Inspiratory Muscle Training Effects on Cycling During Acute Hypoxic Exposure

Mitch Lomax; Heather C. Massey; James R. House

INTRODUCTION: Hypoxic environments increase the physiological demands of exercise. Inspiratory muscle training can reduce the demands of exhaustive exercise in this environment. This study examined the impact of inspiratory muscle training on moderate intensity hypoxic cycling exercise.

METHODS: There were 17 healthy adult men who undertook 4 wk of inspiratory muscle training ($N = 8$) or 4 wk of sham inspiratory muscle training ($N = 9$). Subjects completed four fixed intensity (100 W) and duration (10 min) cycle ergometry tests. Two were undertaken breathing normoxic ambient air and two breathing a hypoxic gas mixture (14.6% oxygen, balance nitrogen). One normoxic and hypoxic test occurred before, and one after, inspiratory muscle training.

RESULTS: Inspiratory muscle training increased maximal inspiratory mouth pressure by 21 ± 16 cmH_2O. Arterial oxygen saturation and its ratio to minute ventilation also increased after inspiratory muscle training during hypoxic exercise from 83 ± 4% to 86 ± 3% (approximately 3%) and 2.95 ± 0.48 to 3.52 ± 0.54% $\cdot$ L $\cdot$ min^{-1}(approximately 21%), respectively. In addition, minute ventilation and carbon dioxide output fell by 12–13% after inspiratory muscle training during hypoxic exercise.

DISCUSSION: Inspiratory muscle training reduced the physiological demand of moderate intensity exercise during acute hypoxic, but not normoxic, exercise. It may therefore be of benefit in adults exercising in a hypoxic environment.

KEYWORDS: exercise, altitude, breathing.

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Exposure to hypoxia causes a number of cardiopulmonary changes. These include elevated minute ventilation ($\dot{V}_E$), reduced arterial oxygen pressure[24,25] and oxygen saturation,[26] and increased cardiac output ($\dot{Q}$).[14,22] A hypoxic environment will also affect the body's ability to undertake exercise. For example, a reduction in maximal stroke volume and maximal heart rate,[22] a fall in arterial oxygen content and saturation, diffusion limitation,[24,25] and exacerbated hypoxemia[20] will all reduce oxygen delivery to the working muscles during hypoxic exercise. Consequently, maximum oxygen uptake ($\dot{V}o_{2max}$) is lower compared with normoxic exercise;[1,2,12] although submaximal $\dot{V}o_2$ may[2,14] or may not[14,25] increase. It is therefore not surprising that exercise time to exhaustion is shorter,[7,10,23] the magnitude of peripheral fatigue[1] and dyspnea[7,23] are greater, and diaphragm fatigue is hastened[7,10] during exhaustive hypoxic treadmill (75–85% $\dot{V}o_{2max}$) and cycle ergometry (82–92% peak power output) exercise.

The increase in ventilation that occurs during hypoxic exercise is a compensatory mechanism for the reduced oxygen intake per breath.[20] Consequently, $\dot{V}_E$ is higher during hypoxic exercise than comparable normoxic exercise,[2,23,25] which increases the oxygen cost of breathing.[8] The breathing musculature will, therefore, require a larger fraction of oxygen uptake to meet the ventilatory requirements.[2,7] This means that the demands placed upon the lungs and respiratory muscles are greater during hypoxic exercise compared with normoxic exercise.[7] It is therefore not surprising that inspiratory muscle training (IMT) and respiratory muscle training (RMT) have been employed to reduce the metabolic strain imposed by these muscles in a hypoxic environment.

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The breathing muscle training programs adopted in such studies have varied. Some studies have used 4 or 8 wk of respiratory (inspiratory and expiratory) muscle endurance training for 5 d/wk for between 10 and 30 min/d.[12,16] Others have used 4 wk of pressure threshold IMT consisting of only 30 to 40 breaths twice daily, 5 to 7 d/wk.[10,18] Regardless of the program adopted, when the fraction of inspired oxygen is reduced to 11–14%, IMT has been shown to reduce arterial oxygen desaturation, $\dot{V}_E$, $\dot{V}O_2$, and $\dot{Q}$ prior to exhaustion during fixed-intensity (85% $\dot{V}O_{2max}$) hypoxic exhaustive treadmill exercise,[10] as well as reduce the magnitude of arterial oxygen desaturation at rest.[18] In contrast, RMT has been shown to increase maximal $\dot{V}_E$[12,16] and $\dot{V}O_{2max}$[16] during incremental hypoxic cycling to exhaustion. However, no studies have examined whether or not IMT provides any benefit to nonexhaustive, moderate intensity hypoxic exercise. The aim of the current study was to examine the physiological responses to such exercise. We hypothesized that IMT would reduce the physiological demand of performing moderate intensity nonexhaustive hypoxic exercise.

METHODS

Subjects

There were 17 healthy men free from cardiorespiratory disease who were randomly assigned to either an IMT (*N*: 8; age: 23 ± 1 yr; body mass: 80.8 ± 14.1 kg; stature: 1.75 ± 0.08 m) or sham IMT (*N*: 9; age: 21 ± 2 yr; body mass: 78.3 ± 10.4 kg; stature: 1.81 ± 0.07 m) group. All subjects were nonsmokers. This study protocol was approved in advance by the BioScience Research Ethics Committee, University of Portsmouth. Each subject provided written consent before participating.

Equipment and Procedures

Subjects completed four fixed-intensity (100 W) and duration (10 min) recumbent cycle ergometry tests in a normobaric chamber (Sporting Edge, Sherfield, UK): two pre (mean ± SD: barometric pressure of 760 ± 9 mmHg; temperature of 21.2 ± 1.5°C; humidity of 30 ± 12%) and two post (mean ± SD: barometric pressure of 765 ± 7 mmHg; temperature of 21.5 ± 1.1°C; humidity of 41 ± 12%) IMT. Recumbent cycling was chosen for safety reasons and the use of cycling exercise is consistent with past hypoxia and RMT studies.[12,16] Previous work in our laboratory indicated that this intensity could likely be classified as moderate intensity (observed METS ranged from 3.9–4.5) and the duration would be sufficient to reach steady state.

Two tests were undertaken in normoxic conditions (these served as control trials), one pre-IMT and one post-IMT, and two tests while breathing a hypoxic gas mixture (14.6% oxygen, balance nitrogen), one pre-IMT and one post-IMT. The normobaric chamber used an oxygen filtration system to achieve the preset percentage of oxygen, which was confirmed using an independent calibrated hand-held gas analyzer (MX6 iBRID, Industrial Scientific, Pittsburgh, PA). Before the first cycle test and on a separate day, subjects attended a pulmonary familiarization session to practice maximal inspiratory mouth pressure (PI_{max}) maneuvers. These maneuvers were performed in accordance with BASES guidelines.[21] PI_{max} was assessed using a calibrated hand-held mouth pressure meter (Micro Medical, Rochester, UK) and was recorded in normoxia pre- and post-IMT. The coefficient of variation for PI_{max} was 3 ± 3% and 8 ± 9% for the sham IMT and IMT groups, respectively.

Before the start of the cycling exercise subjects sat quietly for 3 min. In the normoxic trials subjects breathed the ambient air within the chamber. In the hypoxic trials subjects breathed normoxic air for the first 3 min using an ambient feed from outside of the chamber and then switched to breathing the air within the chamber (14.6% oxygen, balance nitrogen) for a further 5 min, after which cycling exercise commenced.

Each cycle test consisted of 10 min of fixed intensity seated cycling using an electronically braked ergometer (Lode Angio, Groningen, Netherlands). The wattage and cadence were fixed throughout, corresponding to 100 W of external work and 70 to 80 rpm, respectively. During this time, expired air was collected continuously and passed through a mixing chamber connected to a flow meter (calibrated using a certified 3-L syringe) and dyspnea was assessed (modified Borg CR10 scale). The percentages of expired oxygen and carbon dioxide were determined using a gas analyzer (G1R250 gas analyzer, Hitech Instruments, Luton, UK), which was calibrated using ambient normoxic air fed through a sample tube, and gases of a known concentration. Expired $\dot{V}_E$, $\dot{V}O_2$, carbon dioxide output ($\dot{V}CO_2$), respiratory exchange ratio, tidal volume (V_T), and breathing frequency (f_r) were recorded continuously (Power Lab SP16 analog to digital converter, AD Instruments, Sydney, Australia) and displayed on a portable computer using data acquisition software (Chart 6, AD Instruments). The time delay inherent in measuring expired oxygen and carbon dioxide fractions with this method was rectified prior to data analysis.

Heart rate (f_c) and arterial oxygen saturation were measured continuously from a 3-lead ECG (Huntleigh Life Pulse, Cardiff, UK) and pulse oximetry (S_pO_2) (Nonin, 7500, Plymouth, MN), respectively. Data were recorded using data acquisition software (Chart 6, AD Instruments) for subsequent analysis. The ratio of $S_pO_2/\dot{V}_E$, which provides an estimate of ventilatory efficiency,[3] was calculated after each test. Excluding the PI_{max} and dyspnea data, all remaining data are collectively referred to as metabolic data.

After completion of the normoxic and hypoxic pre-IMT trials, subjects completed 4 wk of IMT or sham IMT using a commercially available inspiratory muscle trainer (POWERbreathe®, HaB International, Warwickshire, UK). Subjects completed two sets of 30 breaths daily (one set in the morning and one set in the evening) 7 d/wk in a seated position. In the IMT group, the load on the inspiratory muscle trainer was set up in the laboratory to reflect 50% of each subject's highest baseline PI_{max}. Conversely, the sham IMT group breathed through the trainer but against no load. Subjects in the IMT group were instructed to increase the load weekly so that they could only just complete 30 breaths.[18] All subjects kept a weekly IMT training log for subsequent evaluation of IMT adherence (88 ± 10% and 77 ± 0.1% of breath repetitions completed in the IMT and sham IMT groups, respectively). The two remaining normoxic and hypoxic trials were completed within 5 d of completing IMT.

Statistical Analysis

Data were assessed for normality using the Shapiro-Wilk test, skewness, and kurtosis. All breath-by-breath data, S_pO_2, f_c, $S_pO_2/\dot{V}_E$, and dyspnea were averaged per minute with only the second half of each test analyzed.[14,24] Two-way factorial analysis of variance (ANOVA) was used to assess for differences between groups (IMT vs. sham), simulated altitude (normoxia vs. hypoxia), and IMT status (pre- vs. post-IMT) per dependent variable. In the case of PI_{max}, a one-way factorial ANOVA was used to assess for differences between groups (IMT vs. sham) and IMT status (pre- vs. post-IMT): the highest baseline value recorded pre-IMT and post-IMT was used regardless of simulated altitude trial. Delta change in PI_{max} pre- and post-cycle ergometry was used to assess for inspiratory muscle fatigue (IMF) pre- and post-IMT per simulated altitude trial and was also assessed using repeated measures factorial ANOVA.

Post hoc analyses were undertaken using one-way repeated measures ANOVAs, paired samples *t*-tests, and independent samples *t*-tests, where relevant, and the *P*-value adjusted accordingly. Where relevant, effect sizes were calculated using Cohen's *d* with an effect size of 0.2 deemed small, 0.5 medium, and above 0.8 deemed large.[9] *P* was set at 0.05 and analyses were undertaken using IBM SPSS statistics version 22. Unless otherwise stated data are presented as mean ± SD.

RESULTS

An interaction was observed between IMT status and group for PI_{max} ($F_1 = 8.502$, $P = 0.011$). PI_{max} was higher in the IMT group both before (IMT group: 155 ± 17 cmH_2O; sham group: 123 ± 26 cmH_2O; $P = 0.010$) and after (IMT group: 176 ± 27 cmH_2O; sham group: 125 ± 18 cmH_2O; $P < 0.001$) IMT. Importantly, however, sham IMT had no effect on PI_{max} ($P = 0.715$), but PI_{max} was increased by 21 ± 16 cmH_2O in the IMT group following IMT ($P = 0.008$, $d = -0.93$). Thus, we can be confident that IMT did increase PI_{max} in the IMT group, but not the sham group. Additionally, IMF was not observed following any trial.

It was unsurprising that V_T ($F_1 = 6.264$, $P = 0.024$), f_r ($F_1 = 11.082$, $P = 0.005$), f_c ($F_1 = 13.525$, $P = 0.005$), $\dot{V}_E$ ($F_1 = 33.484$, $P < 0.001$), $\dot{V}O_2$ ($F_1 = 7.154$, $P = 0.018$), respiratory exchange ratio ($F_1 = 21.820$, $P < 0.001$), and dyspnea ($F_1 = 29.562$, $P < 0.001$) were all higher in hypoxic exercise compared with normoxic exercise, regardless of IMT status or group. Similarly, S_pO_2 ($F_1 = 201.130$, $P < 0.001$) and $S_pO_2/\dot{V}_E$ ($F_1 = 137.384$, $P < 0.001$) were also lower during hypoxic exercise (**Table I** and **Table II**).

Importantly, IMT, but not sham IMT, was associated with a reduction in $\dot{V}_E$ ($F_1 = 15.484$, $P = 0.001$) and $\dot{V}CO_2$ ($F_1 = 5.570$, $P = 0.042$) during hypoxic, but not normoxic, exercise. In contrast, S_pO_2 ($F_1 = 29.525$, $P = 0.004$) and $S_pO_2/\dot{V}_E$ ($F_1 = 10.781$, $P = 0.005$) were increased following IMT in the IMT group during hypoxic exercise (**Fig. 1**). Interestingly, dyspnea fell following both hypoxic and normoxic exercise in response to both IMT and sham IMT ($F_1 = 18.255$, $P = 0.001$), but no difference was observed in dyspnea between the groups.

DISCUSSION

The aim of this study was to determine if IMT could lower the physiological demands of moderate intensity nonexhaustive cycling exercise in a hypoxic atmosphere (14.6% oxygen), which simulated an altitude of approximately 3000 m. Our data indicate that 4 wk of IMT increased PI_{max} and reduced $\dot{V}_E$, $\dot{V}CO_2$, the magnitude of arterial oxygen desaturation, and improved ventilatory efficiency in response to an acute hypoxic exposure during moderate intensity fixed-rate cycling exercise. This is the first study to demonstrate that exercise does not need to be exhaustive for IMT to be of benefit when exercising at a simulated high altitude. Furthermore, as there was no evidence of IMF, our data also suggest that IMT can be beneficial in hypoxia even in the absence of such fatigue.

As expected, $\dot{V}_E$, $\dot{V}O_2$, *fc*, and dyspnea were greater, and S_pO_2 lower during hypoxic exercise compared with normoxic exercise (Tables I and II). Interestingly, studies using exhaustive

Table I. Pre- and Post-IMT Data Averaged Over the Second Half of 10-min Fixed-Intensity Normoxic Cycle Ergometry: Mean ± SD.

	IMT GROUP			SHAM IMT		
MEASURE	**PRE-IMT**	**POST-IMT**	***d***	**PRE-IMT**	**POST-IMT**	***d***
$\dot{V}_E$ ($L \cdot min^{-1}$)	22. ± 3.4§§	24.1 ± 3.1	−0.49	22.7 ± 1.4§§	22.5 ± 3.6§§	0.07
$\dot{V}O_2$ ($L \cdot min^{-1}$)	1.16 ± 0.14	1.22 ± 0.13	−0.44	1.21 ± 0.11	1.19 ± 0.24	0.11
$\dot{V}CO_2$ ($L \cdot min^{-1}$)	1.05 ± 0.08	1.04 ± 0.11	−0.10	1.08 ± 0.08	1.03 ± 0.11	0.09
RER	0.92 ± 0.06	0.87 ± 0.10§§	0.61	0.90 ± 0.07	0.89 ± 0.13	0.10
V_T (L)	1.30 ± 0.20§	1.36 ± 0.20	−0.30	1.17 ± 0.08	1.12 ± 0.21	0.31
f_r ($breaths \cdot min^{-1}$)	21 ± 5	21 ± 5	0.00	23 ± 2§	22 ± 4	0.17
S_pO_2 (%)	96 ± 2§§	96 ± 1§§	0.00	96 ± 1§§	95 ± 1§§	1.00
$S_pO_2/\dot{V}_E$ ($\% \cdot L \cdot min^{-1}$)	4.37 ± 0.80§§	4.02 ± 0.58§	0.50	4.31 ± 0.27§§	4.38 ± 0.67§§	−0.14
f_c (bpm)	129 ± 17	132 ± 16*,§	−0.18	125 ± 7	112 ± 11**,§§	1.41
Dyspnea	2.3 ± 1.5§§	2.0 ± 0.8§	0.25	2.5 ± 0.4§§	2.4 ± 0.7	0.18

$\dot{V}_E$ = minute ventilation; $\dot{V}O_2$ = oxygen uptake; $\dot{V}CO_2$ = carbon dioxide output; RER = respiratory exchange ratio; V_T = tidal volume; f_r = breathing frequency; S_pO_2 = pulse oximetry; $S_pO_2/\dot{V}_E$ = ratio of pulse oximetry to minute ventilation; f_c = heart rate.
* $P \leq 0.05$, **$P \leq 0.01$: different to pre IMT within-trial (pre-, post-IMT).
§ $P \leq 0.05$, §§$P \leq 0.01$: different to hypoxia per group (sham, IMT).
d = Cohen's *d*.

Table II. Pre- and Post-IMT Data Averaged Over the Second Half of 10-min Fixed-Intensity Hypoxic Cycle Ergometry: Mean ± SD.

	IMT GROUP			SHAM IMT		
MEASURE	PRE-IMT	POST-IMT	*d*	PRE-IMT	POST-IMT	*d*
$\dot{V}_E$ (L · min^{-1})	28.9 ± 5.1	24.9 ± 4.3*	0.85	24.9 ± 2.1	26.9 ± 3.9	−0.64
$\dot{V}O_2$ (L · min^{-1})	1.10 ± 0.15	0.97 ± 0.14	0.90	1.06 ± 0.14	1.27 ± 0.20	−1.27
$\dot{V}CO_2$ (L · min^{-1})	1.14 ± 0.18	1.00 ± 0.16*	0.82	1.10 ± 0.09	1.12 ± 0.10	−0.21
RER	1.06 ± 0.14	1.03 ± 0.11	0.25	1.05 ± 0.13	0.92 ± 0.10	1.12
V_T (L)	1.57 ± 0.33	1.34 ± 0.31	0.72	1.21 ± 0.13	1.27 ± 0.11	−0.50
f_r (breaths · min^{-1})	23 ± 7	22 ± 5	0.16	24 ± 3	25 ± 5	−0.24
S_pO_2 (%)	83 ± 4	86 ± 3*	−0.85	85 ± 3	82 ± 5*	0.73
$S_pO_2/\dot{V}_E$ (% · L · min^{-1})	2.95 ± 0.48	3.52 ± 0.54*,‡	−1.15	3.62 ± 0.66	3.08 ± 0.42	0.98
f_c (bpm)	138 ± 14	135 ± 18	0.19	129 ± 12	123 ± 120	0.50
Dyspnea	4.8 ± 1.8	2.8 ± 1.0**	1.37	3.8 ± 1.1	2.9 ± 1.0*	0.86

$\dot{V}_E$ = minute ventilation; $\dot{V}O_2$ = oxygen uptake; $\dot{V}CO_2$ = carbon dioxide output; RER = respiratory exchange ratio; V_T = tidal volume; f_r = breathing frequency; S_pO_2 = pulse oximetry; $S_pO_2/\dot{V}_E$ = ratio of pulse oximetry to minute ventilation; f_c = heart rate.
* $P \leq 0.05$, ** $P \leq 0.01$: different from pre-IMT within-trial (pre-, post-IMT).
‡ $P \leq 0.05$: different to sham.
d = Cohen's *d*.

high-intensity cycling ergometry (82–92% of maximal work load and 75% of $\dot{V}O_{2max}$) have shown that the increase in $\dot{V}_E$ can be mediated via f_r[1,7] or V_T[23] when breathing a hypoxic gas mixture of 9–15% oxygen. We observed an increase in both *fr* and V_T with no consistent pattern evident between tests.

Of greater relevance to this study, however, was the impact of IMT on hypoxic exercise. Following IMT $\dot{V}_E$ was reduced in the hypoxic trial, but only in the IMT group (Fig. 1). The individual effects of V_T and f_r following IMT were not significant and only in combination were they able to impact $\dot{V}_E$. Nevertheless, the effect size data suggest that the reduction was predominantly mediated via a fall in V_T (medium to large effect size) rather than f_r (small effect size) (Table II). This is consistent with the findings of Downey et al.[10]

We do not believe that this fall in $\dot{V}_E$ was due to a reduction in the work of breathing per se. Two key observations support this. Firstly, as absolute workload and duration were fixed (100 W and 10 min, respectively), a fall in the work of breathing would be evident during both normoxic and hypoxic exercise. However, $\dot{V}_E$ only declined during hypoxic exercise (Table II). Secondly, had the work of breathing declined post-IMT, the oxygen requirement of the inspiratory muscles would have fallen and $\dot{V}O_2$ would have been lower during both normoxic and hypoxic exercise.[15] However, $\dot{V}O_2$ demonstrated a nonsignificant increase during normoxic exercise (small to medium effect size) and a nonsignificant fall (large effect size) during hypoxic exercise (Table II). It is more likely that the fall in $\dot{V}_E$ in hypoxia post-IMT was linked to the 3% increase in S_pO_2. As a result, the $S_pO_2/\dot{V}_E$ ratio increased (Fig. 1), indicating that the amount of ventilation required to achieve a given level of oxygen saturation fell.[3]

The question of how IMT offers protection against the magnitude of fall in arterial oxygen saturation and in turn reduces $\dot{V}_E$ is yet to be fully elucidated. An increase in lung diffusion capacity is a potential mechanism[10] and could also explain the fall in $\dot{V}CO_2$, the tendency for $\dot{V}O_2$ to fall (albeit nonsignificantly) and the increase in ventilatory efficiency ($S_pO_2/\dot{V}_E$ ratio) observed during hypoxic exercise following IMT in the current study (Fig. 1). Indeed, diffusion limitation (and ventilation-perfusion mismatch) have been observed during light intensity ($\dot{V}O_2$ above 1.0 L · min^{-1}) steady-rate cycling exercise of 7–9 min at a simulated altitude of 3048 m (10,000 ft),[24] which is not dissimilar to the conditions of the current study. Importantly, Downey et al.[10] have found that lung diffusion capacity increased by 23% during hypoxic exercise

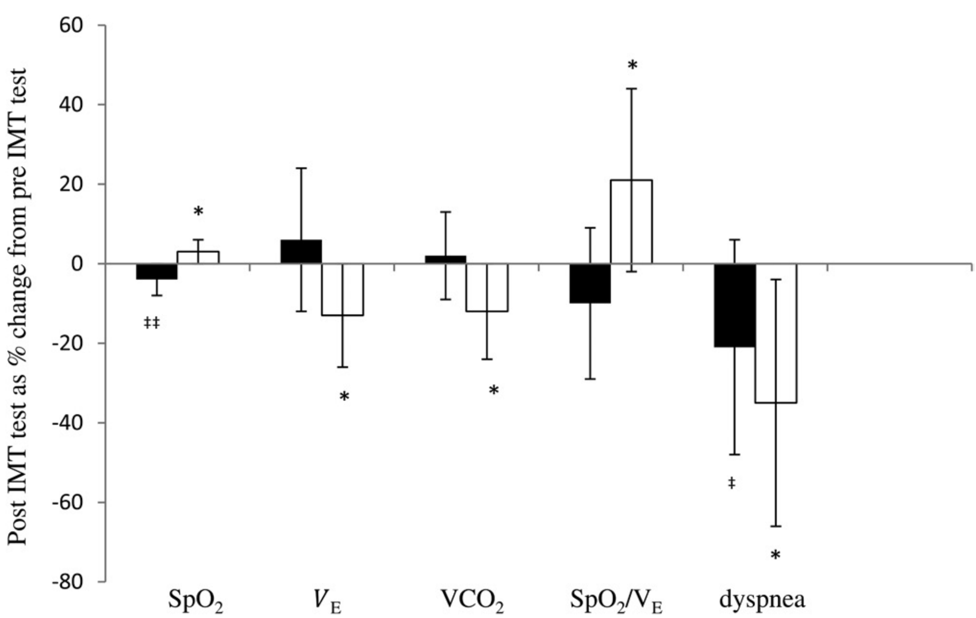

Fig. 1. Post-intervention sham IMT group (black bars) and IMT group (white bars) hypoxic data expressed as percentage change from pre-IMT data: mean ± SD. *$P < 0.05$, different from within-trial for the IMT group only. ‡$P < 0.05$, ‡‡$P < 0.01$, different from sham IMT group post-IMT.

following 4 wk of IMT, and $\dot{Q}$ and $\dot{V}_E$ decreased by 13% and 25%, respectively. They suggested that the time available for gas exchange to occur in the lung was likely increased as a result of pulmonary diffusion and $\dot{Q}$ changes. This, in turn, would lengthen the red blood cell transit time, promoting oxygen-hemoglobin binding and hence increase S_pO_2.[10] Downey et al.[10] postulate that the increase in S_pO_2 might reduce the peripheral chemoreceptor input and in turn lower $\dot{V}_E$.

It should be noted that the metabolic responses observed in the current study and by Downey et al.[10] are different from those reported at exhaustion following an incremental cycle exercise test in hypoxia (11–12% inspired oxygen) post-RMT. Both Keramidas et al.[16] and Esposito et al.[12] reported an increase in maximum $\dot{V}_E$ (12%) at the point of exhaustion, while Keramidas et al.[16] also observed an increase in $\dot{V}O_{2max}$, although cycle time to exhaustion was unaffected. Thus, it appears that IMT is capable of reducing $\dot{V}_E$ and $\dot{V}CO_2$ during submaximal cycling (present study) or running exercise prior to the point of exhaustion,[10] whereas RMT can increase maximal $\dot{V}_E$ during incremental exhaustive cycling exercise and possibly even $\dot{V}O_{2max}$ depending on the level of ventilation-perfusion mismatch.[12,16]

Given the complexity of the pulmonary system and the different exercise and IMT/RMT protocols adopted in past hypoxia studies, delineating exactly how IMT benefits exercise in hypoxia is challenging. It is important to state that the ergogenic effect of IMT is unlikely to be due simply to an increase in inspiratory muscle strength alone.[13] While we are not aware of any studies showing that IMT can increase lung growth, an increase in lung volume has been observed following IMT,[11] and it has been demonstrated that changes in the perceptual and cardiovascular responses to normoxic exercise following IMT are secondary to IMT-induced structural and functional changes within the inspiratory muscles.[13] For example, it has been shown that following IMT, the inspiratory muscle metaboreflex is attenuated during plantarflexion exercise,[19] f_c and the perceptions of breathing and leg effort are reduced during treadmill walking while carrying a 25-kg backpack,[13] and blood lactate concentration is reduced during hyperpnea.[4] Clearly, more studies are needed to delineate how the morphological changes arising from IMT contribute to enhanced exercise performance. Moreover, as the mechanics of breathing are altered in hypobaric hypoxia because air density is lower and pulmonary blood flow is increased,[6] careful consideration should be given as to whether hypobaric or normobaric hypoxic experimental conditions are adopted.

Furthermore, our S_pO_2 data raise an interesting question regarding the potential role of IMT in reducing acute mountain sickness (AMS). The occurrence of AMS following acute exposure to altitude (i.e., minutes to hours) is linked with low S_pO_2 values.[5,17] Loeppky et al.[17] reported that sufferers of early-onset (within 8 to 12 h of hypoxic exposure) AMS exhibited greater hypoxemia than nonsufferers despite an equivalent ventilatory response. The fall in S_pO_2 was, therefore, not because of a lower ventilatory response, which can reduce S_pO_2.[5] Although our data provide no evidence that IMT can offer protection against AMS on initial exposure to altitude, it does provide a rationale for investigating this possibility.

Lastly, it would be remiss to ignore our dyspnea data and the baseline differences in PI_{max} between the sham IMT and IMT groups. That dyspnea fell during hypoxic exercise post-IMT in both the sham IMT and IMT groups should be acknowledged, if only to indicate that IMT was unable to modify dyspnea at the exercise intensity and level of hypoxia (14.6% oxygen) adopted. Thus, the fall in dyspnea that we observed might simply reflect a perceptual familiarization arising from a second exposure to hypoxia.

The difference in baseline PI_{max} between groups occurred because we randomly allocated subjects to one of the groups instead of matching subjects based on inspiratory muscle strength. While we acknowledge this as a limitation and recommend that future studies should endeavor to match for PI_{max}, we do not believe that this invalidates our findings as no significant differences were observed between groups in $\dot{V}_E$, $\dot{V}O_2$, $\dot{V}CO_2$, V_T, f_r, and S_pO_2 pre-IMT. Furthermore, PI_{max} only increased following IMT (average increase of 21 cmH_2O), not sham IMT (average increase of 1 cmH_2O), indicating that a training effect did take place. Rather, such a discrepancy in baseline inspiratory muscle strength would be more likely to curtail the potential gain for an improvement.

In conclusion, 4 wk of pressure-threshold IMT exerted beneficial physiological effects during moderate intensity ($\dot{V}_E \leq 30\ L \cdot min^{-1}$ and $\dot{V}O_2 < 1.28\ L \cdot min^{-1}$), constant-load (100 W), nonexhaustive, fixed-duration (10 min) cycling exercise in acute hypoxia (14.6% oxygen). In contrast, no such benefits were observed post-IMT during identical exercise in normoxia. Specifically, $\dot{V}_E$ and $\dot{V}CO_2$ were lower, and S_pO_2 and $S_pO_2/\dot{V}_E$ higher, during hypoxic exercise after IMT. Interestingly, these changes occurred in the absence of inspiratory muscle fatigue, indicating that such fatigue does not need to be present for IMT to be of benefit. Given that IMT was able to modify the initial $\dot{V}_E$ and S_pO_2 response in acute hypoxia, it should be investigated whether or not IMT can reduce the likelihood or severity of AMS.

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