Respiratory muscle training improves swimming endurance at depth.

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Ray AD, Pendergast DR, Lundgren CEG. Respiratory muscle training improves swimming endurance at depth. Undersea Hyperb Med 2008; 35(3):185-196. Respiratory muscle training (RMT) has been shown to improve divers swimming endurance at 4 feet of depth; however, its effectiveness at greater depths, where gas density and the work of breathing are substantially elevated has not been studied. The purpose of this study was to examine the effects of resistance respiratory muscle training (RRMT) on respiratory function and swimming endurance at 55 feet of depth (270.5 kPa). Nine male subjects (25.9 ± 6.8 years) performed RRMT for 30 min/day, 5 d/ wk, for 4 wks. Pre- and Post RRMT, subjects swam against a pre-determined load (70% \(\text{Vo}_2\) max) until exhausted. As indices of respiratory muscle strength, maximal inspiratory and expiratory pressures were measured before and immediately following the swims pre- and post-RRMT. These measurements showed that ventilation was significantly lower during the swims and, at comparable swim duration, that the respiratory muscles were considerably less fatigued following RRMT. The reduced ventilation was due to a lower breathing frequency following RRMT. The ventilatory changes following RRMT coincided with significantly increased swimming time to exhaustion (~60%, 31.3 ± 1.6 vs. 49.9 ± 16.0 min, pre- vs. post-RRMT, p < 0.05). These results suggest respiratory muscle fatigue limits swimming endurance at depth as well as at the surface and RRMT improves performance.

INTRODUCTION

In the past, the pulmonary system was not considered to be a limiting factor to exercise performance, especially in healthy individuals. However, it is well known that impediments to gas transport in addition to respiratory muscle weakness limits exercise performance in patients with chronic obstructive pulmonary disease (COPD) (1-3). More recently, respiratory muscle weakness has also been shown to reduce sub-maximal and maximal exercise performance in healthy individuals (4-6). Because of the high ventilatory demands associated with maximal exercise, respiratory muscles compete with locomotor muscles for blood flow (7). In general the respiratory muscles account for 4% of the total oxygen consumption but that number can increase to 10-15% during maximal exercise and when there is airflow limitation (8). As exercise intensity increases, type III-IV afferent nerves in the respiratory muscles are stimulated, resulting in respiratory muscle vasodilatation and lower extremity vasoconstriction (9).

In comparison to exercise on land, pulmonary mechanics underwater are severely challenged due to the hydrostatic pressure differences across the chest wall and to the added resistance associated with breathing from
a self contained underwater breathing apparatus (scuba) (10). Because of the progressive increase in gas density at greater depths as well as the effects of immersion on the respiratory system, diver’s experience increases in airflow resistance, both at rest and during exercise (10-15). The similarities between divers, athletes, and patients with lung disease are that their ventilation may become flow limited during high-intensity exercise which makes them vulnerable to an elevated work of breathing and premature fatigue of the respiratory muscles (16).

Leith and Bradley were the first to demonstrate improvements in respiratory muscle strength and endurance following specific respiratory muscle training protocols (17). Since then, multiple studies have shown improvements in running, cycling and rowing performance following respiratory muscle training (18-23) and more recently, it has been shown to improve fin-swimming performance at the surface and at four feet of depth (22). That study (22) also demonstrated that a resistance training protocol was more effective at improving respiratory muscle strength and swimming performance than a voluntary isocapnic hyperventilatory (endurance) protocol (66% vs. 26% improvement of exercise endurance, respectively) (22).

The purpose of the current study was therefore, to evaluate whether resistance respiratory muscle training (RRMT) would improve respiratory muscle strength and fin-swimming performance at a depth of 55 feet of sea water (2.67 ATA, 270.5 kPa), where gas density and hence the work of breathing are significantly increased. Based on previous findings at four feet of depth (22) it is hypothesized that RRMT will: 1) reduce respiratory muscle limitations, 2) increase respiratory muscle strength as demonstrable immediately following the endurance fin-swimming trials and 3) improve fin-swimming endurance at 55 feet of depth.

METHODS

This study evaluated the effects of resistance respiratory muscle training (RRMT) on pulmonary function and swimming endurance at 55 feet of depth (2.67 ATA) in the wet pot of a hyperbaric chamber (www.smbs.buffalo.edu/crese/). The study protocol was approved by the Human Subjects Institutional Review Board at the University of Buffalo.

Subjects

Nine certified and experienced male divers were recruited from the local diving community. Their physical characteristic were: age 25.6 ± 6.8 (SD) years, height 177.0 ± 2.8 cm, and weight 80.0 ± 11.9 kg. All subjects signed an informed consent, delivered a medical history and underwent a physical examination prior to participation. Subjects served as their own controls.

Protocol Overview

Initially, the subjects completed a four week fin-training protocol. This was followed by four weeks of RRMT while a less intense swimming protocol was maintained. In order to prevent the possibility of respiratory muscle fatigue impacting exercise performance, the post-RRMT testing was performed after a rest period of 4-5 days following the last RRMT training session. At the completion of the four week RRMT protocol, subjects repeated pulmonary function tests in addition to performing two fin-swimming endurance tests at depth (55 feet) separated by 3-5 days. In random order, the subjects performed an endurance test to exhaustion (post-RRMT, open-ended) and a second test that was intentionally terminated after the same duration as the individual diver’s respective pre-RRMT
swim time (post-RRMT, post-stop). Most measurements were carried out continuously during the fin-swimming tests, both pre- and post-RRMT, however before and within 1-2 minutes following the swimming tests, subjects performed maximal inspiratory and expiratory pressure maneuvers.

A timed, isocapnic respiratory muscle endurance test (RET) was also performed pre-RRMT at the surface and at depth. Using a tidal volume of approximately 50% of slow vital capacity and a breathing frequency determined by dividing 60% of the maximal voluntary ventilation in 15 seconds by the tidal volume, subjects breathed into a partial rebreathing bag (to prevent hypocapnia) until they were unable to maintain the target ventilation presented to each subject on the computer display (18, 24).

**VO$_2$$_{max}$ Testing**

Maximal oxygen consumption (VO$_2$$_{max}$) during fin-swimming at the surface was measured from a monitoring platform that traveled over the surface of the pool. The surface VO$_2$$_{max}$ test established the fin-training velocity. Subjects swam behind a platform that increased in speed from 0.4 m/sec by 0.1 m/sec every three minutes until the subject could no longer keep up with the platform. Subjects wore a two-hose regulator mouthpiece attached to 5.1 cm diameter respiratory hoses during the VO$_2$$_{max}$ test. Expired gases were collected in Douglas bags during the last minute of each three minute workload and analyzed for volume with a dry gas meter (Harvard Model # AH-50-6164) and for gas temperature (Yellow Springs Instrument Co.). From the expired gas the fractions of carbon dioxide (CO$_2$) and oxygen (O$_2$) were measured at 1 ATA by a mass spectrometer (MGA 1100 Medical Gas Analyzer, Perkin-Elmer Corp., Pomona, California) which was calibrated daily with standard gases. A heart rate monitor (Polar Electro Inc., Lake Success, New York) recorded heart rate continuously during the test. Standard equations were used to calculate VO$_2$$_{max}$ at STPD.

Subjects performed a second VO$_2$$_{max}$ test underwater (4 feet of depth) in our circular pool using the same fins worn during the chamber tests. These tests were used to establish the workload (70% of VO$_2$$_{max}$) for the endurance tests inside the hyperbaric chamber. This VO$_2$ test was a static test requiring the diver to fin-kick against a shoulder harness attached to a pulley system equipped with variable weights, similar to the set-up used inside the chamber. The forward thrust generated from fin-kicking raised the weight from the pool floor. The fin-swimming test started with a weight (dry) of 2.4 ± 0.2 kg and at the end of each three minute workload, 1.4 ± 0.6 kg of weight was added to the system. The weights were set so the test was completed within 15 minutes. When the diver became unable to keep the weight suspended and the weight touched the pool bottom, the time was noted and taken as the end of the test. To collect expired gas from the submersed diver and impose a standardized static load on the subject, a two-hose regulator was positioned at a depth 15 cmH$_2$O shallower than the subject's chest pressure centroid (22) and attached via 5.1 cm diameter pipes to a pressurized “bag in the box” system mounted on the monitoring platform. Expired air was either directed into the bag-in-the-box during gas collection or out the exhaust side of the expiration hose of the two-hose regulator by ball valves that were manually operated. The box pressure was automatically equilibrated to the water pressure acting on the chest of the subject by the position of the two-hose regulator (-15 cmH$_2$O). Expired gas was collected during the last minute of each three minute workload, depressurized to 1 ATA and analyzed for volume and composition and VO$_2$ was calculated as described above. A heart rate monitor was used to measure heart rate during the test.
**Fin Training**

To eliminate a potential fin-training effect on endurance performance, a four week (3 d/wk) fin-training program previously shown to improve and maintain fin-swimming fitness (22) was implemented prior to beginning and during the RRMT protocol. Fin-training was conducted in a 60 m circumference (circular) pool (2.5m wide and 2.5m deep) with an underwater pacing system developed in our laboratory and used in previous studies (22, 25). All subjects wore the same model fin (Jet Fin, Scubapro, El Cajon, California) for both the training and testing phases of the study. Fin-training sessions included three 10 minute fin-swimming sessions interspaced by 10 minute rest periods. A $\dot{V}O_2$ max test, used to establish the individual subject’s fin-swimming speed and fitness level, was performed pre- and post-fin training and post RRMT. The pace of the fin-training was established to require 70-75% of the subjects $\dot{V}O_2$ max and the corresponding velocity was paced by the underwater light system (25). Heart rate was monitored with a heart rate monitor during all training sessions to ensure compliance. At the completion of the four week fin-training protocol, subjects participated in a maintenance program that required the subject to fin-swim twice per week throughout the duration of the study. The maintenance program consisted of three 10 minute swims, each requiring 70-75% of $\dot{V}O_2$ max, interspaced with 10 minute rest periods.

**Resistance Respiratory Muscle Training**

After completing the four week fin-training and baseline testing, the subjects began the RRMT phase of the study. RRMT was performed 30 min/d, 5 d/wk for four weeks. The training was paced and monitored with a dedicated, pre-programmed laptop computer (one for ea. subject) according to a previously described protocol (22). The subject wore a noseclip and breathed through a “T” shaped mouthpiece with spring loaded inlet and outlet valves. These valves imposed a combination of static/resistive loads with opening pressures of $70.1 \pm 16.1$ and $61.0 \pm 9.6$ cmH$_2$O and sustained pressures of $46.6 \pm 4.8$ and $40.1 \pm 3.3$ cm H$_2$O, during expiration and inspiration, respectively. The mouthpiece was connected to a pressure transducer and the computer. A “timer”, displayed on the computer screen, along with an audible beep, was used to prompt each inspiration and expiration against the added resistance. With each beep (every 30 seconds), the subjects took a full inspiration from functional residual capacity (FRC) followed by an exhalation to residual volume (RV). The subjects then removed the mouthpiece, breathed normally, and waited for the next timed cycle. The computer both paced the breathing frequency and recorded each training session. Subject adherence to the training program was evaluated by a researcher reviewing weekly the ventilatory pattern recorded on the computer during the previous weeks training sessions.

**Pre- and post-RRMT Testing**

Pulmonary function: A spirometer (model #131, PK Morgan Ltd., Rainham, Gillingham, Kent, UK) was used to measure maximal voluntary ventilation in 15 seconds (MVV$_{15}$), slow vital capacity (SVC), forced vital capacity (FVC), and forced expiratory volume in one second (FEV$_1$) immediately before the start of RRMT and 4-5 days after the last RRMT session. All of these variables were tested in accordance with American Thoracic Society standards and are reported in BTPS. Maximal expiratory ($P_E$ max) and inspiratory pressures ($P_I$ max) were measured immediately before and immediately after each fin-swimming endurance test. Maximal expiratory pressure was measured at total lung capacity and maximal inspiratory pressure was
measured at residual volume using a pressure transducer (model # DP15TL, Validyne Engineering Corp., Northridge California). A small hole in the mouth piece prevented use of the buccal muscles to generate anomalous pressures during the maximal maneuvers.

Closed circuit breathing system
When positioned in the wet compartment of the chamber, the subject was connected to a closed circuit breathing system (Fig. 1). The flow of oxygen (l/min) was measured by a bellows connected to a linear potentiometer located in the closed circuit system that also measured breathing frequency and tidal volume, which were monitored from outside of the chamber. The fraction of inspired O₂ (FiO₂ = 60%) was maintain constant by adding O₂ to the closed circuit system from compressed gas cylinders located outside of the chamber. Breath-by-breath analyses of end-tidal O₂ and CO₂ fractions were continuously monitored through a port in the subjects’ mouth piece via polyethylene tubing connected to the mass spectrometer. To prevent the accumulation of CO₂ within the closed system, a CO₂ scrubber was included in the breathing circuit. The CO₂ scrubber was re-packed with Sodalime (4 to 8 US mesh; Puritan Medical Products, KS) every second dive. Tidal volume (Vt) and breathing frequency (f₂) were determined from the volume tracings and stored on a computer using Biopac data acquisition software (Biopac Systems, Goleta, California). Minute ventilation (V̇ₑ = Vt x f₂) and carbon dioxide elimination (V̇CO₂ = ḞE CO₂ x V̇ₑ) were calculated from the gas and volume tracings and alveolar ventilation (V̇A) was calculated using the following formula:

\[ V̇A = \frac{(V̇CO₂/PETCO₂)}{K} \]

where V̇CO₂ is the rate of carbon dioxide produced and PCO₂ is the partial pressure of the CO₂ in the end-tidal part of the expired breath. The PET CO₂ was calculated from the integration of the breath-by-breath CO₂ tracing multiplied by the expired volume curve, and K is a constant equal to 863 which corrects for the fact that V̇CO₂ conventionally is expressed at STPD and V̇A at BTPS; it also corrects for the different units in the formula. Values were averaged over a one minute time period.

Under water Swimming Endurance
During the underwater swimming endurance test at 55 feet of sea water (fsw) (2.67 ATA) there were two safety tenders monitoring the subject. One was located in the water within arm’s reach of the subject while the second tender was positioned in the dry section of the chamber where he oversaw the function of the subject’s breathing apparatus. The underwater swimming endurance test was a stationary test performed against a weighted harness inside the wet compartment of the hyperbaric chamber. The harness system inside the chamber is based on the same design and uses the same testing criterion as the one used for the underwater maximal swimming tests in the pool (see above). The chamber endurance test required the divers to swim at 70% of their pre-determined VO₂ max. The water level in the wet pot was adjusted so the diver was positioned at a static lung load.

Fig. 1. Schematic of subject behind the “Buffalo Barrier” breathing from the closed circuit breathing system.
equal to a \(-15\) cmH\(_2\)O (Fig. 2) the maximal values recommended for breathing gear (26). Prior to testing, all subjects underwent three familiarization fin-swimming trials inside the wet compartment of the hyperbaric chamber.

During the swimming endurance test to exhaustion, the following variables were recorded; \(\dot{V}_E\), \(\dot{V}_A\), \(V_t\), \(f_b\), heart rate (HR), carbon dioxide production (\(V_{CO_2}\)) and the breath-by-breath fractions of oxygen and carbon dioxide. Heart rate was taken from a standard three-lead electrocardiogram. All data were analogue to digitally converted and visually displayed in real time and stored for later analysis using Biopac data acquisition software. All variables were analyzed at rest, following 25, 50, 75, and 100\% of their respective fin-swimming endurance time pre- and post-RRMT.

Decompression

At the completion of the study, the subject and the two safety tenders performed a mandatory 20 minute decompression stop at 10 fsw according to standard US Navy dive tables while breathing 100\% oxygen via a full face mask (for additional safety). Following the 20 minute decompression stop, surfacing or further decompression resumed while breathing ambient air, according to the bottom time of that specific dive profile.

Statistical Analysis

All descriptive data are presented as means ± SD. The data were tested for normality prior to statistical analysis, and if they passed parametric statistics were used, while if they failed non-parametric statistics were used (Sigma-Stat 3.5). Fin-swimming endurance times were analyzed using analysis of variance (ANOVA) with repeated measures (\(p \leq 0.05\)) for comparisons of pre- and post-swim times (pre-, post stop and post-open). Analysis of variance with repeated measures was also used to compare \(\dot{V}_E\), \(\dot{V}_A\), \(V_{CO_2}\) in addition to the readings of \(P_{I\text{ max}}\) and \(P_{E\text{ max}}\) immediately following the swims. If significance was established, multiple comparison procedures with the Holm-Sidak method were used to identify specific differences. However, if the normality test failed, Friedman’s repeated measure analysis on ranks test was used to compare differences pre- vs. post-RRMT (\(V_t\) and \(f_b\)), and if significant, multiple comparisons were performed using Tukey’s test. A paired t-test was used to compare the pre- and post-RRMT pulmonary function tests.

RESULTS

Impact of Fin-Training and RRMT on \(VO_2_{\text{max}}\)

Fin-swimming maximal oxygen consumption at the surface increased (13\%) as a result of the 4 week fin-training protocol and was not different following RRMT (pre fin-training 2.4 ± 0.4 l/min; pre-RRMT/post fin-training 2.7 ± 0.5; and post-RRMT 2.6 ± 0.6). These data indicate that the improvements in the post-RRMT data were not due to changes
in the subjects’ maximal oxygen consumption during the study.

**Pulmonary Function Testing**

Pre- and post-RRMT pulmonary function data measured at 1 ATA appear in Table 1. There were no changes in SVC, FVC, and FEV₁; but MVV₁₅ was significantly increased (12.9%) following RRMT. The P₃ max and Pₑ max readings at the surface (1 ATA) and at depth (2.67 ATA) are presented in Table 2. Pre-RRMT, respiratory muscle endurance was reduced 56% at 55 feet of depth (8.9 ± 4.6 min vs. 3.9 ± 2.7, 1.0 ATA vs. 2.67 ATA, respectively, p=0.024).

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<th>Table 1. Pulmonary Function pre- and post-RRMT (1 ATA)</th>
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FVC = forced vital capacity, SVC = slow vital capacity FEV₁ = forced expiratory volume in one sec, MVV₁₅ = maximal voluntary ventilation in 15 sec. Values are means ± SD. * Significant difference between post- and pre-RRMT, p < 0.05.

When Pₑ max was measured immediately following the post-RRMT (post-stop) swim compared to the pre-RRMT swim, it was significantly increased following training (29%, p < 0.05; Table 2). Similarly, P₃ max was also significantly elevated post-RRMT (post-stop) compared to before training (88%, p < 0.05; Table 2). On the other hand, both Pₑ max and P₃ max immediately following the fin-swimming test to exhaustion (post-RRMT, open-ended) were not significantly different compared to after the pre-RRMT fin-swimming tests. However, the subjects swam for a significantly longer period of time following RRMT.

<table>
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<th>Table 2. Maxima Inspiratory and Expiratory Pressures</th>
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Maximal expiratory (Pₑ) and maximal inspiratory (P₃) pressures Before Swim and immediately After each fin-swimming trial, pre-RRMT, post-RRMT (with stop), and post-RRMT (open ended). The post-RRMT Before Swim pressures are the averages of the post-RRMT open-ended and stop-dive data combined. Values are means ± SD, * Significant difference between post-RRMT After Stop and pre-RRMT After Open, p<0.05.

**Ventilation, Tidal Volume, and Breathing Frequency**

The Vₑ, Vᵥ, Vt and fₚ responses at rest and 25, 50, 75 and 100% into the exercise time plotted as a function of time pre- and post-RRMT are displayed in Fig. 3. Pre-RRMT, Vₑ, Vᵥ, and fₚ progressively increased from rest towards the end of exercise, at which point there was a significantly higher Vₑ despite a plateau in carbon dioxide production. The non-significant increase in Vᵥ was secondary to an increase in fₚ, despite a tendency for Vt to decrease towards the end of exercise, thus a ventilatory pattern (tachypnea) that may lead to premature respiratory muscle fatigue and reduced performance.

RRMT altered the ventilatory response during sub-maximal exercise (Vₑ, Vᵥ, and fₚ p<0.001). Post-RRMT, Vₑ, Vᵥ, Vt and fₚ reached an early plateau and did not significantly deviate from this level throughout the duration of the exercise test. Moreover, Vₑ and Vᵥ at 50% and 75% of swimming time
Swimming Endurance

The improved respiratory muscle strength presented above was associated with a significantly improved underwater fin-swimming endurance time following four weeks of RRMT (59 ± 51% longer, 31.3 ± 11.6 min vs. 49.9 ± 16.0, pre- vs. post- respectively, p < 0.05, see Figs. 3 and 4). Heart rates did not change significantly and equaled 121 ± 23 beats/min and 112 ± 19, pre- vs. post-RRMT (respectively, when averaged over the last minute of exercise).
DISCUSSION

The primary findings from this study are that RRMT: 1) demonstrated that improvements in respiratory muscle performance lead to increased fin-swimming performance at depth (55 fsw) where the work of breathing is significantly elevated, 2) resulted in a decrease in \( V_e \), \( f_b \) and \( \dot{V}CO_2 \) and, presumably, \( \dot{V}O_2 \), 3) attenuated the decline in \( V_t \) observed during the pre-RRMT test and 4) blunted the tachypnea seen towards the end of exercise during the pre-RRMT test.

Fin-swimming

When exercising under water, divers are often exposed to a negative static lung load (the pressure difference between the outside of the chest and the alveolar air) and increases in gas density and airflow resistance from their breathing apparatus place additional demands on the respiratory muscles at rest and during exercise. Collectively, these changes are, in all likelihood, conducive to a decrease in respiratory muscle performance and underwater exercise performance.

Fin-swimming endurance at depth was improved by \( \sim 60\% \) following respiratory muscle training and we suggest that the improvements are primarily related to respiratory muscular adaptations following training. The potential independent effects of fin-kicking technique, aerobic capacity or leg strength were most likely eliminated in the present study by the four week fin-training protocol performed prior to and during the respiratory muscle training protocol. Based on the information from the current study and from our previous work (22), we suggest that fin-swimming ability was not a co-variate explaining the improvements in underwater exercise performance. In addition, because the use of placebo control groups in previous studies has shown that sham-RMT has no effect on performance we feel confident that the increase in performance we observed was not related to psychological factors (22, 27-33), a notion strongly supported by the significantly greater respiratory muscle strength in the “stop” trials post-RRMT (than in the equally long-lasting swims pre-RRMT). Thus, the previous results demonstrate the capacity for RRMT to increase respiratory muscle strength as well as improve respiratory muscle and fin-swimming performance, changes which are in agreement with, although not direct proof of, the idea of reduced respiratory muscle fatigue.

Exercise Ventilation pre-RRMT

Prior to RRMT, the increase in \( V_e \) and \( f_b \) combined with a decrease in \( V_t \) at the end of exercise as well as the reduced ability to generate \( P_{\text{E max}} \) and \( P_{\text{I max}} \) post-exercise suggests that reduced respiratory muscle performance may have been a limiting factor during the fin-swimming endurance test. Ventilation is known to be tightly correlated to \( \dot{V}CO_2 \); however, in the presence of metabolic acidosis caused by anaerobic glycolysis and
lactic acid accumulation, $\dot{V}_E$ is increased out of proportion to $\dot{V}_{\text{CO}_2}$ (respiratory compensation for a metabolic acidosis). Although lactic acid was not measured, we suggest that the tachypneic ventilatory pattern at the end of exercise pre-RRMT is consistent with an increase in lactic acid and may have induced premature respiratory muscle fatigue (18, 24, 34). Based on the discussion above and the data from the present study we suggest that during the last minute of exercise the energy cost of respiration was elevated pre-RRMT as the subjects hyperventilated, which by contrast they did not do post-RRMT.

**Exercise Ventilation post-RRMT**

Similar to what was the case during the fin-swimming endurance test pre-RRMT, $\dot{V}_E$ remained elevated throughout the entire exercise test following training. However, the post-RRMT ventilatory response was less pronounced and the hyperventilatory response during the last minute of exercise was eliminated, although the divers exercised significantly longer. Even with the decreased ventilatory response and longer exercise time, Vt was similar to the pre-RRMT volumes during the first 20–25 minutes of exercise and tended to decline more gradually and less pronounced following RRMT. Previously we have demonstrated that RRMT increases Vt at the surface and at 4 fsw (22). The primary difference between the current study and the previous one is that the current study was performed at a depth that significantly impacts pulmonary mechanics and the work of breathing because of the increase in gas density. Although Vt did not increase following training, RRMT appeared to have delayed the decline in Vt during the endurance swim.

The reductions in total and alveolar ventilation in the present study were consistent with a reduced $\dot{V}_{\text{CO}_2}$ following training and we assume there was a similar drop in $\dot{V}_{\text{O}_2}$, although it was not measured; such a change was observed in a previous study using an identical protocol (22). Because RRMT is not expected to affect substrate utilization in fin-kicking muscles and did not change exercising heart rate, we suggest that the reductions in $\dot{V}_{\text{CO}_2}$ and $\dot{V}_{\text{O}_2}$ may be the result of respiratory muscle adaptations following training. It is possible that, despite performing a resistive strength training protocol, the respiratory muscles became more efficient and adapted to the increase in airflow resistance as a result of training. In a study by Gea et al. it was demonstrated that four days of intermittent inspiratory loading (~80 cmH2O) in dogs increased the expression of the slow myosin heavy chain isoform in the costal and crural diaphragm as well as the intercostal muscles (35). An increase in the slower myosin heavy chain isoform may be an adaptation to the increase in airflow resistance and thus, improve respiratory muscle and exercise endurance, especially under conditions of airflow limitation. A similar change in myosin has also been reported in patients with COPD, a condition with continuous airflow limitation similar to swimming at depth (36).

Although not investigated in the current study, there are other mechanisms that may directly have caused the improvements in swimming performance. First, the reduced ventilation may represent respiratory muscular adaptations following training that may also decrease the work of breathing and/or improve respiratory muscle efficiency, particularly towards the end of exercise. The earlier mentioned redistribution of blood flow from leg muscles to respiratory muscles (the steal “phenomenon”) may have occurred pre-RRMT, but not post-RRMT in the present experiments. Secondly, it is unknown what impact RRMT has on pulmonary mechanics and lung volumes while exercising at depth. Previous studies show a decrease in end expiratory lung volume (EELV) with exposure to increased pressure,
water immersion and a negative static lung load (SLL) (10, 14, 37). However, during exercise at depth, a slightly elevated EELV in divers with untrained respiratory muscles has been reported (26). Consequently, it remains to be determined if stronger respiratory muscles can increase lung volume, thus, reducing airway flow resistance, and establish a more optimal operating length of the respiratory muscles during exercise. Therefore, we suggest that additional studies are warranted to address the mechanism involved in the improvements in divers’ respiratory muscle performance resulting from RRMT.

SUMMARY

The current study extends our previous findings from experiments at the surface and four feet of depth to include improved fin-swimming performance at 55 feet of depth (22). The improvements in respiratory muscle strength were sufficient to compensate for the added resistance from the increase in gas density as the improvements in swimming endurance time were similar to those at four feet of depth (22). These findings of respiratory muscle training improving exercise performance in divers are supported by previous studies in runners (23), cyclists (19, 20, 31, 32) and rowers (21).

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