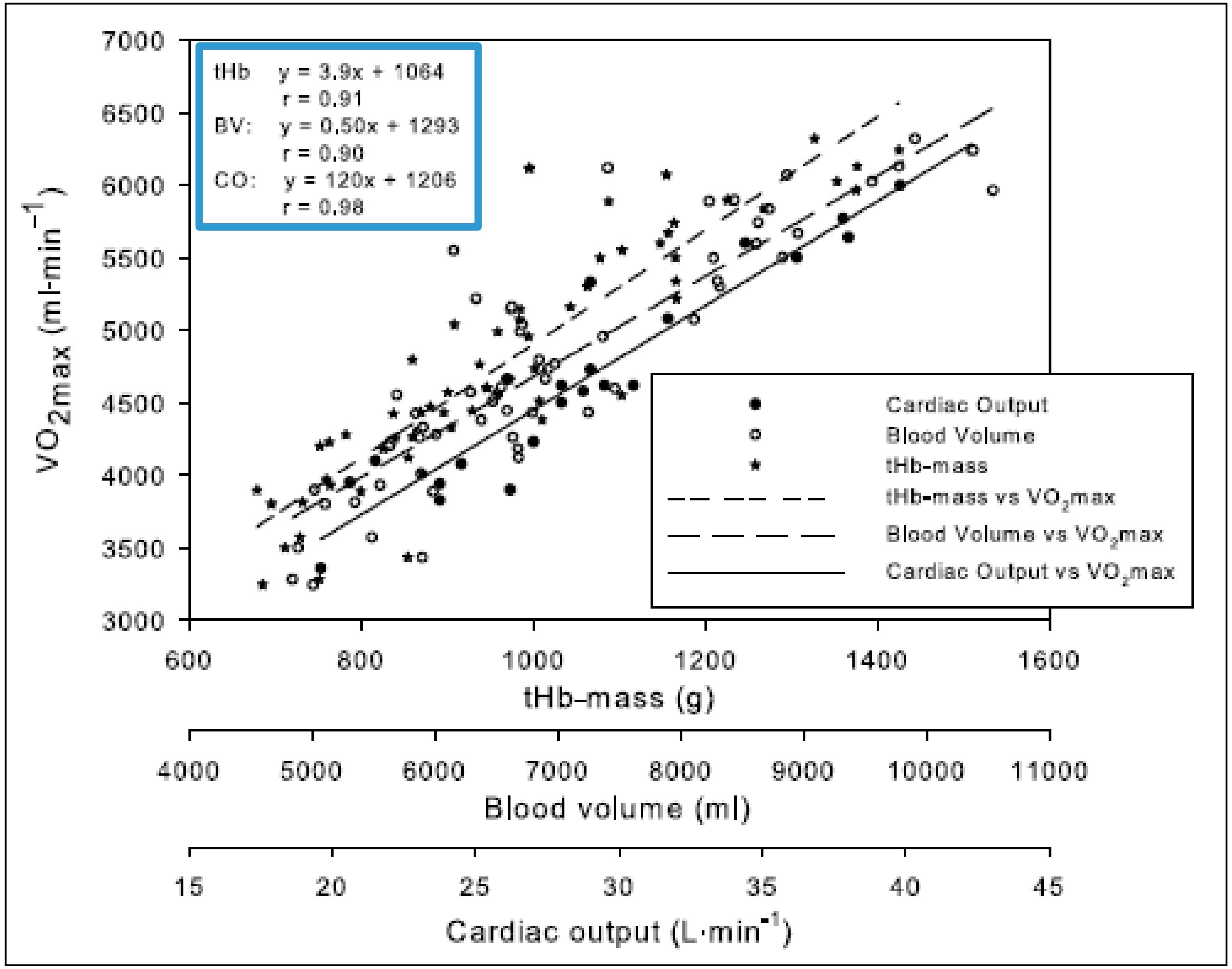

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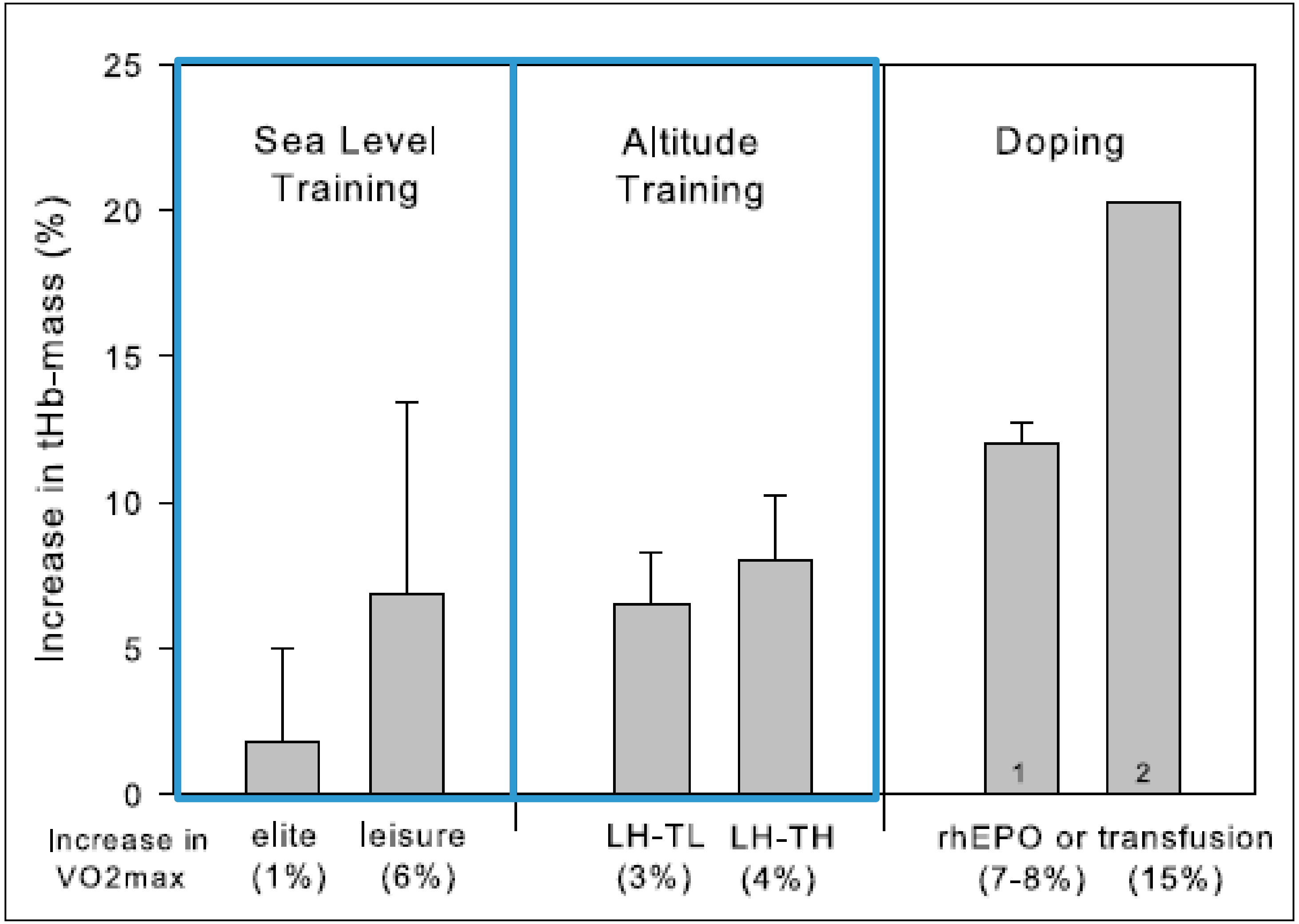

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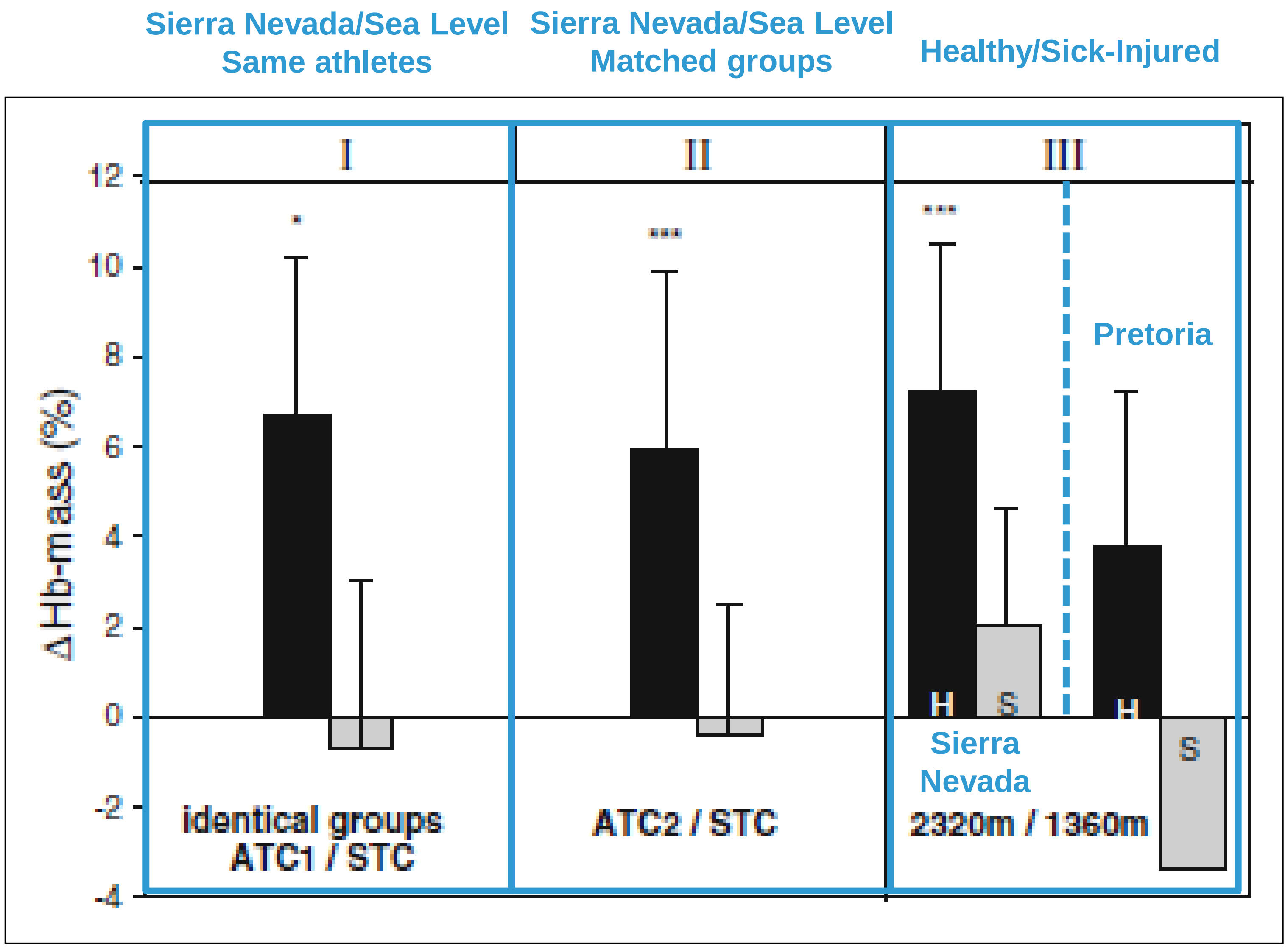

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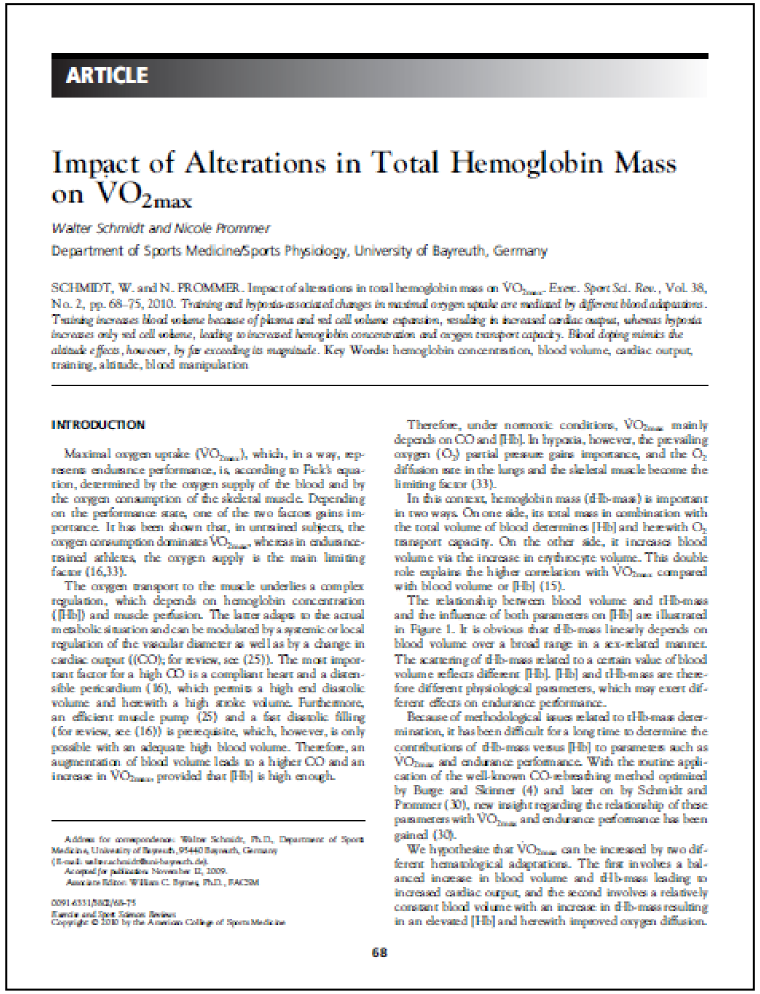
01 IMPACT OF ALTERATIONS IN Hb-MASS ON VO_{2MAX}



ARTICLE

Impact of Alterations in Total Hemoglobin Mass on $\dot{V}O_{2max}$

Walter Schmidt and Nicole Prommer
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SCHMIDT, W. and N. PROMMER. Impact of alterations in total hemoglobin mass on $\dot{V}O_{2max}$. Exerc. Sport Sci. Rev., Vol. 38, No. 2, pp. 68–75, 2010. *Training and hypoxia-associated changes in maximal oxygen uptake are mediated by different blood adaptations. Training increases blood volume because of plasma and red cell volume expansion, resulting in increased cardiac output, whereas hypoxia increases only red cell volume, leading to increased hemoglobin concentration and oxygen transport capacity. Blood doping mimics the altitude effects, however, by far exceeding its magnitude.* Key Words: hemoglobin concentration, blood volume, cardiac output, training, altitude, blood manipulation

INTRODUCTION

Maximal oxygen uptake ($\dot{V}O_{2max}$), which, in a way, represents endurance performance, is, according to Fick's equation, determined by the oxygen supply of the blood and by the oxygen consumption of the skeletal muscle. Depending on the performance state, one of the two factors gains importance. It has been shown that, in untrained subjects, the oxygen consumption dominates $\dot{V}O_{2max}$, whereas in endurance-trained athletes, the oxygen supply is the main limiting factor (16,33).

The oxygen transport to the muscle underlies a complex regulation, which depends on hemoglobin concentration ([Hb]) and muscle perfusion. The latter adapts to the actual metabolic situation and can be modulated by a systemic or local regulation of the vascular diameter as well as by a change in cardiac output ((CO); for review, see (25)). The most important factor for a high CO is a compliant heart and a distensible pericardium (16), which permits a high end diastolic volume and herewith a high stroke volume. Furthermore, an efficient muscle pump (25) and a fast diastolic filling (for review, see (16)) is prerequisite, which, however, is only possible with an adequate high blood volume. Therefore, an augmentation of blood volume leads to a higher CO and an increase in $\dot{V}O_{2max}$, provided that [Hb] is high enough.

Therefore, under normoxic conditions, $\dot{V}O_{2max}$ mainly depends on CO and [Hb]. In hypoxia, however, the prevailing oxygen (O_2) partial pressure gains importance, and the O_2 diffusion rate in the lungs and the skeletal muscle become the limiting factor (33).

In this context, hemoglobin mass (tHb-mass) is important in two ways. On one side, its total mass in combination with the total volume of blood determines [Hb] and herewith O_2 transport capacity. On the other side, it increases blood volume via the increase in erythrocyte volume. This double role explains the higher correlation with $\dot{V}O_{2max}$ compared with blood volume or [Hb] (15).

The relationship between blood volume and tHb-mass and the influence of both parameters on [Hb] are illustrated in Figure 1. It is obvious that tHb-mass linearly depends on blood volume over a broad range in a sex-related manner. The scattering of tHb-mass related to a certain value of blood volume reflects different [Hb]. [Hb] and tHb-mass are therefore different physiological parameters, which may exert different effects on endurance performance.

Because of methodological issues related to tHb-mass determination, it has been difficult for a long time to determine the contributions of tHb-mass versus [Hb] to parameters such as $\dot{V}O_{2max}$ and endurance performance. With the routine application of the well-known CO-rebreathing method optimized by Burge and Skinner (4) and later on by Schmidt and Prommer (30), new insight regarding the relationship of these parameters with $\dot{V}O_{2max}$ and endurance performance has been gained (30).

We hypothesize that $\dot{V}O_{2max}$ can be increased by two different hematological adaptations. The first involves a balanced increase in blood volume and tHb-mass leading to increased cardiac output, and the second involves a relatively constant blood volume with an increase in tHb-mass resulting in an elevated [Hb] and herewith improved oxygen diffusion.

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Exercise and Sport Sciences Reviews

VO_{2max} can increase by: (i) a balanced increase in Hb-mass and plasma volume augmenting cardiac output; and/or (ii) by increasing [Hb] due to an increase in Hb-mass with reduced or unchanged plasma volume, augmenting avDO_2.

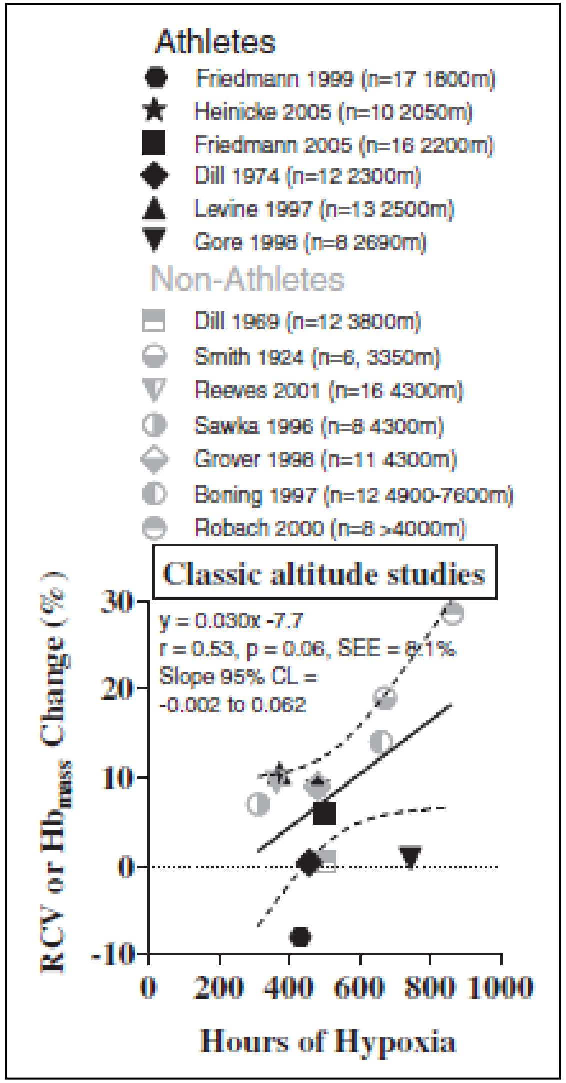
Mechanism (i) is achieved by endurance training; mechanism (ii) by adaptation to altitude or blood manipulation.

A combination of both mechanisms is present in athletes training and living at altitude.

A change in Hb-mass by 1 g causes a change in VO_{2max} by approximately 4 mL/min.

Schmidt & Prommer *Exerc. Sport Sci. Rev.* 38: 68-75, 2010

01 ALTITUDE EXPOSURE, Hb-MASS AND HIF-1α



HIF-1α is present in every body tissue, regulates O_2 homeostasis, and acute cardiovascular and respiratory responses to hypoxia.

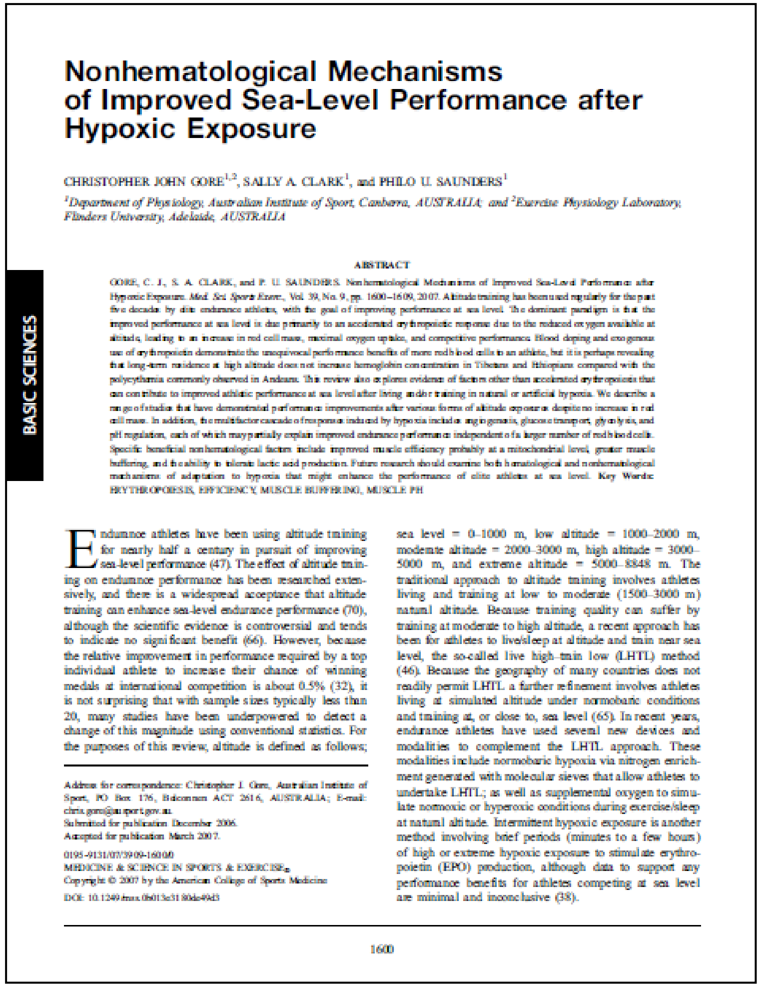
HIF-1α activates EPO and transferrin for iron metabolism and red cell production, growth factors for angiogenesis and cell survival, glycolytic enzimes for energy metabolism, glucose and monocarboxylate transporters for glucose uptake and lactate metabolism by the muscles, carbonic anhydrase for pH regulation, nitric oxide and carbon monoxide vasodilators, dopamine synthesis to accelerate ventilation.

Saunders et al. *High Alt. Med. Biol.* 10: 135-148, 2009

02

ADDITIONAL BENEFITS OF ALTITUDE TRAINING

02 NONHEMATOLOGICAL BENEFITS OF ALTITUDE TRAINING



Nonhematological Mechanisms of Improved Sea-Level Performance after Hypoxic Exposure

CHRISTOPHER JOHN GORE[1,2], SALLY A. CLARK[1], and PHILO U. SAUNDERS[1]
[1]Department of Physiology, Australian Institute of Sport, Canberra, AUSTRALIA; and [2]Exercise Physiology Laboratory, Flinders University, Adelaide, AUSTRALIA

BASIC SCIENCES

ABSTRACT

GORE, C. J., S. A. CLARK, and P. U. SAUNDERS. Nonhematological Mechanisms of Improved Sea-Level Performance after Hypoxic Exposure. *Med. Sci. Sports Exerc.*, Vol. 39, No. 9, pp. 1600–1609, 2007. Altitude training has been used regularly for the past five decades by elite endurance athletes, with the goal of improving performance at sea level. The dominant paradigm is that the improved performance at sea level is due primarily to an accelerated erythropoietic response due to the reduced oxygen available at altitude, leading to an increase in red cell mass, maximal oxygen uptake, and competitive performance. Blood doping and exogenous use of erythropoietin demonstrate the unequivocal performance benefits of more red blood cells to an athlete, but it is perhaps revealing that long-term residence at high altitude does not increase hemoglobin concentration in Tibetans and Ethiopians compared with the polycythemia commonly observed in Andeans. This review also explores evidence of factors other than accelerated erythropoiesis that can contribute to improved athletic performance at sea level after living and/or training in natural or artificial hypoxia. We describe a range of studies that have demonstrated performance improvements after various forms of altitude exposure despite no increase in red cell mass. In addition, the multifactor cascade of responses induced by hypoxia includes angiogenesis, glucose transport, glycolysis, and pH regulation, each of which may partially explain improved endurance performance independent of a larger number of red blood cells. Specific beneficial nonhematological factors include improved muscle efficiency probably at a mitochondrial level, greater muscle buffering, and the ability to tolerate lactic acid production. Future research should examine both hematological and nonhematological mechanisms of adaptation to hypoxia that might enhance the performance of elite athletes at sea level. Key Words: ERYTHROPOIESIS, EFFICIENCY, MUSCLE BUFFERING, MUSCLE PH

Endurance athletes have been using altitude training for nearly half a century in pursuit of improving sea-level performance (47). The effect of altitude training on endurance performance has been researched extensively, and there is a widespread acceptance that altitude training can enhance sea-level endurance performance (70), although the scientific evidence is controversial and tends to indicate no significant benefit (66). However, because the relative improvement in performance required by a top individual athlete to increase their chance of winning medals at international competition is about 0.5% (32), it is not surprising that with sample sizes typically less than 20, many studies have been underpowered to detect a change of this magnitude using conventional statistics. For the purposes of this review, altitude is defined as follows; sea level = 0–1000 m, low altitude = 1000–2000 m, moderate altitude = 2000–3000 m, high altitude = 3000–5000 m, and extreme altitude = 5000–8848 m. The traditional approach to altitude training involves athletes living and training at low to moderate (1500–3000 m) natural altitude. Because training quality can suffer by training at moderate to high altitude, a recent approach has been for athletes to live/sleep at altitude and train near sea level, the so-called live high–train low (LHTL) method (46). Because the geography of many countries does not readily permit LHTL a further refinement involves athletes living at simulated altitude under normobaric conditions and training at, or close to, sea level (65). In recent years, endurance athletes have used several new devices and modalities to complement the LHTL approach. These modalities include normobaric hypoxia via nitrogen enrichment generated with molecular sieves that allow athletes to undertake LHTL; as well as supplemental oxygen to simulate normoxic or hyperoxic conditions during exercise/sleep at natural altitude. Intermittent hypoxic exposure is another method involving brief periods (minutes to a few hours) of high or extreme hypoxic exposure to stimulate erythropoietin (EPO) production, although data to support any performance benefits for athletes competing at sea level are minimal and inconclusive (38).

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1600

- **Angiogenesis.**
- **Glucose transport.**
- **Glycolysis.**
- **pH regulation.**
- **Improved muscle efficiency, probably at a mitochondrial level.**
- **Greater muscle buffering.**
- **Ability to tolerate lactic acid production.**

Gore et al. *Med. Sci. Sports Exerc.* 39: 1600-1609, 2007

02 OTHER BENEFITS OF ALTITUDE TRAINING

Placebo effect: athletes believe in the benefits of altitude training.

High quality training camp: increased focus on training, more recovery between sessions, consistently having training partners, novelty of the venue, sports science support, being away from home distractions.

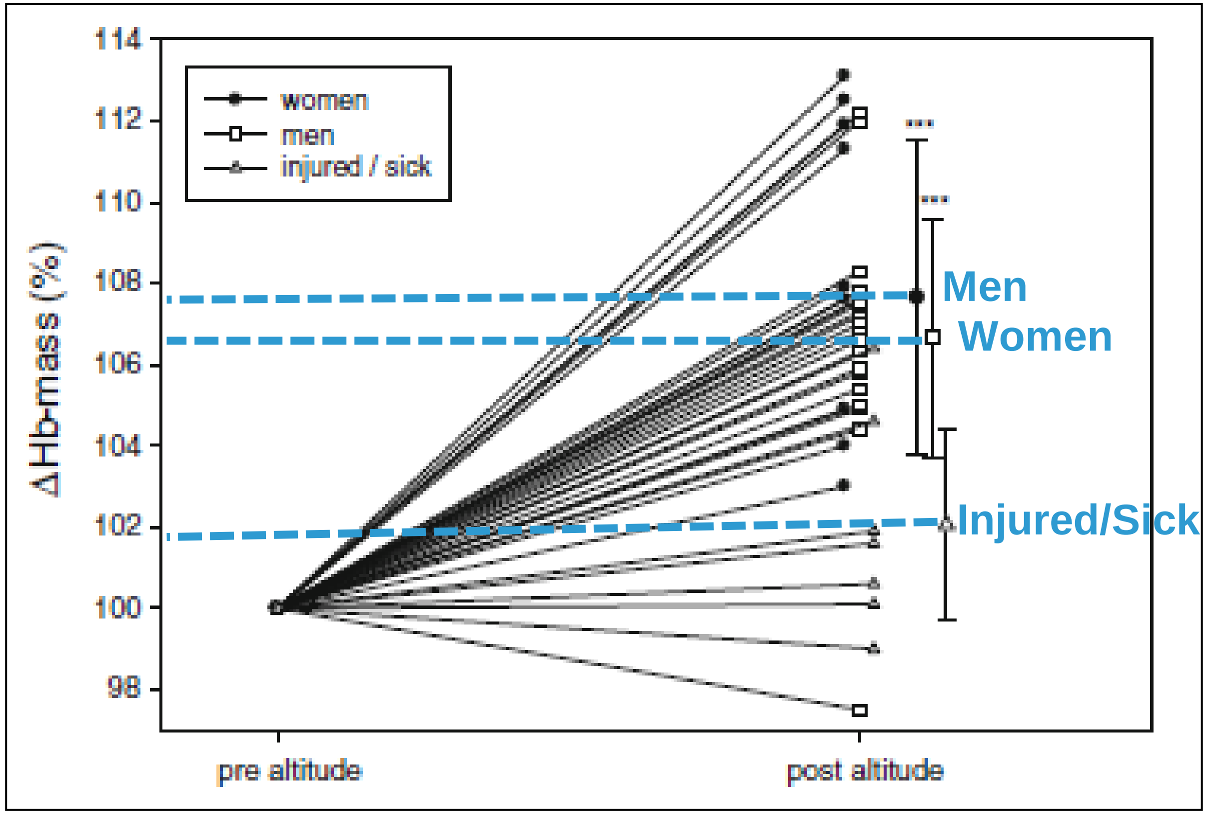
Saunders et al. *High Alt. Med. Biol.* 10: 135-148, 2009

03

INDIVIDUAL RESPONSE AND FACTORS INFLUENCING ADAPTATIONS TO ALTITUDE TRAINING

03 INDIVIDUAL CHANGES IN Hb-MASS IN ELITE SWIMMERS

3-week Altitude Training Camp in Sierra Nevada



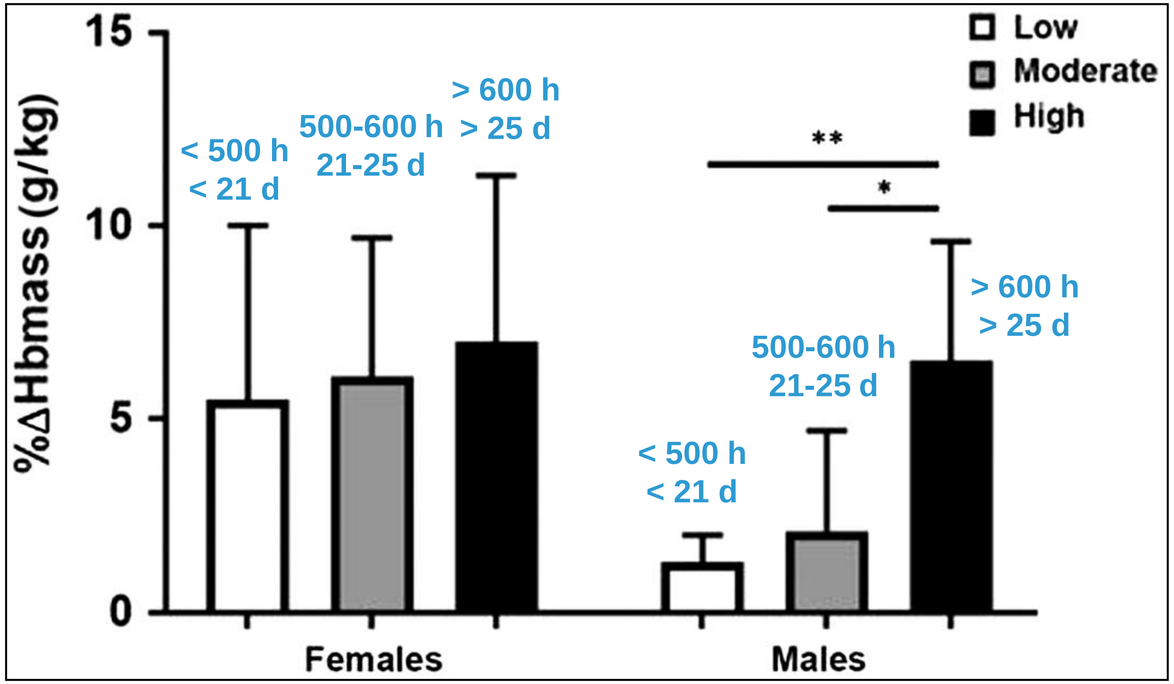
Sierra Nevada: men 7.1 ± 2.1%; women 8.5 ± 3.9%.

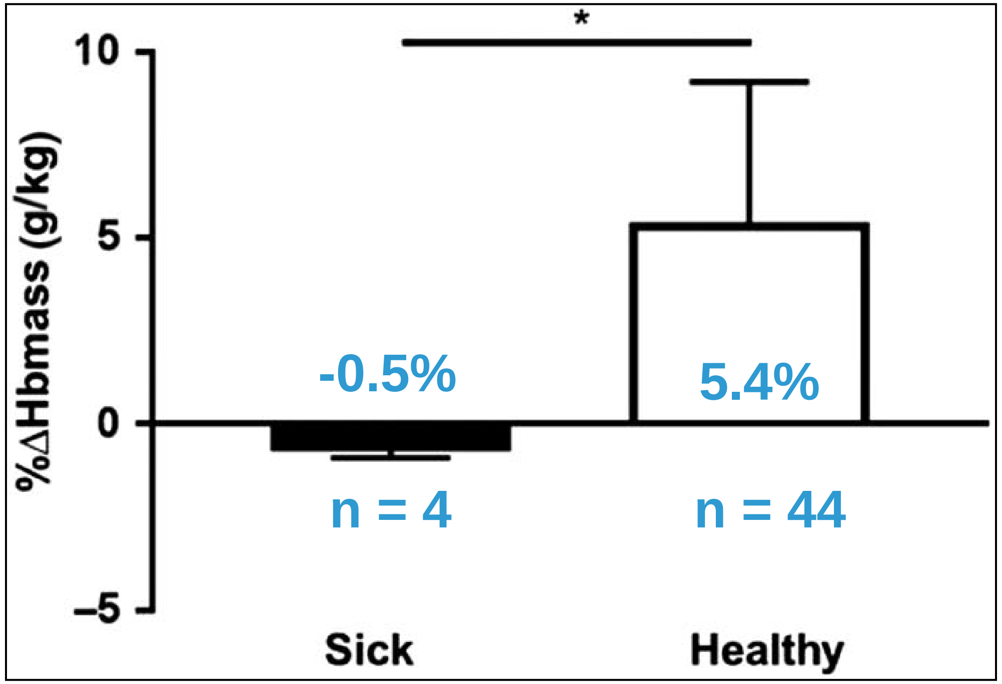
Pretoria: men 6.0 ± 3.2%; women 2.3 ± 2.9%.

Wachsmuth et al. *Eur. J. Appl. Physiol.* 113: 1199-1211, 2013

03 INDIVIDUAL CHANGES IN Hb-MASS IN ELITE RUNNERS AND RACE WALKERS

3-4 weeks altitude training camp in Flagstaff (2133 m), 48 world-class runners and race walkers





Heikura et al. *Int. J. Sports. Physiol. Perform,* 13 (8): 1090-1096, 2018

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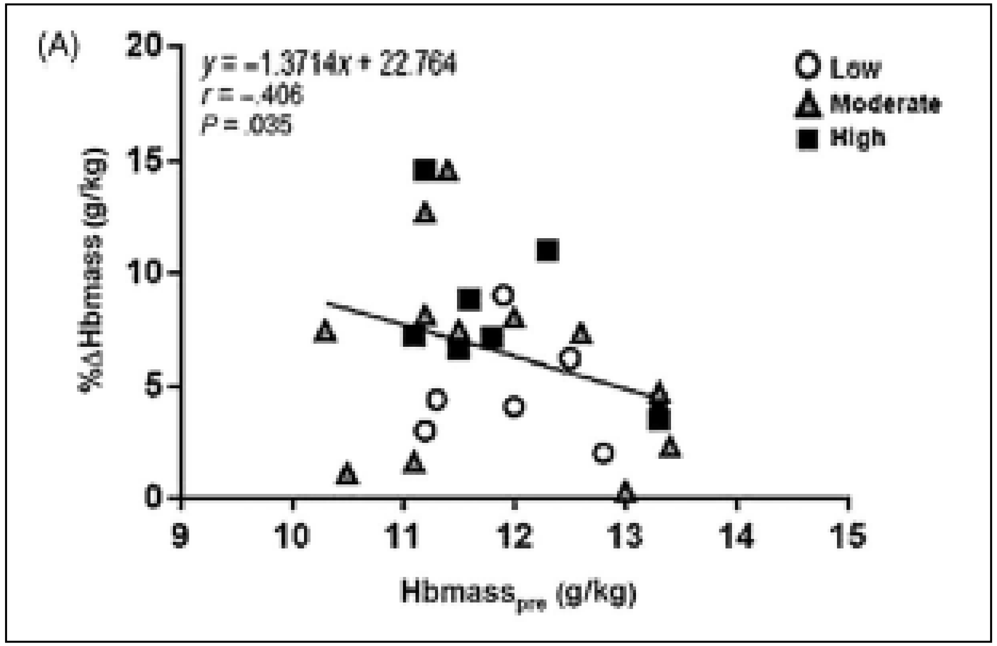
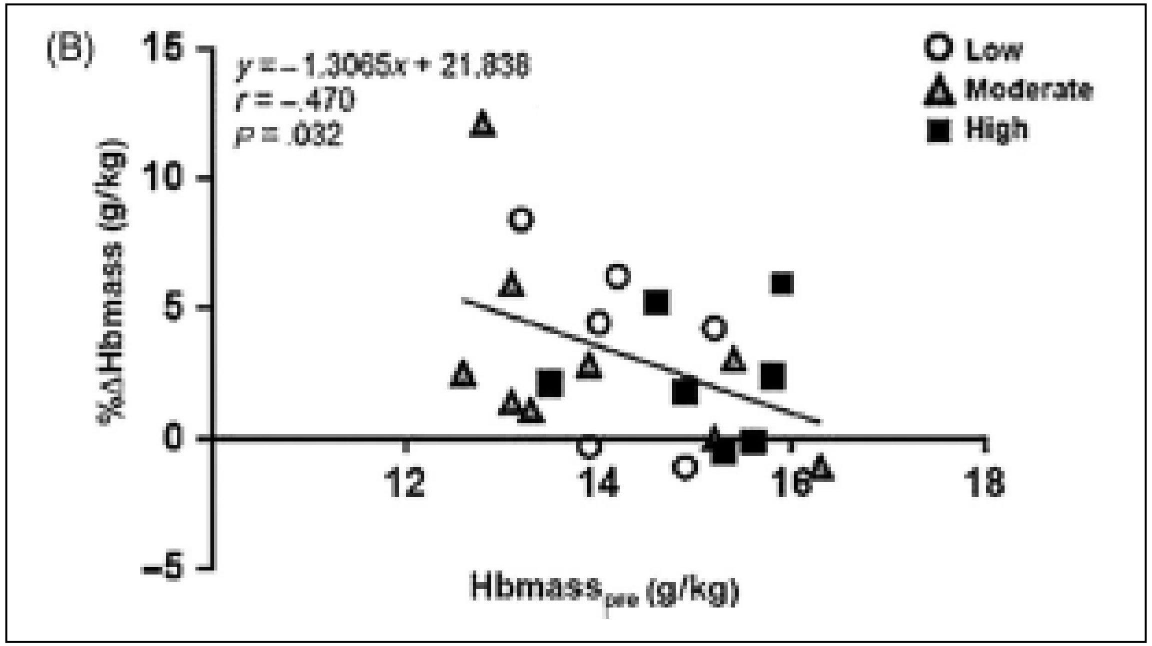
03 INITIAL AND RELATIVE ΔHb-MASS IN ELITE RUNNERS AND RACE WALKERS

3-4 weeks altitude training camp in Flagstaff (2133 m), 48 world-class runners and race walkers

WOMEN

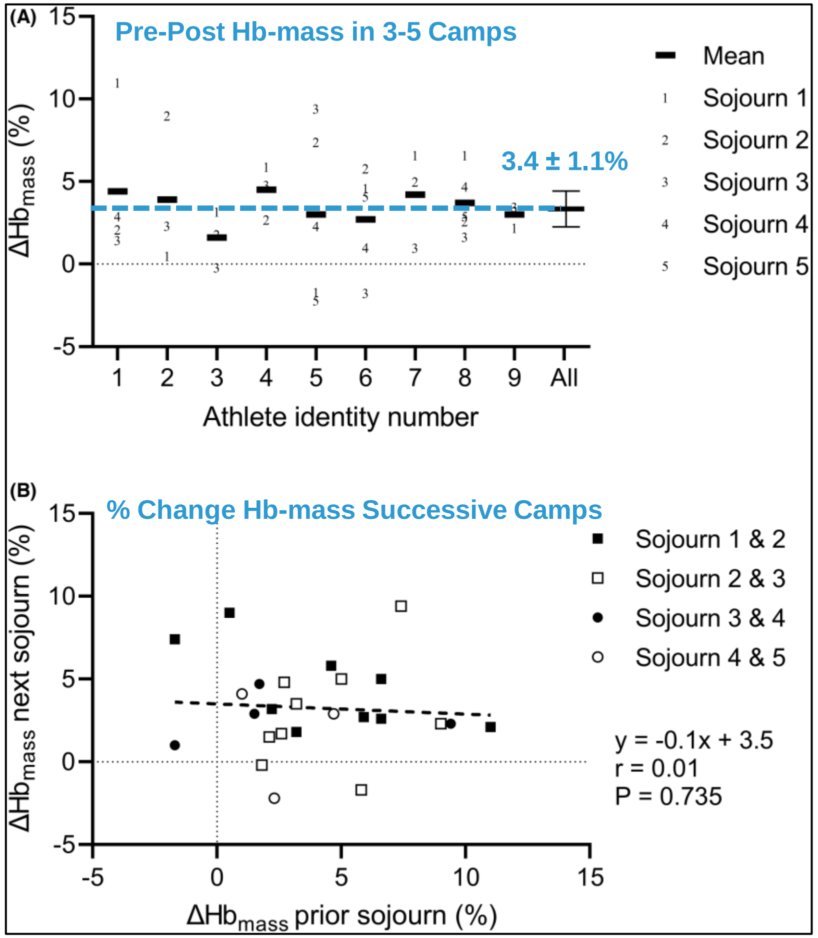


MEN

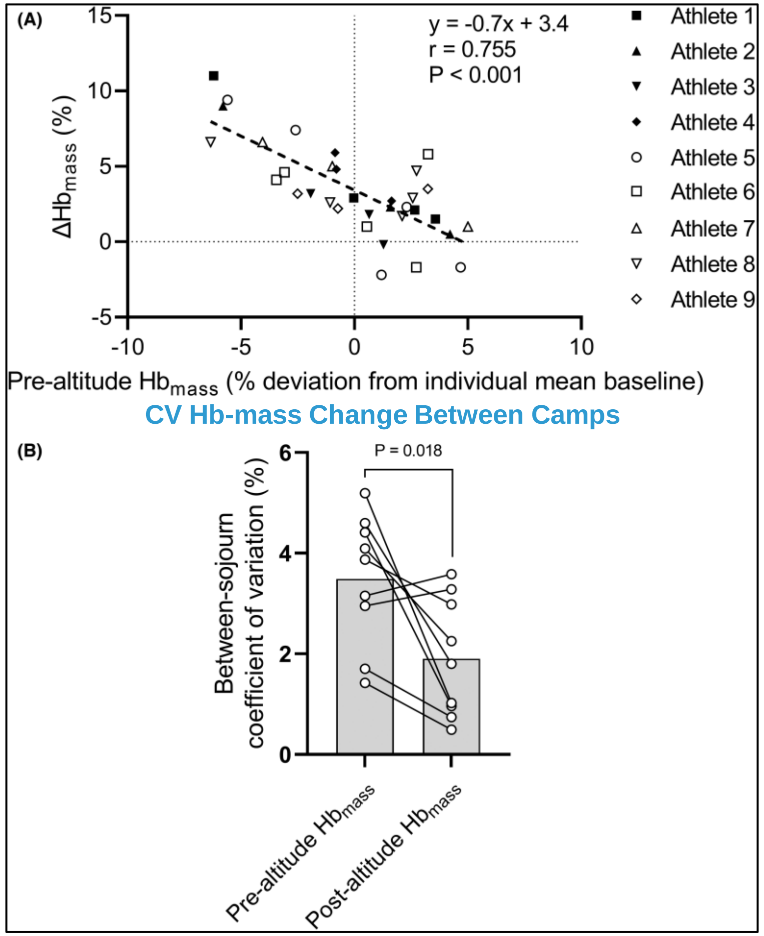


Heikura et al. *Int. J. Sports. Physiol. Perform,* 13 (8): 1090-1096, 2018

03 INDIVIDUAL VARIATIONS IN Hb-MASS DURING REPEATED ALTITUDE CAMPS



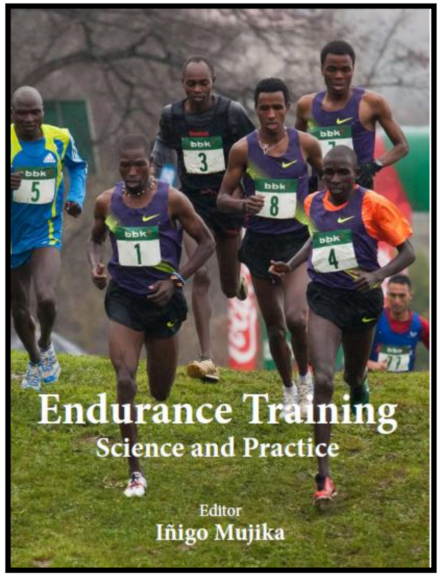
% Change Hb-mass – Pre-Altitude Deviation from Baseline

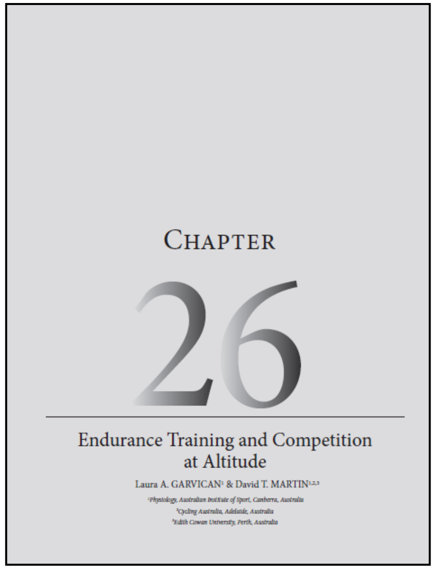


For each % deviation from the individual mean baseline in Hb-mass, an athlete can expect an additional 0.7% increase or a 0.7% smaller increase in Hb-mass than average (~3-4%).

Skattebo & Hallén, *Scand. J. Med. Sci. Sports*, 32: 1493-1501, 2022

03 FACTORS INFLUENCING ADAPTATIONS TO ALTITUDE TRAINING





CHAPTER

26

Endurance Training and Competition
at Altitude

Laura A. GARVICAN[1] & David T. MARTIN[1,2,3]

[1] *Physiology, Australian Institute of Sport, Canberra, Australia*
[2] *Cycling Australia, Adelaide, Australia*
[3] *Edith Cowan University, Perth, Australia*

IRON: Insufficient iron stores and inadequate iron intake may compromise adaptations to altitude training.

INTAKE: Exceptionally low energy diets (essentially not eating in the hope of getting leaner) do not appear to support adaptations to altitude training; sufficient CHO and protein is advised to avoid further stress and facilitate protein synthesis.

INJURY: Prolonged inflammatory responses associated with serious soft tissue injury or broken bones may interfere with altitude adaptations, and hypoxia may lead to slow healing.

ILLNESS: Serious viral and bacterial infections may impair the ability to adapt to altitude training; ill athletes should be advised to get healthy before going to altitude.

INTENSITY: Excessive intensity within the first week of training can promote excessive fatigue; best results tend to come to those that “ease” into training volume and intensity.

Garvican & Martin. In: *Endurance Training – Science and Practice*, 269-278, 2012

04

PERIODIZATION OF ALTITUDE TRAINING

04 PERIODIZATION OF ALTITUDE TRAINING FOR ELITE ENDURANCE ATHLETES

REVIEW ARTICLE

Contemporary Periodization of Altitude Training for Elite Endurance Athletes: A Narrative Review

Iñigo Mujika · Avish P. Sharma · Trent Stellingwerff

Abstract

Key Points

Based on the authors' own extensive experience with elite endurance athletes training at altitude, we would contend that there is no such thing as a non-responding athlete to altitude training camps. Instead, 'non-responder' athletes are probably a product of 'one-off' camps and/or inadequate planning, periodization, programming, and monitoring of altitude training.

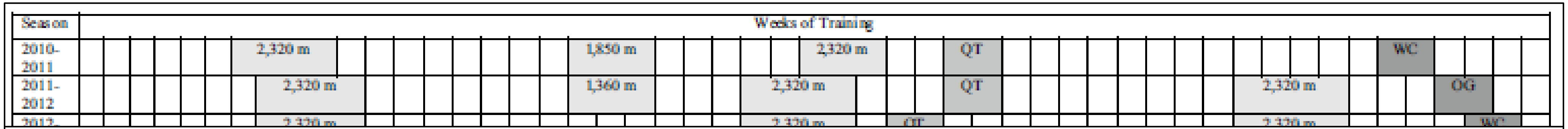
A long- and short-term periodized approach to altitude training seems to be necessary for elite endurance athletes to obtain maximal benefit from the hypoxic stimulus.

Other confounding interventions may need strategic periodization in combination with altitude training, such as nutrition, the combined use of terrestrial altitude and normobaric hypoxia, and/or heat adaptation.

Mujika et al. *Sports Med.* 49 (11): 1651-1669, 2019

04 PERIODIZATION OF ALTITUDE TRAINING FOR AN OLYMPIC CHAMPION FEMALE SWIMMER

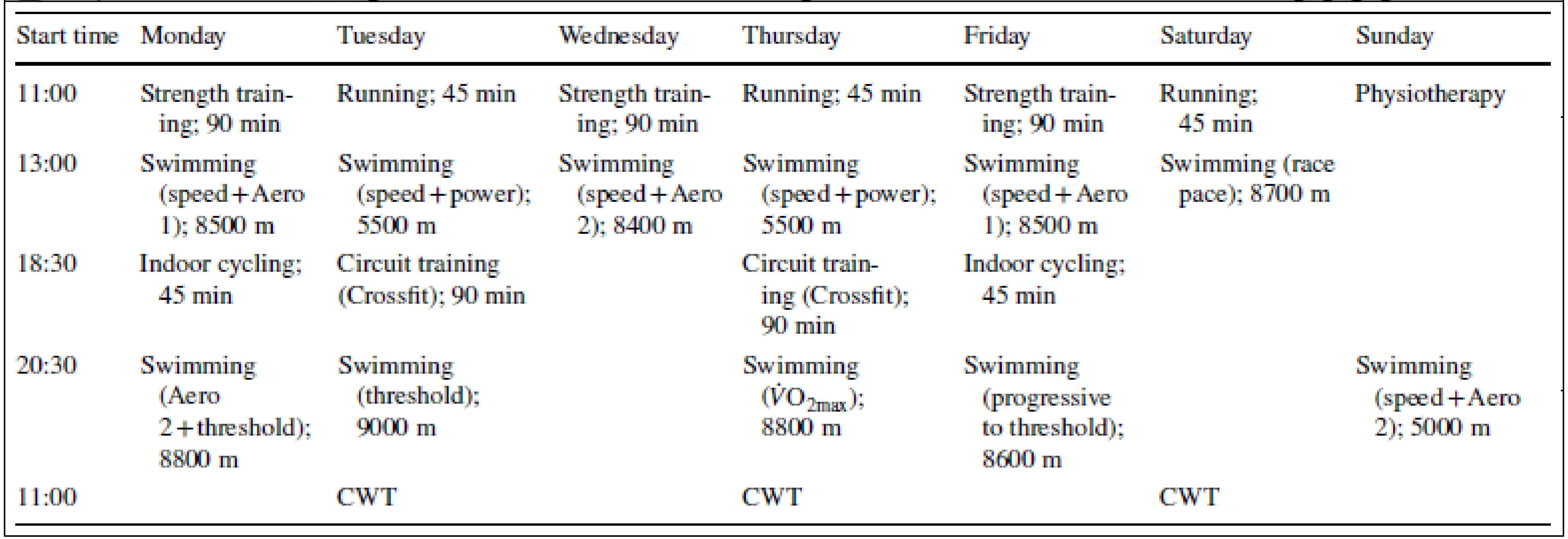
LONG-TERM PLANNING 2010-2018



Season	Weeks of Training
2010-2011	2,320 m 1,850 m 2,320 m QT WC
2011-2012	2,320 m 1,360 m 2,320 m QT 2,320 m OG
2012-	2,320 m 2,320 m QT 2,320 m WC

SEASON VOLUME 2012

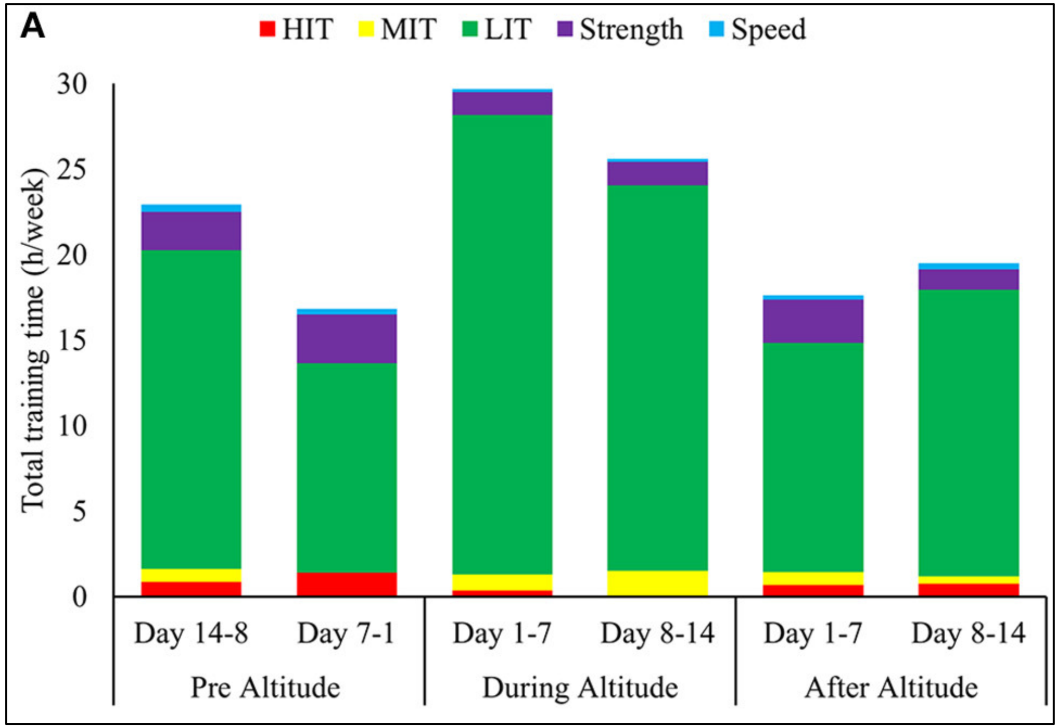
PRE-COMPETITIVE MICROCYCLE 2016



Start time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
11:00	Strength training; 90 min	Running; 45 min	Strength training; 90 min	Running; 45 min	Strength training; 90 min	Running; 45 min	Physiotherapy
13:00	Swimming (speed + Aero 1); 8500 m	Swimming (speed + power); 5500 m	Swimming (speed + Aero 2); 8400 m	Swimming (speed + power); 5500 m	Swimming (speed + Aero 1); 8500 m	Swimming (race pace); 8700 m	
18:30	Indoor cycling; 45 min	Circuit training (Crossfit); 90 min		Circuit training (Crossfit); 90 min	Indoor cycling; 45 min		
20:30	Swimming (Aero 2 + threshold); 8800 m	Swimming (threshold); 9000 m		Swimming ($\dot{V}O_{2max}$); 8800 m	Swimming (progressive to threshold); 8600 m		Swimming (speed + Aero 2); 5000 m
11:00		CWT		CWT		CWT	

Mujika et al. *Sports Med.* 49 (11): 1651-1669, 2019

04 ALTITUDE TRAINING OF THE WORLD'S MOST SUCCESSFUL CROSS-COUNTRY SKIER



Total annual days spent at altitude was 61±9, distributed across 5 camps: 12–14 d Jun/Jul; 12–14 d Aug/Sep; 14–16 d Oct/Nov; 10–14 d Dec; 10–12 d Jan/Feb.

Total training volume at altitude ranged from 170 to 230 h, accounting for 18–25% of the total annual training volume.

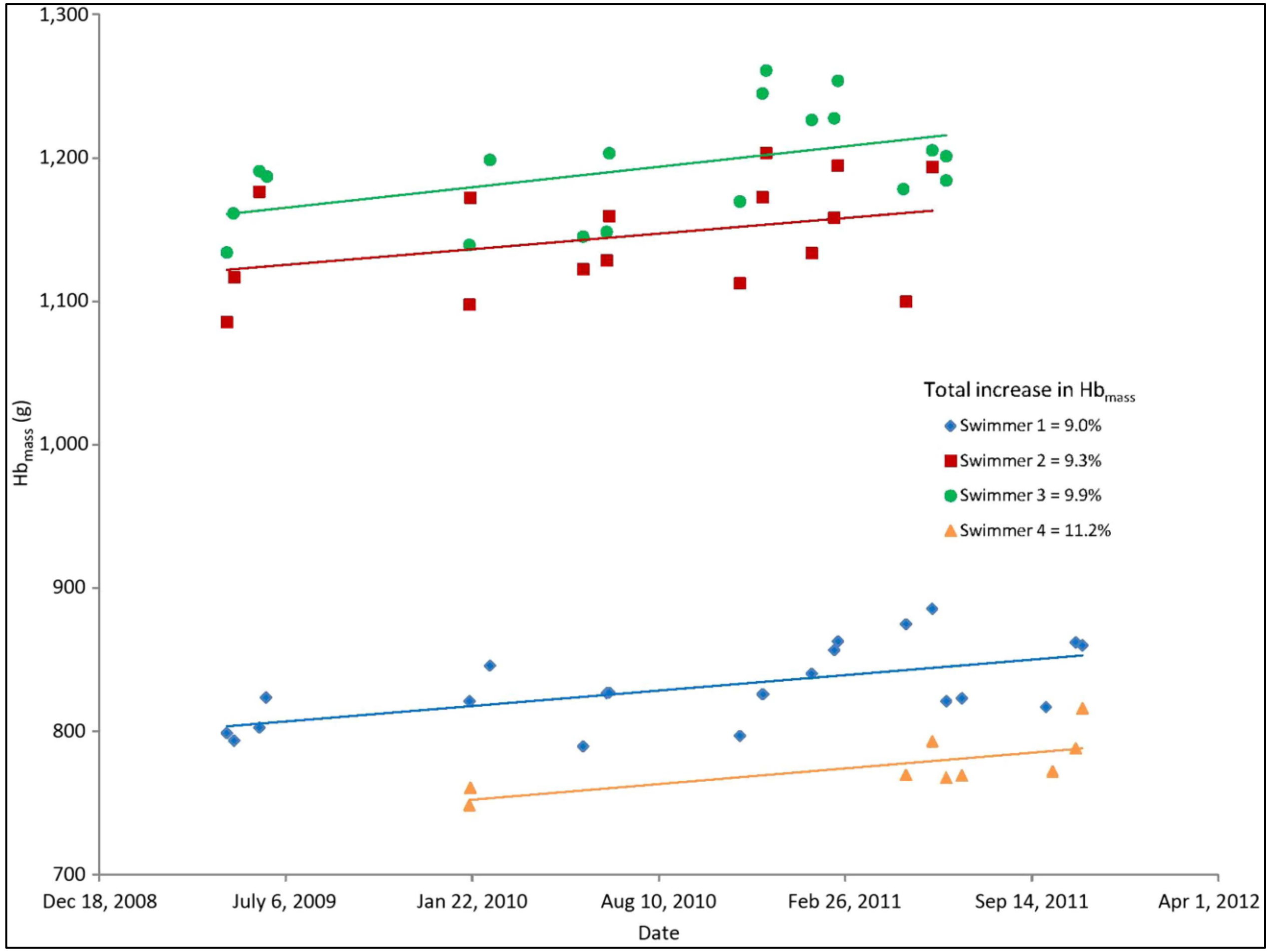
The average weekly training volume decreased from altitude camps performed in GP (26 h) to SP (22 h) and further to CP (20 h).

Total training volume was 35% higher during altitude. The increased training volume occurred due to an increased number of LIT session's ≥ 2.5 h, whereas strength training time was lower compared to the phases before and after.

The amount of training in specific modes increased markedly at altitude, while the total volume of MIT and HIT remained stable (1.5 h/week) across all three phases.

Solli et al., *Front. Physiol.* 8: 1069, 2017

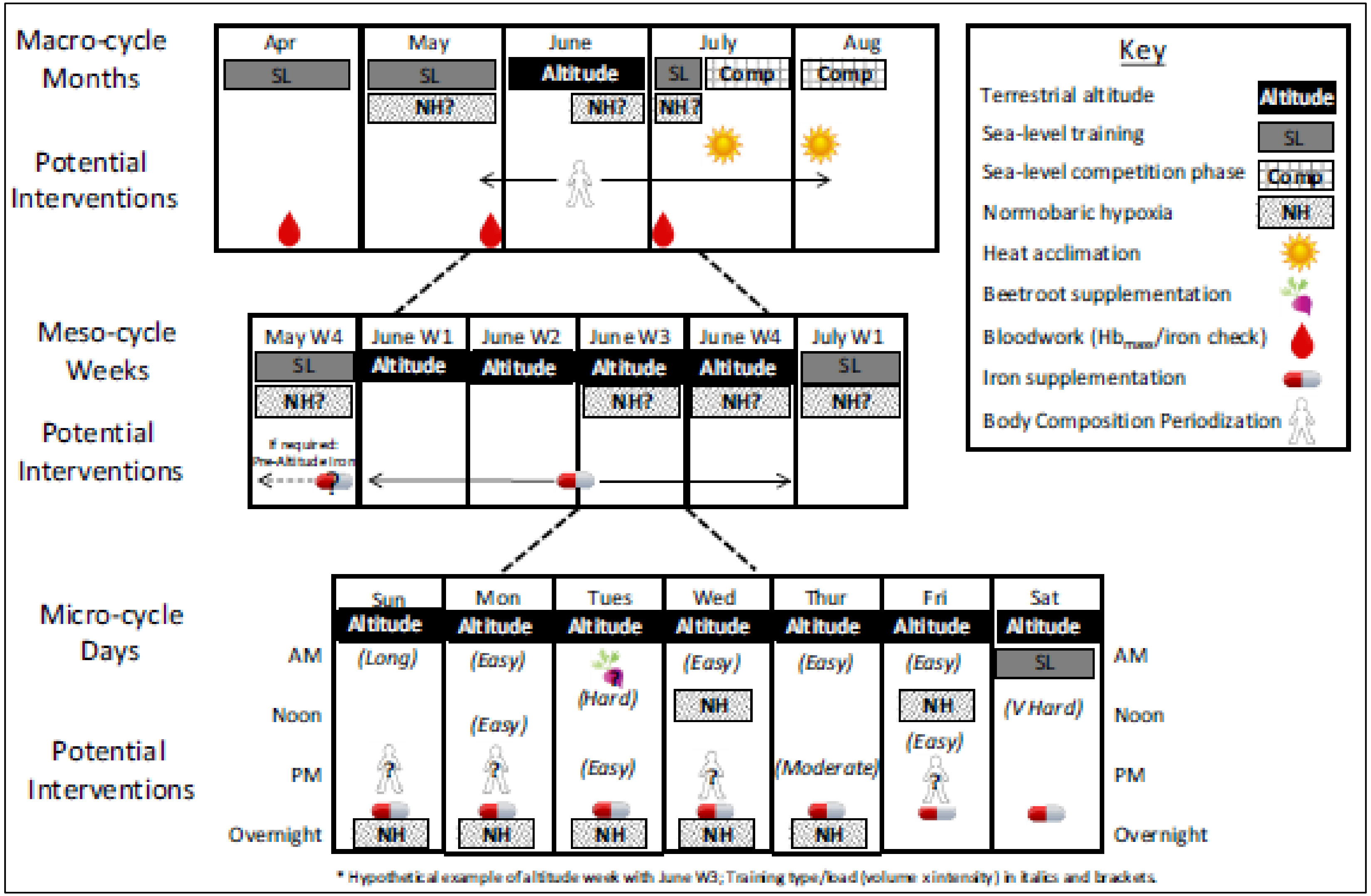
04 Hb-MASS PROGRESSION IN 4 ELITE SWIMMERS OVER A 4-YEAR PERIOD



All swimmers had a linear increase in Hb-mass, with the resultant increase from the end to the start ~10%.

Saunders et al. ***Int. J. Sport Nutr. Exerc. Metab.*** **29: 210-219, 2019**

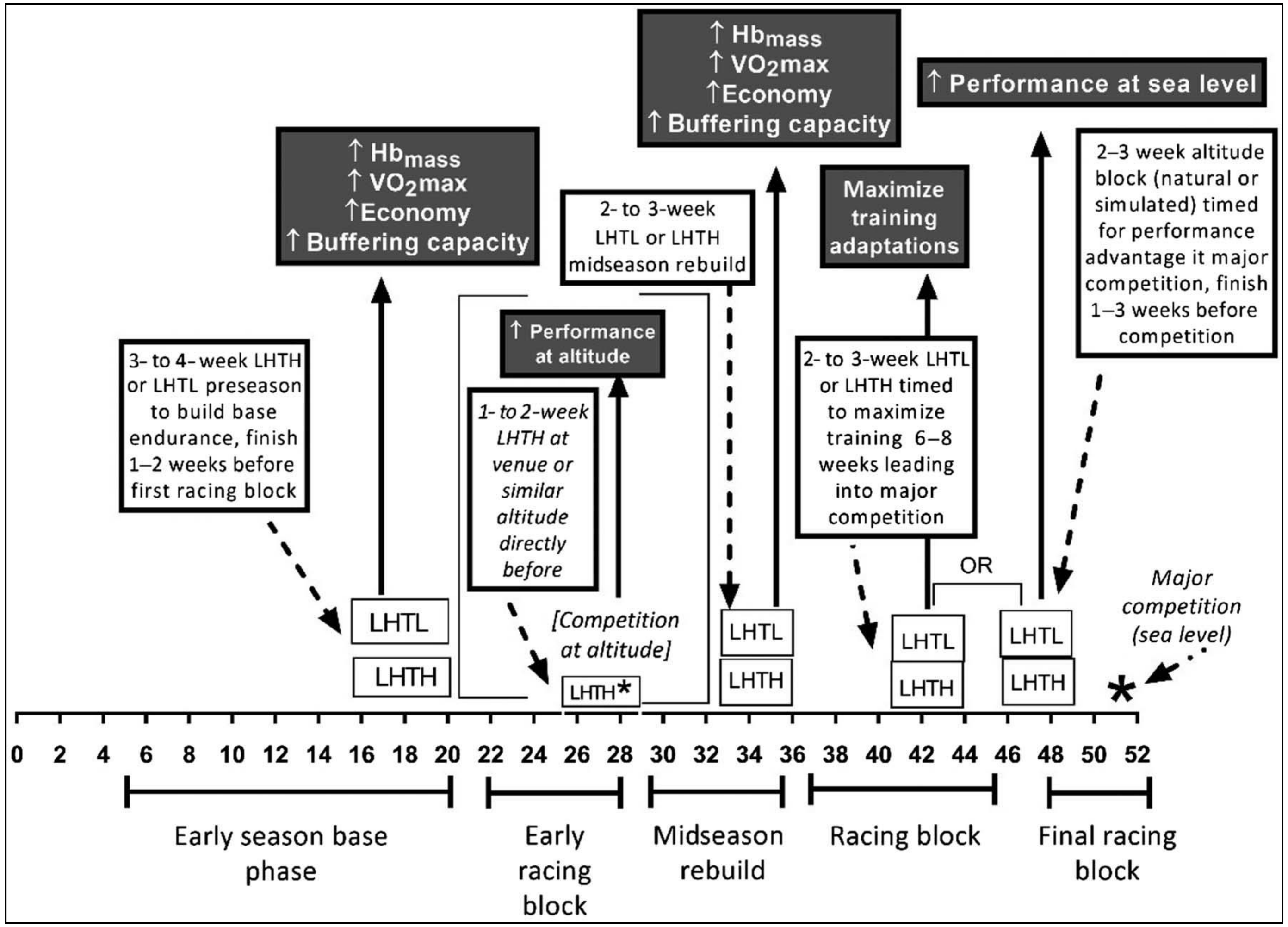
04 INTEGRATED PERIODIZATION OF NUTRITION, HEAT, ARTIFICIAL AND TERRESTRIAL ALTITUDE



* Hypothetical example of altitude week with June W3; Training type/load (volume x intensity) in italics and brackets.

Mujika et al. *Sports Med.* 49 (11): 1651-1669, 2019

04 SAMPLE PERIODIZATION OF ALTITUDE TRAINING WITHIN A SEASON



Particular attention to the training load prior to altitude training, training appropriately while at altitude, and commencing a taper towards the end of the camp are crucial to successful performance immediately following altitude.

Saunders et al. *Int. J. Sport Nutr. Exerc. Metab.* 29: 210-219, 2019

ESKERRIK ASKO!

(“Thank you very much!” in Basque Language)

Iñigo Mujika

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