Altitude training for sea level performance: a systematic review

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Introduction

Altitude training (AT) at natural environment has been a matter of extensive research for half a century and, despite some sceptical views (1-3), it continues to play an important role in the preparation of elite and sub-elite athletes in many countries (4, 5). Paradoxically, there is a remarkable lack of controlled and adequately powered studies on natural AT in the scientific literature, particularly in elite athletes, and there is no clear evidence that AT enhances performance more than training at sea level (SL) (1, 5-7). The theoretical concept behind this practice is the independent and combined effects of the physiological processes of acclimatization to chronic hypoxia and those derived from training under the additional stress imposed by exercising in a hypoxic environment (8). In accordance with some investigations, altitude acclimatization results in central and peripheral adaptations, i.e. augmented red cell volume, haemoglobin (Hb) mass and maximal oxygen uptake ($\dot{V}O_{2max}$) that improve primarily systemic oxygen delivery ("erythropoietic paradigm") (9, 10), while others argue against this view and support the concept of "nonhematological" adaptations such as improved muscle efficiency, greater muscle buffering and the ability to tolerate lactic acid production (11, 12).

Conversely, the combination of intense training and hypoxia may have a negative impact on athlete's performance capacity and health status, causing unfavourable effects such as acute mountain sickness (13), immune suppression (14), iron-deficient erythropoiesis (15), cathecolamine mediated glycogen depletion (16) and increased oxidative stress and tissue damage (17), among others. Interestingly, a recent meta-analysis concluded that AT performance gains could be related to a placebo or nocebo effect (7).

There are different strategies to train at altitude. The classical approach ("live high-train high", Hi-Hi), used since the late 1960s, involves SL-resident athletes who travel to and subsequently live and train at moderate altitude. Despite being used by many elite swimmers and coaches, there is no clear evidence that training at natural altitude enhances performance more than training at SL (6). In a milestone study published in the mid-1990s, Levine & Stray-Gundersen provided evidence that the "live high-train low" (Hi-Lo) strategy can improve 3000- to 5000-m running performance in collegiate/club runners (9). Later, this approach was modified to limit the low-altitude training sessions to only high-intensity workouts and was subsequently termed "live high-train high and low" (Hi-HiLo). The improvement in running performance was associated with increase in red cell mass, the subsequent increase in maximal oxygen uptake ($\dot{V}O_{2max}$), the "high altitude effect", and the maintenance of high-intensity training velocities and oxygen flux to the muscles "the low altitude effect" (18). This paradigm has been sustained by later investigation in elite endurance athletes performing different sports including running (19), orienteering (20), and cycling (21). However, these studies are difficult to compare with each other directly given the many differences in experimental design (12).

The aims of this systematic review are: 1) to collate and to critically evaluate the empirical evidence sustaining the use of natural AT in athletes with the main goal of improving SL performance; and 2) to derive which of the different natural AT strategies is more efficient for enhancing SL performance when the athletes come back to SL training and competition. To achieve these goals, we systematically reviewed controlled and uncontrolled studies through the PubMed and SPORTDiscus databases. The studied participants were athletes from regional to elite level, the exposure of interest was natural AT, and the main outcome of interest was performance.

Methods

Literature search

This systematic review followed the PRISMA statement guidelines (22). To achieve this, a systematic literature search was conducted for studies in any language indexed in the PubMed and SPORTDiscus databases (up to March 2017). This search was performed using the following selected keywords: ALL FIELDS, altitude training AND sport AND performance, NOT simulated OR artificial OR normobaric, NOT review. To manage the bibliographic references the EndNote (ver. X7) software was used.

Eligibility criteria and study selection

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In order to be considered eligible for inclusion, studies had to meet the following criteria: 1) participants were healthy adult competitive athletes; 2) studies were controlled and uncontrolled; 3) altitude exposure was natural (classic or terrestrial, not artificial or simulated); 4) primary focus was SL performance (articles with no performance measures were excluded); 5) original studies were used only (no reviews); and 6) studies published in any language.

The flow chart of literature screening approach and study identification is displayed in figure 1. From the 325 articles initially identified, we removed 51 duplicated articles, 224 were excluded from title and abstract information, and 30 articles were excluded after reading the full text for not meeting the eligibility criteria or due to impossibility to access them. Finally, 20 studies were included in the qualitative review.

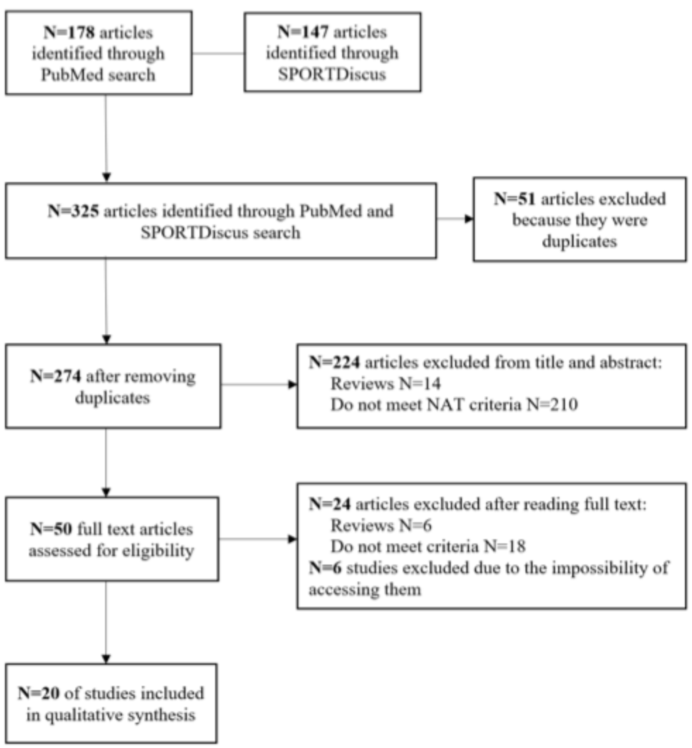

Figure 1. Flow chart of literature screening approach and study identification.

Data extraction

We developed a data extraction table classifying the type/level of athletes, altitude strategy, sample size, study design, follow up during

the intervention, living and training characteristics and effects on performance measures. Performance data extraction was done from time trials, race results, power output and total work capacity (cycle ergometry) and time scores. Weight-adjusted $\dot{V}O_{2max}$ values and selected haematological data (Hb mass, Hb blood concentration and haematocrit ratio) were also extracted.

Results

Study characteristics

A total of 20 studies, 7 controlled and 13 uncontrolled, were identified for inclusion in the systematic review. These studies involved 439 athletes, from which 173 took part in the controlled studies and 266 in the uncontrolled studies. 247 out of the total 439 participants were elite athletes (56%), and the rest were from regional/interregional to subelite level athletes (44%), a fact that can bring about large differences in performance level and range for improvement, making difficult to compare investigation results. The intervention methodologies and type of designed utilized were as follows: 14 Hi-Hi (5 controlled), 4 Hi-Lo (3 controlled), and 3 Hi-HiLo (1 controlled

Classical altitude training (Hi-Hi) controlled studies

Only 5 controlled Hi-Hi studies were identified (table 1). Using a cross-over design, Adams et al. reported no potentiating effect of hard endurance training at 2300 m over equivalent SL training on 2-mile performance time or $\dot{V}O_{2max}$ in well-conditioned middle-distance runners (23) The study by McLean et al. consisted on a Hi-Hi training camp involving a group of 21 Australian football players and 9 Lo-Lo controls. The Hi-Hi group likely improved 2000-m time trial performance by 1.5% after altitude with very large individual variability (90%CI: -3.3–6.3%) and low individual responsiveness (0.8%). This change was paralleled by a very likely increase in Hb mass (2.8%) (24). Levine & Stray-Gundersen failed to find any effect on performance after 4 weeks of Hi-Hi intervention despite an increase of $\dot{V}O_{2max}$ (3.4%) and red cell mass (10%) (9). Burtscher et al. studied two groups of amateur runners and found no group differences in cycling total work capacity between the Hi-Hi group and the Lo-Lo controls: 3 and 16 days after the intervention the Lo-Lo group improved 8% and 17% whereas the Hi-Hi group improved 0.3% and 8%, respectively (25).

Only Rodríguez et al. showed a significant improvement in swimming performance after living and training at 2320 m during 3 or 4 weeks (e.g., 3.1% and 3.4% in specific 100-m or 200-m time trial), but this change was not significantly different from that experienced by the Lo-Lo control group (3.7%) (26). Interestingly, two studies reporting increases in $\dot{V}O_{2max}$ did not find a concomitant improvement in performance compared with SL controls. In summary, only one study actually provided evidence of superior improvement of Hi-Hi altitude training compared with SL (24). However, the magnitude of these changes seems lower than can be expected because of a SL training camp, and placebo or nocebo effects cannot be ruled out.

Hi-Lo and Hi-HiLo controlled studies

Four controlled studies were identified (table 2). Levine & Stray-Gundersen were the first to use the Hi-Lo strategy in their classical study cited above (9), in which they assigned collegiate and club amateur runners to Hi-Hi, Hi-Lo, and Lo-Lo (control) groups. They reported an improvement on 5000-m running performance (1.3%) in the Hi-Lo runners three weeks after the training camp and attributed this to increased $\dot{V}O_{2max}$ (5%) and red cell mass (10%), according to the "erythropoietic paradigm". In a study by Dehnert et al. two groups of subelite triathletes followed a Lo-Lo or Hi-Lo intervention for 2 weeks and found no effects on cycling or treadmill running performance despite a 7% increase in $\dot{V}O_{2max}$ and unchanged Hb mass (27). In contrast, Wehrlin et al. (20) studied a group of 10 elite orienteers using a Hi-Lo strategy for 24 days and comparing them with 7 Lo-Lo cross country skiers, and reported an improvement in 5000-m running performance (1.6%) in the Hi-Lo group, paralleled by increased $\dot{V}O_{2max}$ (4.1%) and red cell mass (5.3%), which are comparable to previous results in runners (9). Finally, Rodríguez et al. conducted the only controlled study using the Hi-HiLo strategy in which athletes live at altitude and train at the same and a lower altitude (26). Four groups of international level swimmers were compared: Hi-Hi for 3 and 4 weeks (previously cited), and Hi-HiLo and Lo-Lo controls for 4 weeks. Although all groups improved after a well-controlled training camp, the Hi-HiLo group of swimmers further improved 50-, 100- (sprinters) or 200- (non-sprinters), and 400-m swimming performance (5.5%, 6.3% and 4.7%, respectively) 2 to 4 weeks after the training camp. However, this substantial improvement in performance could not be attributed to changes in $\dot{V}O_{2max}$, Hb mass or swimming economy and, therefore, to the "erythropoietic paradigm".

Classical altitude training (Hi-Hi) uncontrolled studies

Nine uncontrolled studies using the classical Hi-Hi strategy met the inclusion criteria (table 3). Overall, only 2 studies showed some evidence of beneficial effects on performance (28, 29) and 1 was uncertain (30).

Noteworthy, in the study by Roels et al. the modest increase in 2000-m trial (1.9%) was only significant when the swimmers lived and trained at 1200 m of altitude, but not at 1850 m (29). Moreover, another study showed a decrease in performance after 21 to 27 days of Hi-Hi intervention in four different groups (n = 97) of elite swimmers (31). The other 6 studies did not show significant changes in performance despite some modest changes in $\dot{V}O_{2max}$ (32, 33), Hb mass (31, 34), blood red cell markers (30, 35) or without haematological changes (36).

Hi-Lo and Hi-HiLo uncontrolled studies

The systematic review included 3 uncontrolled studies examining the Hi-Lo strategy and 3 studies using the Hi-HiLo strategy (table 4). These studies were conducted by mostly the same group of researchers and used similar designs and methodologies. In a retrospective study using the Hi-Lo approach, 8 out of 12 collegiate runners were classified as responders and improved their time in a 5000-m time trial by 3.6% whereas the non-responder decreased their performance time by 1.3%. The better times of the responders was paralleled by a non-significant increase in $\dot{V}O_{2max}$ (7.5%) (37). Coincident results were obtained by these authors in a prospective study with elite distance runners (37). Also Stray-Gundersen et al. reported modest but significant performance gains in 22 elite runners on a 3000-m time trial (1.1%) associated to a 3% increase in $\dot{V}O_{2max}$ (18). To identify the optimal altitude for training using the Hi-HiLo approach, Chapman et al. compared four groups of collegiate runners living at four altitudes (from 1780 to 2800 m) and training at varying altitudes from 1250 to 3000 m. They found that only the middle altitudes (i.e., 2084 and 2454 m) evoked significant gains in 3000-m time trial running performance (2.1 to 2.8%), associated to a 3% to 8% increase in $\dot{V}O_{2max}$ (38). Similarly, Saugy et al. conducted a study with 13 well-trained triathletes who lived at 220 m and trained at 1100-1200 m of altitude and found an improvement in 3000-m time trial running performance (3.3%) after 3 weeks upon return to sea level, with no changes 1 and 7 days after the altitude training camp. $\dot{V}O_{2max}$ also increased by 5.2% (39).

Study	Subjects (level)	Strategy[a]	Sample size[b]	Design[c]	Follow up[d]	Training			Effects on performance measures[e] (D% from pre-values)	Other changes		
						Altitude (m)	Duration (d)	Phase		$\dot{V}O_{2max}$	Hb_{mass}	**Other**[f]
Adams et al. 1975 (23)	Runners (middle-distance)	Lo-Lo vs. Hi-Hi	12M	CON X-over	D1-3	16 2300	20 20	?	TT 2mi: 1.3% (n.s. vs. SL)	□2.8%	?	?
Burtscher et al. 1996 (25)	Runners (amateur)	Lo-Lo vs. Hi-Hi	12M 10M	CON R Pre-post	D3,16	187 2315	12	?	CY TWC: 8% at D3, 17% at D16 □0.3% at D3, 8% at D16 (n.s. between groups)	10% at D16	?	?
Levine & Stray-Gundersen 1997 (9)	Runners (collegiate/ club level)	Lo-Lo vs. Hi-Hi	9M, 4F 9M, 4F	CON R Pre-post	D15,43, 71	150 2500-2700	28 28	?	« «	« 3.4%*		RCM « 10%*
McLean et al. 2013 (24)	Australian footballers (elite)	Lo-Lo vs. Hi-Hi	9M 21M	CON Pre-post NR	D1,30	30 ~2130	19 19	Pre-Season	TT 2km: Post1: 1.5%* (±4.8% 90%CL) Post2: trivial changes vs. Post1	?	Hi-Hi: Post1 2.8%* Post2 «	?
Rodríguez et al. 2015 (26)	Swimmers (elite)	Lo-Lo vs. Hi-Hi Hi-Hi	8F, 3M 8F, 7M 10F, 6M	CON NR Pre-post	D1,8,15,21,28	190 or 655 2320 2320	28 21 28	In-season	TT 50, 100/200, 400m: 3.2%, 3.7%, 1.6%* 3.4%, 3.1%, 0.6%* 3.7%, 3.4%, 3.3%*	« « «	« 3.8%* 6.2%*	Economy« « «

Table 1. Summary of CONTROLLED studies on natural altitude training using the Hi-Hi strategy for sea level performance enhancement.

[a] Lo-Lo, live low–train low; Hi-Hi, live high–train high.
[b] F, females; M, males.
[c] CON, controlled trial; UN, uncontrolled trial; R, randomised; NR, non-randomised; X-over, cross-over
[d] D#, testing post-intervention (day number).
[e] TT, time trial in specific sport; CY, cycling test; TWC, total work capacity; TM, treadmill test.
[f] RCM, red cell mass; RCV, red cell volume.
↑, improvement/increase/benefit; <—>, no change; ↓, worsening/decrease/harm; =, same as ab

*, significantly different from values measured before training or compared to sea-level controls ($p<0.05$); n.s., non-significant difference ($p\geq0.05$); ?, uncertain/not reported.

Study	Subjects (level)	Strategy[a]	Sample size[b]	Design[c]	Follow up[d]	Training			Effects on performance measures[e] (D% from pre-values)	Other changes		
						Altitude (m)	Duration (d)	Phase		$\dot{V}O_{2max}$	Hb_{mass}	**Other**[f]
Levine & Stray-Gundersen 1997 (9)	Runners (collegiate/ club level)	Lo-Lo vs. Hi-Lo	9M, 4F 9M, 4F	CON R Pre-post	D15,43,71	150 L 2500, T 1250	28 28	?	« TT 5km 1.3%*	« 5%*		RCM « 5.3%*
Dehnert et al. 2002 (27)	Triathletes (subelite)	Lo-Lo vs. Hi-Lo	8M, 3F 7M, 3F	CON R Pre-post	D7,14	800 L 1956, T 800	14	?	« « Incremental CY ramp, « TM tests, n.s. trend to improve running time	« 7%	« «	? ?
Wehrlin 2006 (20)	Orienteers and cross country skiers (elite)	Lo-Lo vs. Hi-Lo	3M, 4F 5M, 5F	CON NR Pre-Post	D10	500-1600 L 2500, T 1000-1800	24 24	Pre-season	No measures in Lo-Lo group TT 5km 1.6%	? 4.1%	« 5.3%	
Rodríguez et al. 2015 (26)	Swimmers (elite)	Lo-Lo vs. Hi-HiLo	8F, 3M 4F, 8M	CON NR Pre-post	D1,8,15, 21,28	190 or 655 L/T 2320, T 690	28 28	In-season	TT 50, 100/200, 400m: 3.2%*, 3.7%*, 1.6%* 5.5%*, 6.3%*, 4.7%* (Hi-HiLo > Lo-Lo*)	« «	« 1.3%	« Economy « Economy

Table 2. Summary of CONTROLLED studies on natural altitude training using the Hi-Lo or Hi-HiLo strategies for sea level performance enhancement.

[a] Lo-Lo, living low, training low; Hi-Lo, live high–train low; Hi-HiLo, live high–train high and low; L, living; T, training.
[b] F, females; M, males. -over, crossover; R, randomised; NR, non-randomised.
[d] D#, testing post-intervention (day number).
[e] TT, time trial in specific sport; CY, cycling test; TM, treadmill test.
[f] RCM, red cell mass; RCV, red cell volume.
, improvement/increase/benefit; «, no change; ¯, worsening/decrease/harm; =, same as above.
*, significantly different from values measured before training or compared to sea-level controls (p<0.05); n.s., non-significant difference (p≥0.05); ?, uncertain/not reported.

Study	Subjects (level)	Strategy[a]	Sample size[b] e s	Design[c]	Follow up[d]	Training		Effects on performance measures (D% from pre-values)[e]	Other changes			
						Altitude (m)	Duration (d)	Phase		$\dot{V}O_{2max}$	Hb_{mass}	Other[f]
Faulkner et al. 1967 (35)	Swimmers, fit men	Hi-Hi	16M 5M	UN Pre-post	D1	2300	23 14	?	«Tethered swimming 100, 200, 500 yd	«	«	Hb10%* Htc4%*
Faulkner et al. 1968 (32)	Runners (subelite)	Hi-Hi	5M 5M 4M	UN Pre-post	D4 to D13	2300 2300-3100 4300-2300	42 35 38	?	?TT 1mi 1.2% ?TT 2mi -0.5% ?TT 3mi 2.3%	2%	2%	?
Mizuno et al. 1990 (28)	X-country skiers (subelite)	Hi-Hi	10M	UN Pre-post	?	2100 2700	14 14	?	TM running time to exhaustion 17%*	«	?	29 O_2 deficit 6% buffer capacity
Roels et al. 2006 (29)	Swimmers (elite)	Hi-Hi Hi-Hi	9M	UN X-over	D1,3,15,17	1200 1850	13 13	?	TT 2km: 1.9%* «	« «	« «	RBC: « «
Schmitt et al. 2006 (33)	X-country skiers, swimmers, runners (elite)	Hi-Hi	20M	UN Pre-post	D1,15	1200	18	Balanced training load	«CY PPO 1.9%	3.3%*		economy 7%*
Hue et al. 2007 (36)	Swimmers, (regional/ interregional)	Hi-Hi	2F, 6M	UN Pre-post	D10,30	1800	8	Competitive period	«	?	?	?
Siewierski et al. 2012 (30)	Swimmers (elite)	Hi-Hi	6M, 2F	UN Pre-post	Race results pre-post	2300	23	Competitive period	? 3.1% pts	?	?	RBC: 14.4% Hb: 13.5% Htc: 14.8%
Gough et al. 2012 (34)	Swimmers (elite)	Hi-Hi	14M, 3F	UN Pre-post	D1,7,14,28	2135-2323	21	?	«	?	4%*	
Wachsmuth et al. 2013 (31)	Swimmers (elite)	Hi-Hi1 Hi-Hi2 Hi-Hi3 Hi-Hi4	13M, 6F 6M, 4F 5M, 2F 4M, 7F	UN Pre-post	All racing results	2320 2320 2320 1360	27 26 21 23	Two years preparation for Olympic Games	D0-14 ¯11 pts D15-24 ¯4 pts D25-35 ¯2 pts	?	6.5% 7.2% 8.6% 3.8% 3%M, 2,7%F	?

Table 3. Summary of UNCONTROLLED studies on natural altitude training us

[a] Lo-Lo, living low, training low; Hi-Hi, live high–train high; L, living; T, training.
[b] F, females; M, males.
[c] CON, controlled trial (vs. sea level); UN, uncontrolled trial (vs. sea level); X-over, crossover; R, randomised; NR, non-randomised.
[d] D#, testing post-intervention (day number).
[e] TT, time trial in specific sport; CY, cycling test; PPO, peak power output; TM, treadmill test; Re, responders; NRe, non-responders; pts, FINA score points.

[f] RCM, red cell mass; RCV, red cell volume.
, improvement/increase/benefit; «, no change; ¯, worsening/decrease/harm; =, same as above.
*, significantly different from values measured before training or compared to sea-level controls ($p<0.05$); n.s., non-significant difference ($p\geq0.05$); ?, uncertain/not reported.

Study	Subjects (level)	Strategy[a]	Sample size[b]	Design[c]	Follow up[d]	Training			Effects on performance measures (D% from pre-values)[e]	Other changes		
						Altitude (m)	Duration (d)	Phase		VO_{2max}	Hb_{mass}	Other
Chapman et al. 1998 (retrospective) (37)	Runners (collegiate)	Hi-Lo	4F, 9M	UN Pre-post	D3	L 2500 T 1200-1400	28	?	R (n=8) TT 5km 3.6*% NR (n=4) ?¯ TT 5km -1.3%	R 7.5%* NR <–>	?	Hb: R 9.5* NR 8.0* Htc: R5.9* NR 7.9*
Chapman et al. 1998 (prospective) (37)	Distance runners (elite)	Hi-HiLo	8M, 14M	UN Pre-post	D3	L 2500 T 1200-1400	20	?	R (n=9) TT 3km -5.8s* NR (n=5) « TT 3km	R 3.4 ml/ kg·min NR <–> (n.s.)		
Stray-Gundersen et al. 2001 (18)	Runners (elite)	Hi-HiLo	8F, 14M	UN Pre-post	D3	L 2500 T 1250	27	Near season's fitness peak	TT 3 km: 1.1%*	3%		1 g/dl
Chapman et al. 2013 (38)	Distance runners (collegiate)	Hi-HiLo Hi-HiLo Hi-HiLo Hi-HiLo	4F, 6M 4F, 7M 4F, 8M 4F, 8M	UN Pre-post	D1,14	L 1780 L 2084 L 2454 L 2800 (T 1250-3000)	28	?	TT 3 km: « 2.1%*D1, 2.2%*D14 2.8%*D1, 2.1%*D14 <–>	2% D1, 4%* D14 3%* D1, 5%* D14 4%* D1, 8%* D14 6%* D1, 4%* D14	? ? ? ?	RCM: 7.0% 6.3% 6.2% 6.3%
Saugy et al. 2014 (39)	Triathletes (well trained)	Hi-Lo	13M	UN Pre-post	D1,7,21	L 2250 (T 1100-1200)	18	Competitive season	TT 3 km: « at D1, D7 3.3%* at D21	5.2%	1.8%	PPO: 6.6%

Table 4. Summary of UNCONTROLLED studies on natural altitude training using the Hi-Lo or Hi-HiLo strategies for sea level performance enhancement.

[a] Lo-Lo, living low, training low; Hi-Hi, live high–train high; L, living; T, training.
[b] F, females; M, males.
[c] CON, controlled trial (vs. sea level); UN, uncontrolled trial (vs. sea level); X-over, crossover; R, randomised; NR, non-randomised.
[d] D#, testing post-intervention (day number).
[e] TT, time trial in specific sport; CY, cycling test; PPO, peak power output; TM, treadmill test; Re, responders; NR, non-responders; FINA pts, FINA score points.
[f] RCM, red cell mass; RCV, red cell volume.
, improvement/increase/benefit; «, no change; ¯, worsening/decrease/harm;
=, same as above.
*, significantly different from values measured before training or compared to sea-level controls (p<0.05); n.s., non-significant difference (p≥0.05); ?, uncertain/not reported.

Discussion

This systematic review, which aimed at assessing the empirical evidence sustaining the use of AT in athletes with focus on SL performance enhancement, does not appear sufficiently robust to determine the efficacy and appropriate characteristics (duration, altitude and training requirements) of an AT camp. Neither it can conclude which of the natural AT strategies is best for enhancing performance at SL. The reviewed studies are difficult to compare with each other directly, given the many differences in experimental design, type of participants, outcome measures and methodology. Notwithstanding, there seems to be a certain consensus—perhaps lacking compelling evidence to support it—that when athletes are exposed to a high enough altitude, for a long enough amount of time, and are able to preserve fitness by training hard under both hypoxic and normoxic conditions, the majority may improve physical performance (40).

We have reviewed publications from 1967 to 2017, a 50-year period. A total of 20 studies have been appraised, but only 7 published articles (33%) had a controlled design. The remaining 14 studies (67%) were uncontrolled and provide low quality evidence since performance changes can be attributed to training alone, training camp effect or placebo/nocebo effect. Concerning the 5 controlled Hi-Hi studies, only the one published by MacLean et al. (24) provided limited evidence of superior improvement compared with SL controls, although the high interindividual variability (-3.3–6.3%) argues against a real AT effect and placebo/nocebo effects cannot be ruled out.

In the last decade the Hi-Lo approach has gained interest over the classical Hi-Hi strategy in the scientific literature and among many endurance athletes (4). In our review, the results of the 4 controlled Hi-Lo or Hi-HiLo studies seem somewhat more convincing compared with those using the classical Hi-Hi approach. In their milestone study, Levine & Stray-Gundersen showed that the Hi-Lo strategy evoked an increase in 5000-m time trial performance (1.3%) in collegiate and club runners (9), despite some researchers argue that this modest improvement could be attributed to a placebo or nocebo effect, as another Hi-Hi group showed the same improvement in $\dot{V}O2\underline{max}$ and red cell mass without any change in performance (1). Similar limitations can be attributed to the study by Wehrlin et al. since the improved 5000-m running performance (1.6%) lacked of concomitant performance measures in the control group (20). A recent investigation was the first to show substantial performance improvements after a terrestrial Hi-HiLo intervention using a controlled design (26). This investigation showed that SL swimming performance of elite swimmers in 100- (sprinters) or 200-m (non-sprinters) time trials was not altered, or in some cases impaired immediately, but improved significantly by ~3.1–3.7% after 1 to 4 weeks of recovery following completion of a coach-prescribed training camp, whether it was conducted at SL or at moderate altitude (2320 m). By including 2 weekly sessions of high-intensity training at lower altitude (Hi-HiLo strategy) a greater improvement in performance occurred 2 and 4 weeks after the training camp (5.3% and 6.3%, respectively). Similarly, further gains in 400- and 50-m freestyle time trial performance was noted 2 weeks (4.2% and 5.2%, respectively) and 4 weeks (4.7% and 5.5%, respectively) following return to SL. In addition, this study shows that the delayed performance improvements are not linked to changes in $\dot{V}O2\underline{max}$, oxygen kinetics or Hb mass and hence cannot be attributed exclusively to an enhanced systemic oxygen transport capacity.

Globally, these results are in line with estimations published in a meta-analytic review by Bonetti & Hopkins, who concluded that "performance changes in studies using the conventional Hi-Hi approach were unclear, whereas changes using the terrestrial Hi-Lo strategy were considered likely to be effective both for elite and subelite athletes (~4%), or a more realistic 1.5% when performance was predicted from uncontrolled studies" (7). These estimations are in line with a recent review by Saunders et al. (5) in which, by using a regression analysis of average performance changes, it was estimated that a 3-week terrestrial AT camp would elicit mean performance improvements of ~1.8% (Hi-Hi) and ~2.5% (Hi-Lo) (5).

Levine and Stray-Gundersen were the first to test the hypothesis that acclimatization to moderate altitude (2500 m) plus training at low altitude (1250 m) (Hi-Lo paradigm) improves SL performance in well-trained runners more than in equivalent SL or Hi-Hi controls (9). They also concluded that the correlation between the increase in $\dot{V}O2\underline{max}$ and the improvement in 5000-m time after the field training camp argues strongly that this is a key adaptation during altitude training and a necessary mechanism for improving SL performance. Despite this, the performance gain was only 1.3% from pre-training values. Notwithstanding, this study changed the previous AT paradigm that was only focussed on the classical Hi-Hi strategy.

Concerning the 9 uncontrolled Hi-Hi studies included in this review, we can see a very similar picture as for the controlled studies, since only two studies showed some beneficial effects on performance (28, 29), one was uncertain (30), and 1 even showed impaired performance after in a very large number of elite swimmers (31).

Among the uncontrolled Hi-Lo or Hi-HiLo investigations, two (37) should be analysed with caution as the participants, collegiate or elite runners, were categorized post-facto into 'responders' and 'non-responders', as they aimed at investigating the individual variation in response to AT. The other 2 studies showed performance changes similar to the controlled groups, although the risk of placebo or nocebo effects is exacerbated. Interestingly, moderate altitudes of ~2100-2500 m were identified as optimal for benefits in 3000-m running performance (41).

Conclusions

There are several limitations in every study design using terrestrial AT, including the impossibility of blinding the intervention, limitations in recruiting large numbers of participants, difficulties in group randomisation, control of placebo and nocebo effects, large variability in the response, etc. These barriers make difficult the comparison of the existing studies and the design of new investigations that can meet the high standards of scientific research.

Contrary to common expectations, the systematic review of 20 articles published along 50 years (1967 to 2017) shows that the quality of the empirical evidence about using natural altitude training in competitive athletes with the main goal of improving sea level performance is far from being compelling. However, the available evidence supports the concept that the Hi-Lo and Hi-HiLo strategies offer the best potential for performance benefits, as at least two controlled studies provided sound evidence of positive effects on performance in collegiate/club runners and elite swimmers, respectively. Uncontrolled studies also support this concept despite the lower quality of the evidence.

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