Summary
Work in progress: Altitude training and adaptation in swimming

Prologue

The differences in competitive sport at the highest level are so small that they frequently are at the edge of scientific measurability. Moreover, the optimization process that underlies performance in sport, i.e. training, has become an optimization ‘problem’ in the scientific community. Therefore, it seems almost impossible to predict or properly study the effects of training interventions and performance in athletes. However, although science alone may not make champions, it can certainly help to support the process. An interesting challenge still lies in front of us: bringing science and sports practice closer together. This thesis made an attempt in which most of the scientific requirements for intervention studies are met and results are considered within the light of sports practice.

Chapter 1: General introduction

In this chapter science and sports practice are brought together in the discussion on altitude training. Even though many coaches and athletes consider altitude training as a critical component of their preparation for competition, scientists continue to debate its value. Unfortunately, there is a remarkable lack of controlled studies on altitude training in the scientific literature, and the scientific evidence supporting most approaches to altitude training in general is inconclusive (Wolski et al., 1996; Wilber, 2004). Moreover, the physiological mechanisms through which altitude training should be effective in enhancing performance remain controversial.

However, it has been estimated that an Olympic swimmer should improve his or her performance by about 1% within the year leading up to the Olympics to stay in contention for a medal (Pyne et al., 2004), while the expectable performance benefit from altitude/hypoxic training for elite athletes can be as high as 1.6% (Bonetti & Hopkins, 2008). In short, altitude training might be a worthy strategy if a medal is just some tenths of a second away.

The obvious problem the human body has to overcome when at altitude is the maintenance of an acceptable high scope for aerobic metabolism in the face of reduced oxygen availability in the atmosphere. In chapter 1 the acute and chronic effects of altitude on the human body are briefly discussed and the main conclusions regarding altitude acclimatization are summarized. In short, an altitude
of between 2,500-3,000m, for 3-4 weeks, is recommended as an altitude that is high enough to obtain a meaningful acclimatization effect in the majority of people but low enough to avoid the development of symptoms of acute mountain sickness. The most prominent adaptation that has been observed with continuous altitude exposure that has a clear relation to improved performance, is an increase in red blood cell mass. This increases the oxygen-carrying capacity of the blood and improves aerobic power (Levine & Stray-Gundersen, 2001). However, several other adaptations to long-term hypoxic exposure have been reported in literature and have been used to explain alterations in performance as a result of altitude (Mizuno et al., 1990; Gore et al., 2001; Levine and Stray-Gundersen, 1997; Terrados et al., 1990).

The above mentioned adaptations and the degree in which they take place depend on several factors, some characterizing the “dose” of hypoxia (e.g. degree of hypoxia, duration of the exposure to hypoxia), some related to training (e.g. training goals, training program, normoxic or hypoxic training), and some related to nutrition and clinical status (e.g. iron stores, diet, oxidative stress, immune function). Variations in the combination of exposure to hypoxia and exercise, and therewith variations in the use of acclimatization and training effects, have led to the different altitude training strategies applied in sports practice today. The purpose of each of these strategies is unanimously to gain maximal performance benefits. This raises the question which strategy to choose. This thesis attempted to contribute to the unraveling of this question.

The most common altitude training strategy among swimmers is the “living high – training high” (LH-TH) strategy. Interestingly, controlled studies of LH-TH, as conducted so far, have not shown to improve sea level swimming performance. The failure of LH-TH to show improved sea level performances has been attributed to reduced training loads at altitude, particularly concerning intensity (Levine & Stray-Gundersen, 2001). In light of this discussion, Chapter 2 of this thesis has been completely devoted to the effects of hypoxic training (LL-TH) on sea level swimming performances.

**Chapter 2: Hypoxic exercise training**

The effect of high intensity hypoxic training (HT, three sessions per week, for five weeks at a simulated altitude of 2,500m) on sea level swimming performance was investigated in sixteen well-trained collegiate and master swimmers by means of a randomized, double blind, placebo controlled trial. Since the control of training
intensity seems rather critical for an honest interpretation of the occurrence of hypoxia specific effects, it was ensured that relative training intensities were similar between groups by choosing maximal exercise intensities. Since both groups showed similar significant performance improvement, it was concluded that five weeks of high intensity training in a swimming flume improves sea-level swimming performances and maximal oxygen uptake (\(\dot{V}O_2\)-max) in well-trained swimmers, with no additive effect of hypoxic training. Furthermore, it was demonstrated that when both groups train at similar relative intensities the hypoxic group trained at significantly lower swimming speeds and thus lower power outputs compared to the normoxic controls. At the metabolic level this was indicated by significantly lower \(\dot{V}O_2\) in the hypoxic compared to the normoxic group. Thus, although hypoxic exercise may feel harder, the power output generated by the muscle is less, and the stimulus for muscle hypertrophy and myosin synthesis must be equivalently less. Moreover, although both groups significantly improved their flume training speeds, this improvement tended to be smaller in the hypoxic group compared to the normoxic group. This suggests that in the long run hypoxic exercise training might even lead to a relative state of detraining.

**Chapter 3: Intermezzo**

In an attempt to overcome the problem related to LH-TH, the inevitable reduction in training load, Levine and Stray-Gundersen developed the "living high-training low" (LH-TL) altitude training strategy. In essence, LH-TL allows athletes to ‘‘live high’’ for the purpose of facilitating altitude acclimatization, while simultaneously allowing athletes to ‘‘train low’’ for the purpose of replicating sea-level training intensity and oxygen flux (Levine & Stray-Gundersen, 1997). LH-TL has been shown to improve sea level performance in endurance events lasting 8-20 minutes. However, it has never been successfully applied to swimming, in which most events last for less than 5 min. Moreover, there are relatively few places in the world where LH-TL can be readily achieved by terrestrial variations in altitude. The introduction of so-called “altitude houses” (normobaric hypoxia induced by nitrogen dilution) by Rusko and colleagues (1995), and other related devices (hypoxic tents and hypoxic breathing apparatuses) later on, certainly helped to overcome this practical issue and further stimulated the use of LH-TL in sports practice today. Based on data from several laboratories it appears that a minimum of 12–16 hours per day of continuous hypoxia exposure for at least 3 weeks, at (simulated) altitudes of 2,500m, is necessary to induce a statistically and
physiologically significant increase in red cell volume (RCV), hemoglobin mass, and $\dot{V}O_2$-max in trained athletes (Brugniaux et al., 2006; Levine at al., 2006; Rusko et al., 2003). However, this requirement for prolonged periods of exposure has limited the broad application of this technology. This opened the quest to the minimal exposure to hypoxia (a combination of exposure time and level of hypoxia) necessary to induce acclimatization. In this regard, so-called "intermittent hypoxic exposure" (IHE), has been proposed as a more time-efficient variant (Rodriguez et al., 1999) of LH-TL that is more comparable with normal living conditions for its users. IHE applies severe ($\sim$4,000 to 5,500m altitude or its equivalent) hypobaric or normobaric hypoxia at rest for relatively short periods of time (1.5–5 hours per day). The effect of IHE on sea level swimming performance is the main focus of Chapter 4 of this thesis.

**Chapter 4: Intermittent hypoxic exposure**

The effect of intermittent hypobaric hypoxia (IHE, three hours per day, five days a week, for four weeks at a simulated altitude of 4,000-5,500m) combined with training at sea level was investigated in 23 well-trained athletes via a double-blind, randomized, placebo controlled trial. It was concluded that four weeks of IHE was unable to improve field- or laboratory performance in this group of well-trained athletes. Moreover, despite a doubling in EPO concentration 3 hours after hypoxia, IHE did not accelerate erythropoiesis. It is suggested that the 21 hours spent in normoxia each day, as well as the weekend spent in normoxia, were sufficient to counter the transient increases in EPO as induced by IHE and therewith prevented an increase in RCV to occur. Furthermore, it is speculated that any IHE protocol in which the duration of time spent in normoxia exceeds that spent in hypoxia, may be insufficient to induce a robust and sustained erythropoietic response. Overall, it appears that, to accelerate erythropoiesis with IHE, and to have the potential physiological and performance benefits from an increased RCV, not only the level of EPO increase induced by the hypoxic exposure has to be considered, but also other factors such as the duration of the normoxic conditions after each IHE exposure and the extend to which training interferes with the process of erythropoiesis.

**Chapter 5: General Discussion**

The importance of a double blind, placebo controlled, randomized study design for the interpretation of results from intervention studies as presented in this thesis was stressed in the introduction of this thesis. However, statistically significant findings
as observed from intervention studies require relatively large groups of subjects, whereas elite sports ultimately focuses on the outliers. Moreover, statistically significant findings from scientific research are not always meaningful for the individual elite athlete. This is the result of the complexity of sports performance as well as the rather large inter-individual variability that has been observed in response to training (Chapman et al., 1998; Bagger et al., 2003).

The various aspects of altitude and training are discussed within the conceptual framework of ‘dose-response’ relationships and enriched with vivid examples from the world of sports. It is suggested that from a methodological point of view the elite athlete can be considered as a case study in which an in-depth, longitudinal examination of the athlete within its real-life context is conducted. As a result the scientist may gain a larger understanding of why the athlete’s training and performance happened as they did, and what might become important to look at more extensively in future research. However, in this regard it should be noted that what might work for one athlete cannot be generalized to work for another in a similar way.

In short, although science itself may not make champions, scientific knowledge can sure help to support the process by formulating general guidelines that are likely to work for the athlete. Based on the available scientific evidence as presented in this thesis, the following rules of thumb can be given with regard to altitude and swimming:

- hypoxic exercise (as in LH-TH or LL-TH) does not appear to provide any physiologic advantage over normoxic exercise, regardless of training intensity. Moreover, absolute workload and oxygen flux are reduced suggesting that, if anything, hypoxic exercise might be detrimental to sea level performance.

- although the conductance of low-moderate, short duration (less then 3 weeks) altitude training camps (LH-TH) is certainly useful for performance at altitude, there is no objective evidence for LH-TH in order to improve sea level performance in highly trained swimmers.

- approximately 2,500m of altitude, for at least 12 hours per day, for a minimum of 3 to 4 weeks appears necessary to acquire a robust acclimatization response (primarily red cell volume) with lower risk of altitude disturbances in the majority of athletes.

- the optimal altitude training strategy for improvements in sea level performances is likely to be the “living high-training low” (LH-TL) strategy, in which one “lives high” (i.e. 2,500m) to get the benefits of
altitude acclimatization and “trains low” (1,250m or less) to avoid the detrimental effects of hypoxic exercise. Whether the performance benefits would be equally large for swimmers compared to cyclists and runners remains questionable and requires further research.

Although the guidelines formulated above can be used as general rules for altitude training in swimming, there is substantial individual variability in the outcome of every hypoxic/altitude strategy, and more research is warranted to further unravel and optimize the individual dose-response relationship. However in this process, the complexity of human sports performance should be acknowledged and the ‘craftmanship’ of the trainer/coach should be used in the interpretation and communication of results.