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The effects of respiratory muscle training on respiratory mechanics and energy cost

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ABSTRACT

Resistance respiratory muscle training (RRMT) increases respiratory muscle strength and can increase swimming endurance time by as much as 85%. The purpose of this study was to examine potential mechanisms by which RRMT improves exercise endurance. Eight healthy adult male scuba divers underwent experiments in a hyperbaric chamber at sea level (1 atmosphere absolute (ATA)), 2.7 ATA and 4.6 ATA, both dry and fully submersed. Subjects rested, exercised, and rested while mimicking their own exercise breathing (ISEV). Airway resistance (R_{aw}), exhaled nitric oxide output ($\dot{V}_{NO}$), and respiratory duty cycle (T_I/T_{Tot}) were determined before and after four weeks of RRMT. RRMT decreased T_I/T_{Tot} (−10% at rest at 1 ATA), $\dot{V}_{O_2}$ (−17% at 2.7 ATA during submersed exercise), $\dot{V}_E$ (−6% at 2.7 ATA during submersed exercise), and R_{aw} (−34% inspiratory at 4.6 ATA submersed, −38% expiratory at 2.7 ATA dry), independent of changes in $\dot{V}_{NO}$. Most importantly, respiratory muscle efficiency increased (+83% at 2.7 ATA submersed).

1. Introduction

In the underwater environment the cardiopulmonary system faces several distinct challenges, including altered pulmonary mechanics. Submersion increases work of breathing due to (1) increased breathing gas density and flow resistance as a function of increased depth (Lundgren, 1984); (2) translocation of blood to the thorax, and especially to the lungs, which reduces lung compliance and lung elastic recoil (Lundgren, 1999); and (3) the imposition of static lung loading (Lundgren, 1999), which occurs when a diver's breathing gas is delivered at a different hydrostatic pressure than the chest centroid, usually due to a difference in the depth of the second stage regulator and the diver's chest. Due to respiratory muscle fatigue resulting from the increased WOB and poor mechanical efficiency, submersion and depth have been shown to have a negative effect on exercise performance of swimmers and divers (Hesser et al., 1981) and to increase dyspnea scores during exercise (Lundgren, 1984).

Leith and Bradley were the first to demonstrate that respiratory muscle training (RMT) could increase ventilatory parameters such as maximal voluntary ventilation (MVV) and maximal expiratory pressure ($P_{E\,max}$) (Leith and Bradley, 1976), however, they did not study the effect on exercise performance. Since that time, multiple studies have demonstrated that RMT also improves athletic performance. Runners (Leddy et al., 2007; Uemura et al., 2012), cyclists (Boutellier et al., 1992; Markov et al., 2001; McMahon et al., 2002; Stuessi et al., 2001; Verges et al., 2007), and swimmers exercising both at the surface (Lindholm et al., 2007; Wylegala et al., 2007) and at various depths (Ray et al., 2008) have all increased exercise endurance following RMT, sometimes by as much as 85% (Ray et al., 2009).

These improvements in exercise performance were surprising given that the respiratory system was generally not considered to limit exercise. However, it has been shown that at maximal exercise, respiratory muscles consume as much as 15% of total body

Abbreviations: ATA, atmospheres of absolute pressure; EELV, end expiratory lung volume; ERMT, endurance respiratory muscle training; $F_{E\,NO}$, exhaled concentration of nitric oxide; ISEV, isocapnic simulated exercise ventilation; MVV, maximum voluntary ventilation; NO, nitric oxide; P_{AE}, expiratory alveolar pressure; P_{AI}, inspiratory alveolar pressure; $P_{E\,max}$, maximal expiratory pressure; $P_{I\,max}$, maximal inspiratory pressure; $P_{ET\,CO_2}$, partial pressure of end-tidal carbon dioxide; $\dot{Q}$, cardiac output; $R_{aw\,E}$, expiratory airway resistance; $R_{aw\,I}$, inspiratory airway resistance; RMT, respiratory muscle training; RRMT, resistance respiratory muscle training; T_I/T_{Tot}, respiratory duty cycle; VC, vital capacity; $\dot{V}_E$, minute ventilation; $\dot{V}_{NO}$, nitric oxide elimination; $\dot{V}_{O_2}$, oxygen consumption; $\dot{V}_{O_2\,B}$, oxygen cost of breathing; $\dot{V}_{O_2\,peak}$, peak oxygen consumption; V_T, tidal volume; $\dot{W}_E$, expiratory power of breathing; $\dot{W}_I$, inspiratory power of breathing; WOB, work of breathing.

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$\dot{V}_{O_2}$ (Harms et al., 1997) and thus cardiac output ($\dot{Q}$) (Harms et al., 1998), and competition for perfusion reduces locomotor muscle blood flow, even in healthy adults (Harms et al., 1997). This reduction in blood flow is mediated by increased sympathetic output, which decreases locomotor muscle perfusion (Harms et al., 1997), but not diaphragm perfusion (Aaker and Laughlin, 2002a, 2002b). A metaboreflex has been identified (St Croix et al., 2000), which substantially reduces locomotor muscle perfusion following respiratory muscle fatigue (Sheel et al., 2001). Importantly, reducing inspiratory muscle work has been shown to reduce $\dot{Q}$ (Harms et al., 1998), increase locomotor muscle perfusion (Harms et al., 1997), increase locomotor muscle twitch force (Belvisi et al., 1992), and increase time to fatigue at a given work rate (Harms et al., 2000).

Resistance respiratory muscle training (RRMT), which consists of respiratory efforts against high inspiratory or inspiratory and expiratory resistance but produces little or no flow (Leith and Bradley, 1976), is most effective for exercise during submersion (Wylegala et al., 2007). Interestingly, studies have demonstrated even greater benefits of RRMT when the depth at which subjects exercised increased from 1 atmosphere absolute (ATA) to 2.7 ATA (Ray et al., 2008). A reduction in the work of breathing (WOB) (Ray et al., 2009) or in the oxygen cost of breathing per unit of work (Simpson et al., 2012) appeared to underlie the improvements in exercise endurance, but the reason for the decrease in respiratory muscle work and its impact on the absolute oxygen cost of breathing ($\dot{V}_{O_2\,B}$) were not investigated.

One potential contributor to increased exercise performance and increased respiratory efficiency in particular is the possibility of increased nitric oxide (NO) levels in the airways. NO is a potent bronchodilator (Adnot et al., 1995), and higher exhaled levels have been observed in athletes (Maroun et al., 1995) and during exercise (Chirpaz-Oddou et al., 1997; Maroun et al., 1995) and heavy breathing (West et al., 2005). While these results must be interpreted cautiously—higher exhaled NO concentration does not necessarily indicate higher rates of production—they at least suggest a link between airway NO levels, work of breathing, and subject fitness, which may be of particular interest when considering the effects of RMT.

As RRMT has been shown to prolong exercise time (Ray et al., 2008; Wylegala et al., 2007), we theorize that there is a reduced WOB following RRMT that decreases respiratory muscle metabolism, reduces the accumulation of metabolites, and thereby delays the onset of the metaboreflex described above. We hypothesized that RRMT would decrease the work of breathing via one or both of two mechanisms: (1) by allowing subjects to utilize a slower breathing pattern or (2) by increasing airway NO levels. According to the relationships described by Poiseuille's Law, both of these changes would reduce airway resistance. In addition, we hypothesize (3) that RRMT would increase the mechanical efficiency of the respiratory muscles, secondary to the improved strength of the respiratory muscles and the reduced airway resistance.

2. Methods

The study protocol was approved by the University's Health Sciences Institutional Review Board, and the volunteer subjects provided written informed consent before participating in the study.

2.1. Study rationale

The work rates and simulated depths tested in this study were chosen as they have practical use in diving and because they mimicked the test conditions utilized in previous studies (Pendergast et al., 1999; Ray et al., 2008, 2009; Simpson et al., 2012), so findings from this study may be related to previous work.

2.2. Study design

This study was designed to test the effects of RRMT on variety of measures of exercise and pulmonary function. Subjects completed pulmonary function tests (PFTs), CO_2 sensitivity tests, peak oxygen consumption ($\dot{V}_{O_2\,peak}$) tests (both dry and submersed), and measurement of maximal inspiratory and expiratory pressures at the mouth ($P_{I\,max}$ and $P_{E\,max}$, respectively) before and after RRMT. In addition, a set of experiments was undertaken to measure ventilation at the surface (1 ATA) and two simulated depths (2.7 ATA, and 4.6 ATA), both dry and fully submersed in a hyperbaric chamber. Subjects served as their own controls: they underwent experiments at each of these conditions both before and after four weeks of RRMT. The pre-RRMT data describing the effects of submersion and depth on respiratory mechanics have been reported previously (Held and Pendergast, 2013). With permission, some of those data are reproduced here to allow the comparison with post-RRMT values.

2.3. Subjects

Volunteers from the local diving population provided a medical history and underwent a physical examination, including a chest X-ray, spirometry, MVV_{15}, and peak inspiratory and expiratory pressures, and were medically cleared for participation. Eight male certified scuba divers were recruited and completed the study protocol. At the start of the study, they were 28 ± 8 (mean $\pm$ SD) years old, weighed 81 ± 12 kg, and were 179 ± 4 cm. All subjects were non-smokers, but subject #10 chewed tobacco in the two years prior to the study and had a history of smoking (1 pack/day for 9 years) prior to that.

2.4. $\dot{V}_{O_2\,peak}$ testing

The protocol used to measure $\dot{V}_{O_2\,peak}$ has been described previously (Held and Pendergast, 2013). Briefly, subjects were seated upright on a cycle ergometer in a hyperbaric chamber at sea level. Subjects pedaled at 60 ± 5 rpm while work rate increased incrementally from 50 W (in the dry) until subjects were unable to maintain cadence. Exhaled gas was collected every other minute during the test for analysis. Subjects provided a blood sample from a finger prick 5–6 min after cessation of exercise. Subjects were considered to have reached a maximum work rate if they met at least two of the following criteria: (1) blood lactate concentration > 4.0 mmol/L, (2) respiratory exchange ratio for the last minute of exercise > 1.2, and (3) the difference in oxygen consumption between the last minute of exercise and the previous collection was < 150 ml/min. Submersed experiments were performed in exactly the same manner, with the exception that subjects wore standard scuba-type face masks, and work rate was reduced by 25 W to account for hydrodynamic drag of the movement of the legs. Subjects performed the test in the dry and submersed both before and after RRMT.

2.5. CO_2 sensitivity testing

Using methods that have been reported before (Pendergast et al., 2006), subjects' ventilatory responses to increasing CO_2 levels were measured once at the start of the study and again after completing RRMT. Briefly, subjects breathed from a spirometer prefilled with a hypercapnic gas mixture (5% CO_2, 50% O_2) while a mass spectrometer sampled gas composition at the mouthpiece, and a flowmeter