ALTITUDE TRAINING ENHANCES PERFORMANCE IN ELITE SWIMMERS: RESULTS FROM A CONTROLLED FOUR PARALLEL GROUPS TRIAL (THE ALTITUDE PROJECT)*

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ABSTRACT
Introduction. Based on available scientific literature, training at natural altitude has failed so far to prove useful for the enhancement of sea level performance in swimmers 1,2. This controlled nonrandomized four parallel groups trial examined the effects on performance, oxygen transport and total hemoglobin mass (Thbmax) of four training interventions: terrestrial living high-training high for 3 or 4 weeks (Hi-Hi3, Hi-Hi), living high-training high/low (Hi-HiLo), and living and training at sea level for 4 weeks (Lo-Lo). Methods. From 65 elite swimmers, 54 met all inclusion criteria and completed sea-level time trials over 50 and 400 m front crawl (TT50, TT400), and 100 (sprinters) or 200 m (non-sprinters) at best personal stroke (TT100/TT200). VO2max was measured on an incremental 4x200-m front crawl test. Training load was estimated using TRIMP and session RPE assessment. Initial performance and measures (PRE) were repeated immediately after the camp (POST) and once weekly on return to SL during 4 weeks. Thbmax was measured in duplicate at PRE and once a week during the camp. Intervention effects were analysed using mixed linear modelling.

Results. TT100 or TT200 improved by ~3.5% regardless of living or training at sea level or at altitude, but Hi-HiLo improved more two (5.3±1.6%) and four weeks (6.3±1.9%) after the intervention as compared to the other groups. Hi-HiLo and Hi-Hi improved more in TT400 (4.6±1.4% and 3.3±1.4%, respectively). There were no changes in VO2max in any of the groups after the intervention. Thbmax increased in Hi-Hi (6.2±2.6%) and Hi-Hi3 (3.8±5.6%), whereas no significant changes were noted in Hi-HiLo (1.3±4.3%). Conclusions. Hi-HiLo is an effective strategy to enhance performance in elite swimmers over a range of distances, clearly exceeding the smallest worthwhile enhancement effect for Olympic-standard swimmers (0.8–1%) 3. This substantial performance improvement was not linked to changes in VO2max or Thbmax, hence could not be attributed to enhanced oxygen transport capacity.

KEYWORDS: hypoxia, swimming, haemoglobin, elite athletes, oxygen transport, VO2max

INTRODUCTION
Altitude training (AT) has been matter of extensive research for half a century and it still plays an important role in the preparation of athletes in many countries 4,5 despite the sceptical view of some investigators on its efficacy to enhance sea-level performance, particularly in elite athletes 6. Despite being used by very many elite swimmers and coaches, there is a remarkable lack of controlled studies in swimming, and there is no evidence that training at natural altitude enhances performance more than training at sea level (SL) 1,2. Even though in the last decade the Hi-Lo approach has largely supplanted classical AT in the scientific literature 5, no studies have been conducted using this strategy in natural altitude in swimmers.

In view of the vast disconnect between research evidence and practical use of AT, particularly in elite swimmers, an international group of investigators conducted an international collaborative research study (The Altitude Project) to examine the impact of different current AT strategies on performance, technique, and health status of elite swimmers.

This study aimed 1) to contrast the hypothesis that living at moderate altitude (2,230 m) and training both at moderate and at lower altitude for four weeks (Hi-HiLo) improves SL swimming performance more than living and training at altitude (classical terrestrial AT) for 3 (Hi-Hi3) or 4 weeks (Hi-Hi), or than living and training at low altitude (conventional Lo-Lo sea-level training); 2) to elucidate whether the adaptive mechanisms conform with the “erythropoietic paradigm” (i.e., are mainly hematologic in nature, via the activation of erythropoiesis by induced hypoxia, with subsequent increase in VO2max); and 3) to quantify the eventual effect of the different interventions on performance on return to SL and to track changes during a lengthy period of 4 weeks without concurrent tapering.

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METHODS
This study is a controlled, nonrandomized, four parallel groups trial, comparing changes in swimming performance, VO₂max, and tHbₐ₉ after an experimental intervention consisting of training camps in 4 different conditions: 1) living and training at moderate altitude (2,320 m) for 4 weeks (Hi-Hi); 2) identical intervention for 3 weeks (Hi-Hi3); 3) living at altitude and training at both moderate and low altitude (690 m) for 4 weeks (Hi-HiLo); and 4) living and training near SL (190 or 655 m) for 4 weeks (Lo-Lo).

After a low intensity lead-in period all swimmers and their coaches travelled to Sabadell (190 m) or Madrid (655 m), Spain, where they stayed for 3-5 days for baseline testing. Next, all swimmers allocated to the AT groups (n = 43) travelled to the High Altitude Training Center (CAR) at Sierra Nevada (2,320 m), Spain, where they lived for 3 or 4 weeks. The two Lo-Lo sub-samples lived and trained in Sabadell (n = 10) and the High Performance Center (CAR) at Madrid (n = 7). One of the Hi-Hi3 subgroups (n = 6) was tested in Granada, Spain (690 m). In all cases, baseline and final testing were conducted at the same location and facility.

65 swimmers of both sexes (35 women and 30 men) were recruited from eight countries (AUS, BRA, CHI, GBR, NED, SLO, ESP, and TUN). Selection criteria included to have competed internationally during the previous season and/or being pre-selected as a member of their National and/or Olympic teams. Their competitive level was quantified using the FINA Point Scoring (FPS) system.⁷

The primary outcome assessment was swimming performance, as measured in time trials (TT) on 100 m (sprinters) or 200 m (non-sprinters) at personal best stroke (TT100 or TT200). Secondary outcomes were VO₂max assessed with a 4x200-m incremental swimming test and tHbₐ₉. After warm-up, subjects swam 3x200 m crawl at paced speeds (F: 0.9, 1.0, and 1.1 m·s⁻¹; M: 1.0, 1.1, and 1.2 m·s⁻¹). After 10 min of passive recovery, subjects completed an all-out 200 m swim to determine VO₂max using a telemetric portable gas analyzer (K4 b⁵, Cosmed, Italy) connected to the swimmer by a low resistance respiratory snorkel.⁸,⁹ VO₂ data were fitted by nonlinear regression and the maximal asymptotic VO₂ was taken as the swimmer’s VO₂max (TE = 3.1%; 95% CI: 1.1–5.1; n = 9). tHbₐ₉ was measured using the optimized CO-rebreathing method, as described by Schmidt and Prommer¹⁰ with some modifications¹¹,¹² (TE = 1.35% (95% CI: 0.10–2.65).

The study was carried out during the first macrocycle of the Olympic year prior to the London 2012 Olympics. Individualised training plans were developed by the swimmers’ personal coaches. HR monitors and beacon transmitters (CardioSwim, TX H₂O; Freemap, Switzerland) were used to register the lap times, rest intervals, and 50-m average speed. A modified TRIMP calculation suited for interval training was used to estimate the “cumulative TRIMP” (TRIMPC)¹³. Each athlete kept a detailed training log which included self-administered questionnaires to assess session-RPE (s-RPE)¹⁴ and total state of fatigue (TSF-10). Iron supplementation was prescribed or strongly recommended to all swimmers at altitude based on their ferritin levels monitored weekly in all altitude groups during the intervention period.

All training camps were conducted in training centres of international standards, where subjects lived and trained as a group for the whole intervention period. In the recruiting phase, coaches were offered to choose among the 4 different interventions. To evaluate information bias of the intervention, two ad hoc questionnaire were administered to coaches and swimmers at the beginning and at end of training camp.

Effects on performance, VO₂max, and tHbₐ₉, are expressed as percent change values (Δ%; ±90% CI)¹⁵. Correlation was assessed by the Pearson’s coefficients (r). In assessing the effect of the intervention on TT performance and tHbₐ₉ over time the linear mixed modelling procedure (Proc Mixed, SAS, v. 9.1.3) for repeated measures was used to estimate means for main effects and group x test interaction, with Tukey’s post hoc pairwise multiple comparisons to identify the source of differences. An ANCOVA analysis was carried out using TRIMPC as a covariate for performance. To evaluate the effects of the intervention on VO₂max a 2-tailed paired t-test was used.

RESULTS
54 subjects (30 F, 24 F) successfully completed the intervention protocol of the original total of 65 subjects. After the intervention period, all coaches responded to the ad hoc questionnaire that they would have chosen again the same intervention, and that they expected that it would help the swimmers to improve their performance. On POST, the swimmers’ answers to the latter question were ‘yes’ (91%), or ‘not sure’ (9%). These participants belonged to the Lo-Lo (n = 1), Hi-Hi (n = 2), and Hi-Hi3 (n = 3) groups. No subjects answered ‘no’.

Daily average TRIMPC was greater in Hi-HiLo (258±95) than in Hi-Hi (205±102; P = 0.01), Hi-Hi3 (177±115; P<0.001), and Lo-Lo (209±100; P = 0.006). Mean daily s-RPE scores were greater in Hi-Hi3 (5.3±1.8), than in the other three groups (Hi-Hi: 4.4±1.9, P<0.001; Hi-HiLo: 4.8±1.6, P = 0.01; and Lo-Lo: 4.2±1.8, P<0.001). Mean daily TSF-10 scores were also higher (P<0.001) in Hi-Hi3 (8.2±2.4), than in the other three groups (Hi-Hi: 6.8±2.1; Hi-HiLo: 6.2±1.7; and Lo-Lo: 6.3±2.9).

Relative percent changes in TT100 (sprinters) or TT200 (non-sprinters) time trial tests in the different groups are presented in Figure 1.
There were no changes in VO_{2\text{max}} in either Lo-Lo (1.9%; ±1.5%), Hi-Hi3 (1.5%; ±2.5%), Hi-Hi (1.1%; ±2.6%), or Hi-HiLo (1.3%; ±1.4%). No relationship between change in VO_{2\text{max}} and change in TT400 performance was found for the entire group of subjects (r=-0.01, P=0.95) or for the swimmers in each group. Likewise, there was no relationship between changes in VO_{2\text{max}} and changes in TT100 or TT200 performance, neither for all subjects (r=0.10, P=0.50) nor for each group.

Compared to PRE, increase in tHb_{mass} was more pronounced in Hi-Hi group (at W4: 6.2%; ±1.1%; P<0.001) than in the Hi-Hi3 group (at W3: 3.8%; ±2.3; group x test interaction P=0.02), whereas no changes were found in the Hi-HiLo group (at W4: 1.3%; ±1.8; P=0.71). Changes in tHb_{mass} and in VO_{2\text{max}} were not associated neither for all subjects (r=0.01; P=0.96) nor for each group.

**Figure 1.** Percent changes in 100 m (sprinters) or 200 m (non-sprinters) at best personal stroke (TT100 or TT200). Differences are group x test interactions among groups (P<0.05): Hi-HiLo vs. Lo-Lo (#), Hi-Hi3 (¶), and Hi-Hi (+); Lo-Lo vs. Hi-Hi3 ($) and Hi-Hi (§).

**DISCUSSION**

To the best of our knowledge, this is the first investigation to show performance improvements after a terrestrial AT intervention using a controlled design in swimmers, and one of the few in truly elite athletes. Although the vast majority of studies in the AT literature are uncontrolled and underpowered especially with elite athletes, there seems to be a growing consensus that when athletes are exposed to an adequate “dose” of altitude exposure and training, the majority may improve endurance performance. In a recent meta-analysis, Bonetti and Hopkins concluded that changes in studies using the Hi-Hi approach were unclear, whereas changes using terrestrial Hi-Lo were considered likely both for elite and subelite athletes (~4%–5% from uncontrolled studies). These estimations are in line with a recent review that estimated that a 3-week terrestrial altitude camp would elicit mean performance improvements of ~1.8% (Hi-Hi) and ~2.5% (Hi-Lo).

The evidence in swimming is less compelling. Six uncontrolled studies have tested the Hi-Hi strategy in swimmers. Three of them were entirely negative, and two others showed modest and statistically unclear improvements in performance of ~1.6–1.8%. In the only controlled study, the small increase in performance in 100- and 200-m races (0.1–0.7%) was likely below the smallest worthwhile enhancement effect of the intervention. Why should swimming be different from land-based endurance sports regarding AT effects? First, swimming performance is more dependent on economy (energy cost) than on maximal metabolic power, it follows that the benefit of enhanced metabolic capacity can be outweighed by impaired technique and economy. Second, the benefit of AT might be more or less potent for swimmers of different events.

A distinguishing feature of the present study was that the follow-up period after the intervention covered up to 4 weeks post-intervention. If we focus on the stroke/distance specific assessment (TT100 or TT200), it becomes clear that
best performances were attained 4 weeks after returning to SL, although the superior benefits of the Hi-HiLo intervention became evident already 2 weeks after the training camp.

A key factor in the individual response to training, whether at altitude or at SL, is the training load. When TT performance data were adjusted for TRIMPc, there remained significant between-group differences suggesting that not all of them could be attributed solely to training. Ultimately, the fact that the Hi-HiLo group achieved a greater training internal load, but not training effort, may be a core element of the Hi-HiLo training paradigm.

The remarkable improvement observed in swimming performance could not be attributed to enhanced O2-transport capacity. Consistent with previous reports, we found that tHbmass clearly increased in those swimmers living and training at altitude for 3 (3.8%) or 4 weeks (6.2%). The magnitude, time course, and large variability of the erythropoietic response was in line with a recently published meta-analysis including data of 16 AT studies 32. However, in contrast to the Hi-Hi groups, mean tHbmass did not change in our Hi-HiLo swimmers (at W4: 1.3; ±1.8%) who were also exposed to the same degree of sustained hypobaric hypoxia for 4 weeks. The simplest explanation for these contrasting results may be the individual variability in tHbmass changes, since half of the subjects actually showed an increase of tHbmass over the TE of the measurement. However, comparable results were found in elite track cyclists 33, and in endurance athletes exposed to normobaric hypoxia 34. We must consider also that a wide variability in the erythropoietic response to moderate hypoxia has been consistently shown 32, 34-39.

In the present study, changes in tHbmass were not associated with changes in VO2max. These results are in line with those reported in a recent review 40 of 10 recent studies involving four different sports, which estimated a mean ~3% increase in tHbmass and VO2max and a similarly significant, albeit weak, correlation between both parameters (r² = 0.15). It should be emphasized that this relationship between changes in tHbmass and VO2max after altitude exposure is somewhat lower than that observed after rhEPO administration (e.g. r² = 0.28) 40-42 emphasising that VO2max is a complex parameter that is not exclusively determined by the red cell mass 43.

The present study underpins the complex interaction among altitude acclimatization effects (such as Hbmass among others), altitude and SL training effects, VO2max, and performance in events of different sports and different durations/intensities requiring widely divergent metabolic demands 22, 36, 37, 44. Despite failing to demonstrate an increase in tHbmass or VO2max, the swimmers in the Hi-HiLo group clearly improved performance more than the altitude controls. Possible explanations include: a) swimming, especially in the shorter distances, may not be as dependent on oxygen transport as endurance running or cycling; b) there are other factors (e.g. differences in training intensity) that may have played a greater role in improving swimming performances through as yet undetermined mechanisms.

We were committed to recruit truly elite athletes. Working with such unique individuals in a real-word setting, particularly during an Olympic season, we were confronted with the virtual impossibility to conduct a fully controlled experiment without seriously compromising the ecological validity of the study or limiting its external validity. As subjects were not allocated randomly, selection bias may have occurred despite our attempt to minimize its likelihood by allocating swimmers from at least two different squads and nations in each intervention group, after ensuring that the 4 experimental groups were properly matched for performance level, weight, height, VO2max and tHbmass.

**Practical Implications for Training and Performance.** Swimming performance might be expected to substantially improve (~3.5%) as a result of a well-implemented coach-prescribed training camp, regardless of whether the camp is held at altitude (Hi-Hi) or not. However, a much greater benefit (~6.3%) can be expected using the Hi-HiLo strategy for 4 weeks. Mid-term swimming aerobic endurance performance (400 m) can be expected to improve more by living and training at altitude for 4 weeks than by living and training at SL, though the additional benefit is most likely to be larger using the Hi-HiLo (~3%) than the Hi-Hi strategy (~1.7%). Similarly, Hi-HiLo can be expected to improve sprinting capacity 1 to 3 weeks after the altitude camp (4.8–5.5%), the benefit being superior to any other intervention at the second week from return to SL. Care should be taken not to generalize these improvements to all swimmers, since substantial individual variability was noted in this as well as other studies 16, 35, 36. While performance can be stabilized or even worsened immediately on return from altitude, the greatest benefits are likely to be attained after 2 to 4 weeks after return to SL. This relatively long time interval could eventually be used to intensify training in the following few macrocycles and/or may provide a time window for tapering before competition. Monitoring individual training load and adaptation during and after the altitude camp to avoid excessive overload or detraining, as well as assessing individual peaking performance profile, are strongly recommended before applying these rules to individual cases.

**CONCLUSION**

Swimming performance of elite swimmers in 100- (sprinters) or 200-m (non-sprinters) improved significantly by ~3.1–3.7% in response to a coach-prescribed training camp whether at SL or at altitude. With 2 weekly sessions of high-intensity training at lower altitude (Hi-HiLo), a remarkably greater improvement was attained 2 (5.3%) and 4 weeks (6.3%) after the training camp. This substantial improvement was not linked to changes in VO2max, oxygen kinetics or tHbmass, hence could not be attributed exclusively to enhanced oxygen transport capacity. We conclude that: a) a well implemented training camp improves performance even in elite swimmers; b) living high-training low improves
performance in swimming above and beyond altitude and SL controls, through complex mechanisms involving altitude living and SL training effects.

REFERENCES


