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REVIEW

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Effects of Hyperoxic Training on Human Performance

Auswirkungen des hyperoxischen Trainings auf die menschliche Leistungsfähigkeit

Summary

- **In contrast to** the various acute and chronic responses to hypoxia (i.e., lowering of the partial pressure of oxygen in the air, for example by various forms of altitude training), far less is known about the responses to acute, and especially to chronic exercise in hyperoxia (i.e. elevation of the fractional oxygen content of air). The acute exposure to hyperoxia while exercising improves e.g. oxygen uptake and neural drive and lowers levels of blood lactate and ratings of perceived exertion.
- **Therefore,** training in hyperoxia may allow higher exercise intensity, thus imposing a greater physiological training stress. With this systematic review (n=7 studies; years: 1996-2016), we aimed to analyze the medium-term ergogenic properties of hyperoxic vs. normoxic training.
- **Based on the existing data** for cycling and running (3-6 wks with 2 to 5 sessions per week) in hyperoxia (oxygen fraction 0.60-1.00) vs. normoxia, we conclude that hyperoxic training improves performance (Cohen's d=1.79) and oxygen uptake (d=0.57) in normoxia to large and medium extents, respectively. Future studies are warranted to investigate the long-term performance and health effects of hyperoxic training for athletes in different disciplines.

Zusammenfassung

- **Akute Reaktionen** und chronische Anpassung auf Sauerstoffmangel (induziert bspw. durch verschiedene Formen des Höhentrainings) sind mittlerweile gut evaluiert. Im Gegensatz dazu sind die akuten Reaktionen und vor allem aber die mittel- und längerfristigen Anpassungen durch Einatmung erhöhter Sauerstoffkonzentration (Hyperoxie) recht unerforscht. Akute Sauerstoffatmung erlaubt höhere Belastungsintensitäten im Vergleich zu Training in Normoxie. Sauerstoffatmung während körperlicher Arbeit verbessert u. a. die Sauerstoffaufnahme und reduziert gleichzeitig den Blutlaktatspiegel und das subjektives Belastungsempfinden.
- **Es wird vermutet,** dass der höhere hyperoxiebedingte Trainingsreiz im Vergleich zum Training in Normoxie mittel- und langfristig höhere Anpassungen, z. B. höhere Leistungsfähigkeit in Normoxie bewirkt. In diesem systematischen Übersichtsartikel (n=7 Studien aus den Jahren 1996-2016) wurden die mittelfristigen, leistungssteigernden Eigenschaften von Training mit Sauerstoffatmung im Vergleich zu Training in Normoxie analysiert.
- **Auf Grundlage der vorhandenen Daten** für Laufen und Radfahren (Trainingsstudien über 3-6 Wochen mit 2-5 Einheiten pro Woche) scheint Hyperoxietraining (fraktioneller O_2-Anteil: 0.60-1.00) im Vergleich zu Normoxietraining die Leistungsfähigkeit (Cohen's d=1.79) und die maximale Sauerstoffaufnahme (d=0.57) mit großen bzw. mittelgroßen Effekten zu verbessern. Zukünftige Studien müssen die längerfristigen Effekte von Hyperoxietraining im Hinblick auf die körperliche Leistungsfähigkeit und Gesundheit von Athleten/innen unterschiedlicher Sportarten untersuchen.

KEY WORDS:
Acclimation, Fatigue, Cycling, Running
Oxygen Uptake, Oxygen Partial Pressure,
Systematic Review

SCHLÜSSELWÖRTER:
Adaptation, Ermüdung, Laufen, Radfahren,
Sauerstoffaufnahme, Sauerstoffpartialdruck,
Systematisches Review

Introduction

In contrast to what is known about the various acute and chronic responses to hypoxia (i.e., the lowering of the inspiratory oxygen partial pressure) far less is known about the acute and especially the chronic responses to exposure to hyperoxia (i.e. elevation of the fractional oxygen content ($F_{in}O_2$) of the air).

Two recent reviews have extensively dealt with the various physiological responses to elevation of $F_{in}O_2$ at rest, during exercise, and during recovery (3, 27). In hyperoxia, oxygen content of the arterial blood augments primarily due to physically dissolved oxygen, since arterial haemoglobin is nearly fully saturated in normoxia (27). With elevated $F_{in}O_2$ the arterial pO_2 increases and the pO_2-gradient between blood and tissue (the primary determinant of the rate of oxygen diffusion) reduces the ›

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Table 1

Summary of studies comparing exercise in normoxia vs. hyperoxia. $F_{in}O_2$=inspired oxygen content; TTE=time-to-exhaustion; TT=time trial; n.d.=no difference between hyperoxia and normoxia; HR_{max}=maximum heart rate; VO_2peak=peak oxygen uptake; MAS=maximal aerobic speed; PPO=peak power output; HE=hyperoxic training group; CON=Control training group; M=Male; F=Female.

AUTHOR	REF	MODE OF EXERCISE	$F_{IN}O_2$	N	INTERVENTION	PRE-TO-POST CHANGES			
						VO_2PEAK	STROKE VOLUME	TTE/TT	OTHER MEASURES
Ploutz-Schneider et al. 1996	(23)	cycling	0.70	19 M untrained 8 HE; 11 CON)	5 wks; 5 sessions/wk 40 min at 70% HR_{max}	+25.8% HE +18.4% CON	+9.8% HE +19.9% CON		
Armstrong et al. 2000	(2)	cycling	0.80	12 M, 5 F regularly active (9 HE; 8 CON)	5 wks; 3 sessions/wk 40 min at 60% VO_2peak	+14.6% HE +7.3% CON n.d.		+314% HE +156% CON n.d.	
Perry et al. 2005	(20)	cycling	0.60	8 M, 3 F untrained (12 HE; 12 CON; cross-over design)	6 wks; 3 sessions/wk 10x4 min intervals at 80% VO_2peak	+8.3% HE +6% CON n.d.		TTE at 90% VO_2peak +117% HE +50% CON	
Perry et al. 2007	(21)	cycling	0.60	6 M, 3 F recreational (9 HE; 9 CON; cross-over design)	6 wks; 3 sessions/wk 10x4 min at 90% VO_2peak	+11% HE +12% CON n.d.		TTE at 90% VO_2peak +129% HE +129% CON n.d.	
Kilding et al. 2012	(10)	cycling	0.60	14 M well-trained (8 HE; 8 CON)	4 wks; 2 sessions/wk 12x2 min, 5x5 min as much work as possible	+1.9% HE +4.7% CON n.d.		20km TT +2.1% HE +4.9% CON n.d.	
Murray et al. 2016	(18)	Running for hockey players	1.00	15 F trained (5 HE; 5 Normoxia; 5 CON)	6 wks; 2 sessions/wk 7-12x2min at 85% MAS				MAS: +1% HE & Normoxia +1.8% CON n.d.
Burgos et al. 2016	(4)	Cycling for soccer players	1.00	12 M trained (6 HE; 6 CON)	3 wks; 5 sessions/wk 30 min at 75% VO_2peak	+13.4 HE -9.2 CON			PPO: +12.7 HE -8.3 CON

limitations in peripheral diffusion thereby explaining improved oxygen utilization in hyperoxia (27). This chain of mechanism may be especially important during exercise because during heavy exercise the arterial oxygen saturation may decline notably (31) thus hyperoxia is a measure to diminish exercise-induced hypoxemia.

The main acute responses of hyperoxic exposure explaining improved performance are briefly summarized in Figure 1.

Based on a recent summary (26) we may conclude that acutely elevated $F_{in}O_2$ (>0.21-1.00) increases power output by 2-17% during both maximal and submaximal cycling (1, 8, 9, 11, 12, 13, 14, 19, 22, 24, 25, 28, 29, 30). Exercising while breathing elevated $F_{in}O_2$ (compared to normoxia) may provide a greater overall physiological stimulus because (although not exclusively) of elevated oxygen uptake and neural drive (27) both allowing to cycle with increased power output or run with higher speed. The greater workload during training in hyperoxia might induce greater gains of performance when compared to exercise in normoxia. However, it remains unclear whether the greater acute workload in hyperoxia will translate to increased normoxic performance over a longer period.

The aim of this brief systematic review was to investigate existing studies involving hyperoxic training and analysing the pre to post medium-term changes (3-6 weeks) in performance related variables in comparison to normoxic training.

Methods

Data Sources and Literature Survey

A systematic review was conducted employing a comprehensive computerized search of the electronic databases PubMed and SPORTDiscus during September 2018, with no restriction for the publication year. We employed the following search terms: "hyperoxia" OR "oxygen supplementation" OR "inspired oxygen" AND "performance" OR "training". The search was limited to original research studies published in peer-reviewed journals written in English. The titles and abstracts of identified articles were then assessed against the inclusion criteria. Then, full-text articles that passed the initial level of assessment were retrieved and assessed against the same inclusion criteria. In addition, the reference lists of the identified articles were manually scrutinised for additional applicable titles.

Inclusion and Exclusion Criteria

Studies were considered eligible according to the following criteria: (1) intervention group exposed to >2 sessions per week of $F_{in}O_2$>0.21 for 3-wks or longer; (2) invervention group compared to a control group with the same amount of normoxic training sessions; and (3) pre- and post-testing took place in normoxia. Exclusion criteria: Studies without a normoxic control group were excluded, as well as studies without physiological measurements before and after the training period.

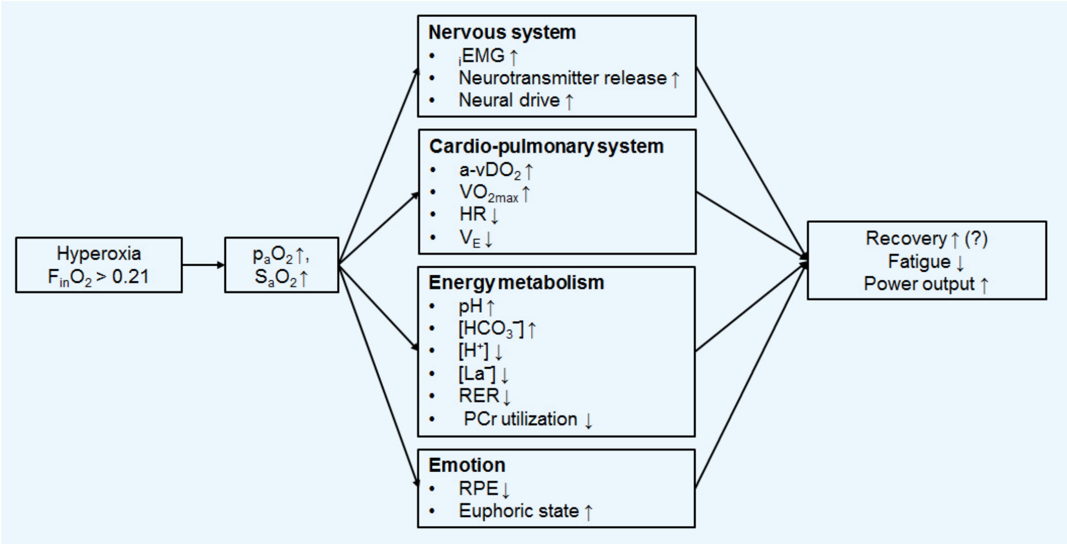

Figure 1

Various main acute responses when exposed to hyperoxia compared to normoxia (adapted from (27)).

Effect sizes were calculated by using the between-group difference of the pre- and post-intervention means divided by the pooled baseline standard deviation (16). According to Cohen's guidelines, a value of 0.2-0.49 denotes a small, 0.5-0.79 a medium, and >0.8 a large effect size (6). A negative effect size for a certain variable denotes that normoxic training is superior to hyperoxic training for that variable.

Results

To the best of our knowledge, seven studies (2, 4, 10, 18, 20, 21, 23) have investigated various physiological outcomes in connection with exercise in hyperoxia vs normoxia over a period greater than 3-wks. One study (17), employing a 5-wk (5 sessions/wk) one-legged knee extensor ($F_{in}O_2$=0.60) in six male participants was designed without a control group and was therefore excluded from further analysis. The main intervention characteristics and outcomes of all included studies are summarized in Table 1.

Overall, 97 participants took part in all studies, a total of 71 male and 26 female participants. The $F_{in}O_2$ for training in all studies ranged from 0.60 to 1.00. The intervention period ranged from 3 to 6 weeks, with 2 to 5 sessions per week. The main training modality was cycling (six studies), with one study implementing running (18). Four studies (10, 18, 20, 21) involved high-intensity interval training as the main training method, and the other three studies (2, 4, 23) employed constant submaximal intensity exercise during the intervention period (Table 1).

Most studies in which maximal oxygen uptake ($\dot{V}O_2$peak) was measured showed improved $\dot{V}O_2$peak after hyperoxic training. Two investigations showed significantly higher improvements in $\dot{V}O_2$peak after hyperoxic vs normoxic training (23, 4). One study showed decreased $\dot{V}O_2$peak in the control group after training (4). Performance improved in all hyperoxic training groups as well as in the control groups, except for the control group of one study (4).

Cohen's d (effect size) calculations for changes in $\dot{V}O_2$peak after hyperoxic (compared to normoxic) training are summarized in Figure 2 they ranged from small negative to large positive effects. The mean Cohen's d (d=0.57) for changes of $\dot{V}O_2$peak after hyperoxic vs. normoxic training showed a medium positive effect (Figure 2). The effect sizes (d) of the six studies measuring performance variables (i.e. time trials, maximal aerobic speed, peak power output) ranged from -0.56 to 6.29 (Figure 3). The mean effect size for performance was large (d=1.79).

Discussion

As initially described, evidence indicates that normobaric hyperoxia during exercise significantly improves performance by 3-30% (depending on the duration and level of exercise intensity, modality and level of $F_{in}O_2$ (27).

One motivation for exposing an athlete to an elevated fraction of oxygen is the assumption that "training in hyperoxia allows to exercise at higher intensities, thus imposing a larger physiological training stress" (15). Based on the existing data regarding exercise (3-6 wks with 2 to 5 sessions per week) in hyperoxia vs normoxia and our effect size calculations, we conclude that hyperoxic training as well as normoxic training improves performance and oxygen uptake to large and medium extents, respectively. The current findings are based on cycling and running, both forms of exercise that are predominantly limited by oxygen uptake, transport and utilization. Earlier data (3, 27) provide a solid overview of the potential benefits of hyperoxia for alteration in circulation and metabolism (for detail please see Figure 1), together explaining greater and longer exercise intensity when $F_{in}O_2$ is altered on an acute basis. The main acute (although not exclusive) physiological mechanisms of hyperoxia vs. normoxia for performance improvements include: (i) elevated arterial oxygen saturation; (ii) increased arterio-venous oxygen difference; (iii) elevated cardiac output; and (iv) lowered blood lactate concentration at a given intensity. All these mechanisms, taken together, assist in improving oxygen uptake, transport and utilization when athletes are exposed to hyperoxia, and explains why, for example, runners or cyclists may exercise for a longer time or at higher intensity in hyperoxia vs normoxia. Based on our analysis with untrained, recreational and well-trained individuals we may conclude that chronic exposure to hyperoxia (i.e. 2-5 sessions/week for 3-6 week with $F_{in}O_2$=0.60-1.00) may improve time-trial performance and time-to-exhaustion in cycling by 140±129% vs 85±70% (2, 10, 20, 21). ›

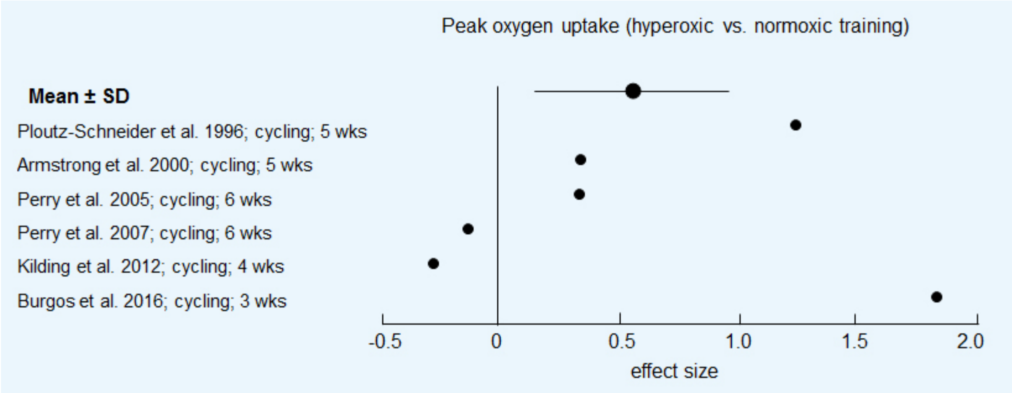

Figure 2

Effect sizes of peak oxygen uptake between hyperoxic and normoxic training groups.

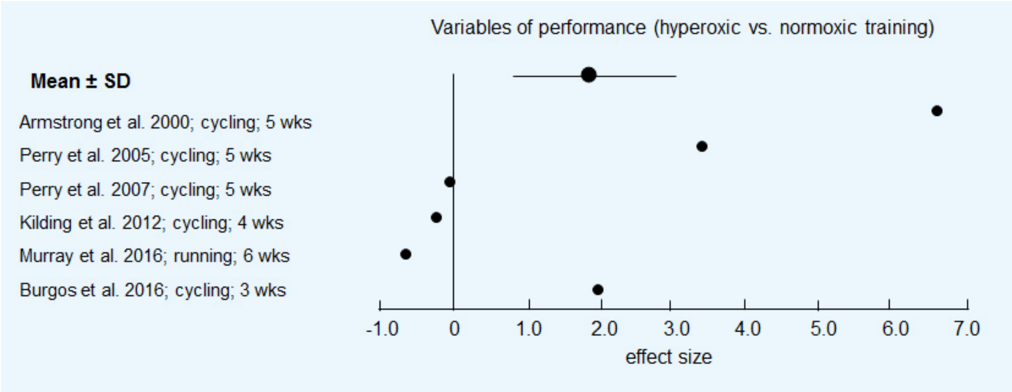

Figure 3

Effect sizes of variables of performance (i.e. time trials, maximal aerobic speed, peak power output) between hyperoxic and normoxic training groups.

However, it remains unclear whether hyperoxic training applied to elite endurance athletes with already substantial adaptations to their oxygen transporting and utilizing system may further benefit from this type of training.

As shown in Table 1, the studies in our analysis vary largely in the type and intensity of exercise, number of participants, $F_{in}O_2$, and number of sessions per week, which prevents us from drawing strong conclusions regarding the ergogenic potential of hyperoxia training. Unfortunately, due to the low amount of studies a more detailed sub-group analysis regarding the influence of the training intensity was not possible. Furthermore, only one study was conducted solely with female participants which makes it impossible to draw conclusions about potential sex differences of hyperoxic training. Currently two other reviews (although with fewer studies analyzed) have also investigated the potential benefits of hyperoxic training on performance concluding, “there was a large overall effect of training in hyperoxia on exercise performance” (15) and “[…] a likely positive effect on performance compared to normoxic training“ and “[…] unclear effect on $\dot{V}O_2$max” (5).

Further Consideration

Although the use of supplemental oxygen is not prohibited by the World Anti-Doping Agency, recent data (27) clearly demonstrates that acute exposure to hyperoxia results in instant, unnatural enhancement in performance both at sea-level and elevated altitude. This has stimulated others to pose the question whether the use of hyperoxia in sports is safe and ethical (26).

In this context it is known that chronic exposure to hyperoxia (depending on its duration and the level of $F_{in}O_2$) may induce health problems as a result of cell damage or dysfunction (7) due to the elevated levels of reactive oxygen species, and thus, hyperoxia should therefore be administered with care, if at all. Exercising at higher intensity and for a longer period of time may also elevate the chances an athlete will exercise at too-high chronic workloads with the associated risk of developing symptoms of overtraining. Hence, careful monitoring of recovery seems paramount with hyperoxic training.

Currently, our knowledge of hyperoxic training is limited to the findings of studies involving an intervention period of 3-6 wks (with 2 to 5 sessions per week) in subelite endurance athletes. A question arises as to whether simply including more sessions, or sessions at higher normoxic intensity, would have resulted in similar adaptations. Longer intervention periods involving more sessions per week may be necessary to allow more concise findings.

Conclusion

Based on the existing data regarding hyperoxic vs. normoxic training (3-6 wks with 2 to 5 sessions) and our effect size calculations, we conclude that hyperoxic training improves performance and peak oxygen uptake to large and medium extents, respectively. For athletes seeking performance improvement, exposure to hyperoxia during training may enhance performance. Since the long-term responses to hyperoxic training are unclear, and health concerns may arise from frequent use of high concentrations of oxygen, we recommend approaching such training with caution.

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Conflict of Interest

The authors have no conflict of interest.

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