Review

Is resistance exercise with controlled frequency breathing superior to training of the same program with normal breathing? – future challenges

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The specific internal environment in the body during exercise can influence the muscle hypertrophy and strength response. Unlike chronic hypoxic exposure, exercise training under intermittent hypoxia may lead to muscle hypertrophy with relatively low workloads.

Objectives: The purpose of this brief review is to discuss how a hypoxic condition can be attained without providing ambient inspiratory hypoxic gases or inducing hypobaric hypoxia.

Design and Methods: Evidence-based implications and future challenges.

Results: Pulse oximetry is a simple method that measures percutaneous oxygen saturation (SpO_2). Several studies reported that hypoxia is produced with increasing duration of apnea, especially in the last half of the breath-hold, with SpO_2 reaching levels as low as 80%. Similarly, studies have reported changes in SpO_2 during dynamic exercise at various workloads with controlled frequency breathing.

Conclusions and future challenges: These results suggest a possibility that moderate- or high-intensity exercise combined with controlled frequency breathing may produce a low level of SpO_2, which may be a model for muscle hypertrophy by moderate- or high-intensity exercise training with hypoxia. However, there are no published studies on the effects of resistance exercise with controlled frequency breathing on muscle size and function. Additionally, it is unclear the magnitude change in SpO_2 during resistance exercise with a combination of different frequencies of breathing and various workloads. Furthermore, the safety of such a technique, particularly with respect to hypercapnia and the possible elevation of arterial pressures, is also unknown and should be investigated further.

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Key words: hypoxia ■ muscle hypertrophy ■ apnea ■ breath holding

Introduction

The specific internal environment in the body during exercise can influence the muscle hypertrophy and strength response. High altitude mediated hypobaric hypoxia creates many morphological and physiological changes. One study reported that thigh muscle cross-sectional area (CSA) decreased by 10% after sojourn at high altitude (Himalayas, greater than 5000 m for over 56 days), although whether changes in physical activity and food intake occurred is not clear. In that study, the loss of thigh muscle size was mainly due to a decrease in myofibrillar proteins.[1] Mizuno et al[2] also reported that muscle fiber CSA decreased at an average of 15% in the vastus lateralis and biceps brachii muscles in both active and less active men after 75 days of altitude (greater than 5250 m) exposure. Tanner and Stager found that energy intake, in part, accounts for changes in body composition variables during a 21-day expedition between 2200 m and 4300 m altitude.[3] However, some studies have reported that no significant changes occur in muscle fiber CSA following ~8 weeks of high altitude exposure.[4,5] In the study by Lundby et al[4], subjects had free access to physical activities such as jogging, hiking, and soccer, which may have counteracted the acute disuse muscle atrophy. In addition, a recent study investigated the effects of chronic hypobaric hypoxia on muscle protein metabolism and suggested that whole body amino acid flux is increased due to an elevated protein turnover. Furthermore, the myocontractile protein synthesis rate is elevated following chronic hypobaric hypoxia.[6] Therefore, the large increase in protein degradation is the underlying mechanism for the loss of skeletal muscle mass under high altitude mediated hypobaric hypoxia;[6,7] although total time of exposure, the degree of hypoxia, food intake, and physical activity levels may all be influencing factors.

In contrast to chronic hypobaric hypoxia, one study found that muscle fiber size increased after exposure to intermittent normobaric hypoxia. In this study, subjects performed bicycle ergometer exercise (70-80% of VO_{2max}; VO_{2max} was measured in an ambient fractional oxygen concentration [FIO_2] of 11.6%, equivalent to an altitude of 4800 m) for 3 weeks under normobaric hypoxia (ambient FIO_2 decreasing from 12.7% to a final level of 10%) with recovery in normoxia.[8] Furthermore, a recent study found that intermittent systemic

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hypoxia high-intensity (70% 1RM) resistance training increases muscle hypertrophic responses more than that of a normoxia condition in young men.[9] However, Friedmann et al[10] reported low-intensity (30% 1RM) resistance training combined with hypoxia (FIO_2 12%) did not promote either muscle hypertrophy or strength gains. Despite these findings, the influence of more severe hypoxia (arterial oxygen saturation ~80% during exercise sessions) combined with low-intensity exercise has been tested and contrasting results have been reported.[11] The authors examined the effects of a 5-week low-load resistance exercise training program (20% 1RM, 3 days per week) combined with severe normobaric hypoxia upon muscle morphology and function in young women athletes. The authors concluded that substantial increases in strength and muscle CSA are observed following low load resistance training under hypoxia.[11] One reason for the different results as compared to other studies may be the duration of exercise as the duration of hypoxic exposure during the exercise session was relatively shorter (12-13 min) than previous studies (Table 1). However, potential effects of the menstrual cycle were not controlled for in this study and it is possible that premenustral fluid retention may have affected muscle hypertrophy.[12] Mechanistically, it has been demonstrated that lower levels of oxygen may cause an accelerated recruitment of type 2 fibers,[13] which is superior for increasing muscle size when compared with an exercise intensity matched to the normoxic condition. These findings suggest that exercise training under intermittent hypoxia may lead to muscle hypertrophy even with relatively low training workloads. The purpose of this brief review is to discuss how hypoxic conditions may be attained without providing ambient inspiratory hypoxic gases or inducing hypobaric hypoxia.

Arterial oxygen saturation during breath-hold exercise

Pulse oximetry is a simple method that measures percutaneous oxygen saturation (SpO_2). Lindholm et al[14] investigated changes in SpO_2 using both ear lobe and finger probes. Seven healthy young men performed a submaximum breath-hold for 60 s while performing cycle ergometer exercise at 50W. They found that SpO_2 at the end of the 60 s breath-hold was lower in ear lobe probe (78%) than the finger probe (84%). The average time delay between the two probes was 15 s. When the ear probes were at their nadir (SpO_2 78%), the finger probes showed an SpO_2 of 95% (nadir 84%). The authors concluded that finger probe pulse oximetry is probably not valid for apneic studies. Another study investigated cardiac and ventilatory responses to apneic exercise (upright cycling exercise with 40W, 80W and 120W) in young trained breath-holding divers.[15] They found that mean breath-hold times decreased from 152 s for resting apneas to 85 s for 40W, 69 s for 80W and 62 s for 120W. SpO_2 (ear lobe probe) began to decrease slowly at one minute after the start of the resting apnea and reached a minimum of 84% at the end of apnea. During apnea with exercise, SpO_2 began to decrease 45 s after the start of the apnea and declined rapidly towards the end of the apnea. Minimum values of SpO_2 are around 82% for each exercise intensity.[15] In addition, a recent study investigated cardiovascular changes during resting apnea and dynamic apneic dives (swimming while submerged) in elite breath-hold divers and reported that on average the divers endured about 4 min for resting apnea and 82 s for dynamic apneic dives (average swimming length was 74 m).[16] During the apneas, SpO_2 began to decrease toward the end of apnea and reached similar levels of SpO_2 in

Table 1 Summary of the effects of intermittent hypoxia training on muscle size and strength

Authors	Sex/Age	Number of subjects	Group	Hypoxia/ Normoxia	Duration of exposure*	Period Frequency	Training program	Muscle size		Strength	
Desplanches et al. (1993)	M/22	5	Nor T	Normoxia		3 weeks	Bicycle ergometer	fCSA	NS	DNM	
	M/23	5	Hyp T	FIO_2 12.7-10%	1 hr/session twice a day	6 days/wk	70-80% VO_{2max}		10%		
Friedmann et al.(2003)	M/24	9	Nor T	Normoxia		4 weeks	Knee EXT	qCSA	NS	Isok KE	NS
	M/25	10	Hyp T	FIO_2 12% SpO_2 >70%	40 min	3 days/wk	30% 1RM 6 sets × 25 reps		NS		NS
Nishimura et al. (2010)	M/22	7	Nor T	Normoxia		6 weeks	Elbow EXT/FLX	bCSA	3%	1RM EF	39%
	M/23	7	Hyp T	FIO_2 16% SpO_2 94-95%	73 min¶	2 days/wk	70% 1RM 4 sets × 10 reps		10%		62%
Manimmanakorn et al. (2013)	W/20	10	Nor T	Normoxia		5 weeks	Knee EXT/FLX	tCSA	3%	Isom KE	NS
	W/20	10	Hyp T	SpO_2 ~80%	12-13 min	3 days/wk	20% 1RM, 6 sets 28 to 22 reps for KE 36 to 26 reps for KF		6%		15%

* Approximate duration. ¶ Duration includes 30 min resting recovery before and after the exercise session. M, men; W, women; Nor T, normoxia training; Hyp T, hypoxia training; FIO_2, ambient fractional oxygen concentration; SpO_2, percutaneous oxygen saturation; EXT, extension; FLX, flexion; 1RM, one repetition maximum; fCSA, fiber cross-sectional area; qCSA, quadriceps muscle cross-sectional area; bCSA, biceps muscle cross-sectional area; tCSA, thigh muscle cross-sectional area; KE, knee extension; EF, elbow flexion; NS, non-significant; DNM, did not measure

resting apnea (78%) and dynamic apneic dives (77%). The average slope representing the speed of reduction in SpO_2 is ~2.5 time steeper in the dynamic apneic dives compared with resting apnea.[16] These previous studies suggest that hypoxia is produced with increasing duration of apnea, especially in the last half of the breath-hold, and SpO_2 reached a minimum value around 80%. Values of SpO_2 measured via pulse oximetry have been shown to be similar to arterial oxygen saturation (SaO_2) obtained from the radial artery during a breath-hold dive.[17]

Arterial oxygen saturation during exercise with controlled frequency breathing

Several studies reported changes in SpO_2 during dynamic exercise at various workloads with controlled frequency breathing (intermittent breath holding lasting from ~10 sec between breaths). For instance, Matheson and McKenzie[18] investigated changes in arterial blood gases during intense exercise with breath-hold. The endurance-trained runners repeated five intervals of a 15-s treadmill run (at 125% of VO_{2max}) with and without breath-holding, with 30-s of unrestricted breathing at rest between the runs. They found that arterial O_2 pressure (~70 mmHg) and SpO_2 (~92%) decreased immediately after each of the 15-s breath-holding runs, although there were no changes in arterial O_2 pressure (105 mmHg) and SpO_2 (97%) immediately after the 15-s free breathing runs. Another study by Yamamoto et al[19] examined the change in arterial oxygen saturation (SaO_2) during intermittent exercise (ten 30 s cycle exercise with 30 s rest intervals) in young men. During exercise (workload of 210W), the subjects breathed with two different patterns: 1) continuous breathing with 1-s each for inspiration and for expiration, and 2) non-continuous breathing, a 4-s period of breath-holding at functional residual capacity, followed by 2-s of same breathing pattern as continuous breathing (1-s each for inspiration and expiration). This was followed again by 4-s breath-holding, which repeated until the end of the 30 s exercise period. Breathing was uncontrolled during the rest periods. They reported that a marked increase in alveolar-arterial O_2 pressure difference ($P_AO_2 - P_aO_2$) with the breath-holding trial as compared to the continuous breathing trial. SpO_2 decreased to 89% on average. Regarding different frequencies of breathing, Stager et al[20] observed changes in SpO_2 during arm crank exercise (5 min at 80% VO_{2max}) with three different breathing frequencies (30, 20, and 15 breaths/min). These frequencies were chosen to approximate the breathing frequency used by competitive swimmers during normal (30 breaths/min) and hypoxic training (20 and 15 breaths/min) work bouts. The authors reported that SpO_2 (ear lobe probe) began to decrease after the start of the exercise in 20 and 15 breaths/min while SpO_2 was relatively constant during exercise in 30 breaths/min. Because the study was conducted in moderate altitude (Fort Collins, Colorado; 1520 m) baseline SpO_2 averaged 93%. The drop in SpO_2 was 9% (84%) in 15 breaths/min and 6% (87%) in 20 breaths/min. The subjects were able to compensate for the reduced breathing frequency by increasing tidal volume at 20 breaths/min, but not at 15 breaths/min.

Conclusions and future challenges

The results of previous studies suggest a possibility that moderate- or high-intensity exercise combined with controlled frequency breathing may produce a low level of SpO_2, which may be a model for muscle hypertrophy by moderate- or high-intensity exercise training with hypoxia. However, there are no published studies on the acute and chronic effects of resistance exercise with controlled frequency breathing on muscle/tissue oxygenation, muscle size and function. Additionally, it is unclear the magnitude of change in SpO_2 during resistance exercise with a combination of different frequencies of breathing (e.g., one breath every 3 repetitions) and various workloads (exercise intensity and tempo). Furthermore, a person who is less sensitive to increased levels of CO_2 (hypercapnia) may perform exercise when SpO_2 is reaching a lower level. Although the effects of hypercapnia on human health are not completely understood, hypercapnia may have deleterious effects in the lung.[21] Thus, the safety of such a technique, particularly with respect to hypercapnia and the possible elevation of arterial pressures, should be investigated further.

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