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ORIGINAL ARTICLE

# Respiratory muscle training improves swimming endurance in divers

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**Abstract** Respiratory muscles can fatigue during prolonged and maximal exercise, thus reducing performance. The respiratory system is challenged during underwater exercise due to increased hydrostatic pressure and breathing resistance. The purpose of this study was to determine if two different respiratory muscle training protocols enhance respiratory function and swimming performance in divers. Thirty male subjects (23.4 ± 4.3 years) participated. They were randomized to a placebo (PRMT), endurance (ERMT), or resistance respiratory muscle training (RRMT) protocol. Training sessions were 30 min/day, 5 days/week, for 4 weeks. PRMT consisted of 10-s breath-holds once/minute, ERMT consisted of isocapnic hyperpnea, and RRMT consisted of a vital capacity maneuver against 50 cm $H_2O$ resistance every 30 s. The PRMT group had no significant changes in any measured variable. Underwater and surface endurance swim time to exhaustion significantly increased after RRMT (66%, $P < 0.001$; 33%, $P = 0.003$) and ERMT (26%, $P = 0.038$; 38%, $P < 0.001$). Breathing frequency ($f_b$) during the underwater endurance swim decreased in RRMT (23%, $P = 0.034$) and tidal volume ($V_T$) increased in both the RRMT (12%, $P = 0.004$) and ERMT (7%, $P = 0.027$) groups. Respiratory endurance increased in ERMT (216.7%) and RRMT (30.7%). Maximal inspiratory and expiratory pressures increased following RRMT (12%, $P = 0.015$, and 15%, $P = 0.011$, respectively). Results from this study indicate that respiratory muscle fatigue is a limiting factor for underwater swimming performance, and that targeted respiratory muscle training (RRMT > ERMT) improves respiratory muscle and underwater swimming performance.

**Keywords** Respiratory muscles · Pulmonary function · Exercise · Airway resistance · Diving

## Introduction

Until recently, pulmonary limitations to oxygen transport in healthy individuals during sub-maximal and maximal exercise were not considered to limit exercise performance (Sheel 2002). In patients, such as those with chronic obstructive pulmonary disease (COPD), pulmonary limitations due to increased airway resistance are recognized as limiting maximal oxygen transport and exercise performance (Belman and Mittman 1980; Pardy et al. 1981; Sonne and Davis 1982). However, it has been shown that, even in heal-

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thy individuals, ventilatory limitations may cause a reduction of maximal exercise performance (Aaron et al. 1992; Harms et al. 2000; Mador and Acevedo 1991). The reduced exercise capacity has been attributed to a reduction in locomotor muscle oxygen transport secondary to reduced locomotor muscle blood flow. During maximal exercise, stimulation of type III–IV afferent nerves in the diaphragm and other respiratory muscles cause vasodilation of the vasculature in the respiratory muscles and a reflex vasoconstriction of the exercising limb vasculature (Harms et al. 1997; Weiss 1991). Inadequate oxygen delivery to the respiratory muscles could be due to the increased work of breathing and/or the short transit times of blood flow through the lung, leading to incomplete arterial hemoglobin saturation during maximal exercise (Dempsey et al. 1996; Wagner 1988). However, some investigators have been unable to demonstrate ventilatory limitations (Sonetti et al. 2001), while others suggest that ventilatory limitations to exercise endurance exist during prolonged exercise of moderate to heavy intensity (Babcock et al. 2002; Dempsey et al. 1996; Loke et al. 1982). In several studies, respiratory muscle fatigue has been reported as a contributing factor in reducing endurance exercise performance (Aaron et al. 1992; Harms et al. 2000; Mador and Acevedo 1991).

In comparison to exercise on land, respiratory function is further challenged during underwater exercise due to the hydrostatic pressure differences across the chest (Lundgren 1984). Previous studies have demonstrated an increased work of breathing at rest and particularly during exercise while utilizing self-contained underwater breathing apparatus (SCUBA) at depth which is principally due to added airflow resistance from both the apparatus and increased gas density (Lundgren 1984; Maio and Farhi 1967; Van Liew 1983).

In the 1970s, Leith and Bradley (1976) demonstrated that respiratory muscle strength and endurance can be improved through specific respiratory muscle training (RMT). Studies in animals have also shown that training can remodel the oxidative metabolic machinery in the respiratory muscles (Powers et al. 1990, 1992). Moreover, significant improvements in whole-body exercise endurance following isolated respiratory muscle training have been documented in elite athletes, suggesting that respiratory muscle fatigue may limit exercise performance in healthy individuals (Boutellier et al. 1992; Markov et al. 2001; Romer et al. 2002; Volianitis et al. 2001).

The purpose of this study therefore, was to evaluate whether respiratory muscle training could improve respiratory function and surface swimming with snorkel and underwater swimming performance while utilizing SCUBA. Based on data showing increased resistance and work of breathing during underwater exercise (Van Liew 1983), we hypothesized that there is a respiratory limitation to sub-maximal underwater exercise and that targeted respiratory muscle training will reduce this limitation and improve whole-body underwater exercise performance. We further hypothesized that RMT will increase the strength and endurance of the respiratory muscles, thus allowing for longer swimming times before exhaustion. We also hypothesized that compared to breathing freely at the surface, swimming endurance will be more improved in the submersed condition of a diver because of the added respiratory loads imposed by UBA and higher breathing-gas density.

## Methods

This was a randomized-controlled trial that compared the effects of two respiratory muscle training (RMT) protocols, specifically endurance (ERMT) and resistance (RRMT), against those of a placebo protocol (PRMT). Comparisons were made of pulmonary function and swimming endurance of physically fit certified divers swimming at the surface with snorkel and underwater utilizing SCUBA.

### Subjects

Thirty experienced male swimmers were recruited as subjects. The study protocol was approved by the Human Subjects Institutional Review Board at the University at Buffalo. Informed consent was obtained from each subject prior to enrollment into the study. The physical characteristics of the subjects were: age 23.4 ± 4.3 (SD) years, height 180.1 ± 6.4 cm, and weight 82.4 ± 10.4 kg.

### Fin training

To eliminate a separate effect of fin swim training during the RMT and ensure uniform fitness for fin swimming, all subjects underwent SCUBA training and 4 weeks of fin training (3 days/week) prior to participation in the RMT. Fin training was conducted in an annular pool (60 m circumference) equipped with an underwater pace-light system that the swimmers followed (Termin et al. 1999). The same model of fins was worn by all subjects (US Divers-Blades, Aqua-Lung Corp, Vista, CA, USA) for all swimming. Three 10-min fin swimming periods, interspersed with 10-min rest intervals were performed during each training session. The pace of each 10-min swimming interval was established to require an effort of approximately 80, 90, and >95% maximum heart rate, respectively. Heart rates were monitored with Polar heart rate monitors (Polar Electro Inc., Lake Success, New York, USA). This swim training program has previously been shown to optimally improve $\dot{V}O_{2max}$ and fitness in swimmers (Kame et al. 1990). Paced surface endurance swims and $\dot{V}O_{2max}$ tests were conducted prior to and after fin training. After the fin training period and during the 4 weeks of RMT, all subjects participated in a maintenance swim program. This was conducted twice per week and incorporated three, 10-min swim periods, each paced at an effort requiring 60–65% maximum heart rate, interspersed with 10 min rest periods.

After the fin training period and during 4 weeks of RMT, all subjects participated in a maintenance swim program twice/week following the protocol they used in the last week of the training phase (paced at 60–65% max heart).

Pre- and post-RMT testing

Pulmonary function testing: A Morgan Spiroflow Spirometer Model#131 (PK Morgan Ltd., Rainham, Gillingham, Kent, UK) was used to obtain maximal voluntary ventilation in 15 s (MVV), slow vital capacity (SVC), forced vital capacity (FVC), and forced expiratory volume in 1 s ($FEV_1$). All of these variables were tested in accordance with ATS standards (anonymous 1987) and are reported at BTPS. Respiratory muscle strength was estimated from measurements of maximal inspiratory pressure ($P_{Imax}$) at residual volume (RV) and expiratory pressure ($P_{Emax}$) exerted at total lung capacity (TLC). These pressures were measured with a manometer connected to a mouthpiece. A small hole in the manometer system generated a leak that prevented the use of buccal muscles to generate false pressure readings. A timed, isocapnic respiratory muscle endurance test (RET) was also performed. Using a tidal volume of approximately 50% SVC and a frequency determined by dividing 60% of the MVV value by the tidal volume, subjects breathed into a mouthpiece and rebreathing bag until they were unable to maintain the target ventilation presented to each subject on the computer display (Boutellier et al. 1992).

$\dot{V}O_{2max}$ testing

During $\dot{V}O_{2max}$ testing, subjects swam behind a monitoring platform that traveled over the pool. The platform moved at incremental speeds, starting at 0.4 m/s, and remained at each speed for 3 min intervals. Speed continued to increase until the subject could no longer maintain his position behind the platform. Expired gases were collected in ''Douglas'' bags during the final minute at each speed. Expired gas volume was measured with a calibrated dry gas meter (Harvard Model#AH-50-6164) and $CO_2$ and $O_2$ concentrations were analyzed with the previously calibrated mass spectrometer (MGA1100, Perkin-Elmer, Pomona, CA, USA). Standard equations were used to calculate $\dot{V}O_2$ and $\dot{V}CO_2$ and values were expressed at standard temperature and pressure dry (STPD).

Swimming endurance

To determine surface swimming endurance, subjects swam with fins and snorkel, paced by the underwater light system, at a rate requiring an effort of approximately 75% max heart rate, until they could no longer maintain the pace.

The underwater fin-swim endurance test was a stationary test. The subject maintained a prone position on a sliding platform with shoulders against a padded harness. The platform/harness was attached to a frame fastened to the pool wall. A pulley system incorporated a weight which hung off the back of the sliding platform and tethered the swimmer. The forward thrust generated by the swimming diver kept the weight off of the pool bottom. The inability of the subject to keep the weight off the pool floor marked the end of the endurance swim. The test was conducted at a depth of 4 ft with the subject utilizing SCUBA. A standard 80 cu ft cylinder (3,000 psi) connected to a two-hose/two-stage balanced regulator (Royal Aqua-Master#747709, Aqua Lung Corp, Vista, CA, USA) was used. The position of the regulator imparted a 10–15 cm negative static lung load to the subject and the compressed air breathed by the subjects was delivered from gear adjusted to impose a breathing resistance that generated a maximal work of breathing of 1.5–2.0 J/l in the ventilation range of 30–75 l/min, as recommended for SCUBA (Warkander and Lundgren 1995).

In order to collect expired gas from the diver and impose a standardized negative exhalation pressure on the subject, the two hoses of the regulator were attached to a pressurized ''bag in the box'' containing a Douglas air bag. The ''bag in the box'' was located at the surface and was connected via PVC pipes and manually operated valves, 2½ in. in diameter. Expired gas was directed either into the bag, into the box, or back out through the exhaust side of the regulator depending upon the stage of gas collection or gas analysis. The box pressure was automatically equilibrated to the water pressure acting on the chest of the subject at a depth of 4 ft (approximately 2 psi) by a two-hose breathing regulator. Expired gas was collected for one min, every fourth min, depressurized to one atmosphere, and analyzed for volume with the dry gas meter, temperature (Yellow Springs Instrument Co.), and $CO_2$ and $O_2$ fractions by mass spectrometer. Standard equations were used to calculate $\dot{V}O_2$ and $\dot{V}CO_2$ at STPD. Heart rates were monitored every 4 min. The dry gas meter was calibrated using a Tissot spirometer. The mass spectrometer was calibrated prior to each testing session using known calibration gases.

The forward thrust required by the subject during the stationary swimming was set by adjusting the weight pulling back on the sled so as to require a steady-state oxygen consumption of approximately 70% (approximately 1.5–2.0 l/min) of the subject's swimming $\dot{V}O_{2max}$. The required thrust was established utilizing the following regression formula derived from sets of pilot data:

$$14.593 + (2.599 \times \dot{V}O2_{max}) - (0.151 \times \text{fin training pace (s)}).$$

The weight supported by subjects in this study was 5.62 ± 1.35 kg.

At least 2–3 days prior to the administration of the underwater endurance swim test, all subjects underwent a familiarization trial on the underwater equipment. Prior to the actual study, pilot data reflected that $\dot{V}O_{2max}$ values obtained on the surface, swimming at incremental speeds, were equivalent to the $\dot{V}O_{2max}$ values obtained at depth swimming against incremental weight loads on the sled.

## Respiratory muscle training

After completing all baseline testing, subjects were randomly assigned to an endurance (ERMT), a resistance (RRMT), or a placebo respiratory muscle training protocol (PRMT). Training for all protocols was 30 min/day, 5 days/week, for 4 weeks. The training device consisted of a nose clip, mouthpiece and a plastic bag connected to a tube equipped with one-way inlet and outlet valves. The valves permitted the addition of fresh inspired air into the rebreathing bag in order to maintain a constant (isocapnic) end-tidal $CO_2$ fraction. The breathing apparatus was connected to a pressure sensor, the output of which was registered on a laptop computer. The laptop computer was used to pace the breathing frequency and to record each RMT session.

Each subject performed one RMT session per week under the supervision of the investigator. The subjects' adherence to prescribed RMT schedules during training at home was ascertained by weekly review of the laptop recordings of the ventilatory pattern used during each training session.

### *PRMT protocol*

The control group underwent placebo training for 4 weeks. Each subject was instructed, using the breathing valve assembly (without the bag), to inhale and hold his breath as timed by the computer program/recorder. Under this protocol, the subject inhaled to total lung capacity and held his breath for 10 s. This procedure was repeated every 90 s for 30 min during the first week. The rest interval was decreased to 80-, 70-, and 60-s during weeks 2, 3, and 4, respectively. Like the subjects who completed ERMT and RRMT training, PRMT subjects were told that the breathing maneuver was a technique being evaluated for its effect on swim endurance.

### *RRMT protocol*

The subjects assigned to the resistive-load (pressure-threshold) training group (RRMT) utilized the previously described equipment with some modifications. A ''timer'', displayed on the computer screen, along with an audible tone, was used to prompt each breath (starting from residual volume) taken against an opening pressure of ±50 cm $H_2O$ by properly spring loading the inspiration and expiration valves. At time zero, the subject took a deep full inspiration from FRC followed by a complete exhalation to RV. The subject then removed the mouthpiece, breathed normally, and waited for the next timed cycle. This procedure was repeated every 30 s for 30 min. The opening pressure remained constant throughout each session during the 4 week training protocol. Thus, the subject performed 60 vital capacity breaths against resistance during each training session.

### *ERMT protocol*

For the ERMT protocol, the subjects employed the equipment previously described. The volume of the bag was initially set at a value representing approximately 55% of the subject's SVC. The breathing frequency ($f_b$) was then determined by dividing 60% of MVV by the bag volume such that $f_b$ = MVV (0.60)/$V_{bag}$. The bag volume was established so that it corresponded with a frequency (breathing rate) that the subject could maintain for approximately 30 min. In each session, the subject was instructed to increase the $f_b$ by 1–2 breaths per min after 20 min of training. When possible, they then continued at this higher frequency for the last 10 min of training. The next training session began at the highest frequency achieved from the previous session and this was then maintained for 20 min followed by an increase of 1–2 breaths/min for the remaining 10 min. When $f_b$ reached 50, the bag volume was increased by 0.1 l and $f_b$ was then reduced to the value that would maintain the same level of ventilation, and the cycle was then repeated. To ensure that the ERMT protocol was isocapnic, expired end-tidal $CO_2$ was monitored using a mass spectrometer during each of the ''in-lab'' sessions with the investigator.

### Statistical analysis

Fin training data were analyzed utilizing an ANOVA with repeated measures ($P \leq 0.050$) for comparisons of pre- and post-surface endurance swim times as well as $\dot{V}O_{2max}$. Pre- and post-RMT data for surface endurance swims, pulmonary function tests (PFT's), underwater endurance swim times and related variables were also analyzed by a one-way ANOVA with repeated measures ($P \leq 0.050$). These variables included $\dot{V}O_2, \dot{V}_E$ (total ventilation), the ratio of $\dot{V}_E/\dot{V}O_2$, $\dot{V}CO_2$, RER (respiratory exchange ratio), as well as $V_T$, $f_b$, and HR throughout the endurance swim. Comparisons between means of subjects in PRMT, ERMT, and RRMT protocols were analyzed by ANOVA ($P \leq 0.05$).

## Results

### Fin training

No changes in subjects' body weights occurred during the pre-RMT 4-week fin training period. Mean $\dot{V}O_{2max}$ during surface fin swimming increased significantly (approximately 17%) for all subjects following the 4 weeks of fin-training, (2.6 ±0.54 l/min post-fin training vs. 2.2 ±0.58 l/min pre-fin training, $P < 0.001$). Additionally, fin training resulted in no change in maximal $\dot{V}_E$ (66.71 ± 18.71 vs. 68.43 ± 18.91 l/min, pre- and post-fin training, respectively). Swimming endurance on the surface, following fin training, improved by approximately 130% compared to pre-training (13.83 ± 0.29 min vs. 31.17 ± 0.4 1 min, $P < 0.001$ pre- and post-fin training, respectively).

### Effects of respiratory muscle training

#### *Training*

Compliance by the subjects to the RMT program was recorded by computer during each training session. Compliance during the RRMT and PRMT protocols was determined by breath counts from the recordings of the 30 min training sessions. Compliance with participation in the ERMT protocol was determined by the $\dot{V}_E$ changes shown on the recordings of the 30 min training sessions. The mean $\dot{V}_E$ during each ERMT session is shown in Fig. 1. The data revealed that the subjects from all groups complied with their respective RMT protocols and all data were thus included in subsequent data analysis.

#### *Pulmonary function testing*

Mean (± SD) pre- and post-RMT training pulmonary function values appear in Table 1. No significant changes were noted in the placebo group for any tested variable. In the RRMT group, neither MVV, SVC, FVC, nor $FEV_1$ changed significantly. However, both $P_{Imax}$ and $P_{Emax}$ increased significantly, post-training, by 10.8 and 15.2%, respectively. In addition, respiratory muscle endurance, as measured by the respiratory endurance test (RET), increased significantly by 30.7% with RRMT.

In the ERMT group, significant, but small, increases were observed in MVV (7.4%), SVC (2.6%), FVC (2.6%), and $FEV_1$ (3.1%). No significant changes were observed for either $P_{Imax}$ or $P_{Emax}$. Respiratory muscle endurance increased 216.7% post-training.

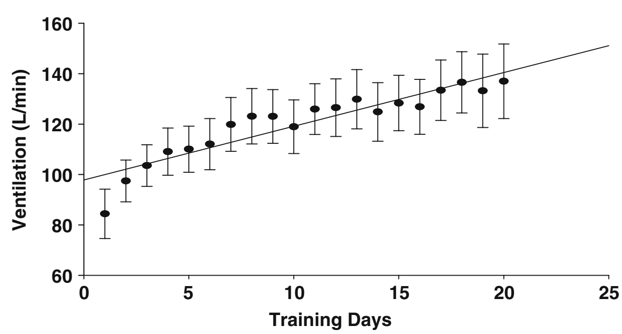


**Fig. 1** The mean (± SD) ventilation for each 30 min training session for all subjects in the ERMT protocol is plotted as a function of training days. The *solid line* is a linear regression best fit through the data

**Table 1** Pre-RMT and post-RMT values for pulmonary function and respiratory endurance (RET) are presented in this table for the placebo, endurance and resistive RMT groups

| Variable | Placebo group | | Endurance group | | Resistive group | |
|---|---|---|---|---|---|---|
| | Pre-RMT | Post-RMT | Pre-RMT | Post-RMT | Pre-RMT | Post-RMT |
| $P_{Imax}$ (cm $H_2O$) | 124.6 ± 43.1 | 123.6 ± 36.3 | 120.7 ± 35.4 | 125.7 ± 29.9 | 117.4 ± 23.7 | 130 ± 21.6 * |
| $P_{Emax}$ (cm $H_2O$) | 124 ± 36.4 | 128.2 ± 38.1 | 120.3 ± 28.5 | 126.1 ± 26.4 | 124.6 ± 25.2 | 143.5 ± 31.2 * |
| MVV (l/min) | 191.3 ± 22.1 | 195.6 ± 15.8 | 189.9 ± 31.1 | 203.9 ± 29.1* | 213.6 ± 35.3 | 206.3 ± 22.2 |
| SVC (l) | 5.70 ± 0.6 | 5.66 ± 0.8 | 6.08 ± 1.03 | 6.24 ± 1.04* | 6.10 ± 0.7 | 6.22 ± 0.6 |
| FVC (l) | 4.99 ± 0.4 | 4.76 ± 0.5 | 5.77 ± 0.95 | 5.92 ± 1.02* | 5.83 ± 0.7 | 5.93 ± 0.7 |
| $FEV_1$ (l) | 4.74 ± 0.5 | 4.54 ± 0.5 | 4.88 ± 0.7 | 5.03 ± 0.70* | 5.05 ± 0.6 | 5.12 ± 0.6 |
| RET (min) | 8.69 ± 5.5 | 10.36 ± 6.4 | 12.67 ± 8.8 | 40.13 ± 15.5* | 9.88 ± 4.7 | 12.91 ± 5.9* |

The values are mean ± SD and the (*) denotes significant differences ($P < 0.05$) from the respective pre-RMT values. Pulmonary volumes are expressed at BTPS

*Swimming endurance*

The mean surface swim (endurance) times for the placebo, resistive, and endurance RMT groups before fin training, post-fin training, and after 4 weeks of RMT appear in Fig. 2. The surface swim endurance time did not change in the placebo group after PRMT. Mean surface swim endurance time increased in the RRMT group from 31.6 ± 6.8 to 42.1 ± 8.8 min (approximately 33.2%) and from 35.4 ± 11.9 to 48.9 ± 15.4 min (approximately 38.1%) in the ERMT group.

Figure 3 illustrates the mean underwater swim time before and after RMT in the PRMT, RRMT, and ERMT groups. The swimming endurance did not change in the PRMT group. However, the mean endurance time increased by approximately 66% (18.9 vs. 31.4 min) in the RRMT group and by approximately 26% (20.3 vs. 25.7 min) in the ERMT group. The individual increase (pre- to post-RMT) in underwater swim time averaged for all subjects was 89% for RRMT and 39% for ERMT.

Underwater $\dot{V}O_2$ and heart rate response

Prior to RMT, $\dot{V}O_2$ during the underwater endurance, swim test averaged approximately 2.0, 2.0, and 2.2 l/min in the PRMT, RRMT, and ERMT groups, respectively. Post-RMT, a small (8%), yet significant, decrease in the mean $\dot{V}O_2$ values for the same load used in the pre-test and over the course of the underwater endurance swim test (2.197 ± 0.38 vs. 2.024 ± 0.42 l/min, $P = 0.040$) was noted exclusively in the RRMT group.

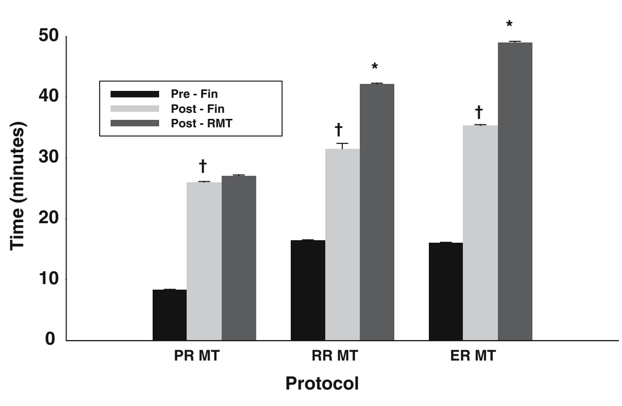


**Fig. 2** Mean (± SD) time (in min) to exhaustion for the surface endurance fin swim is plotted for each RMT training protocol. The (†) indicates a significant difference pre-fin training compared to post-fin training and (*) represents a significant difference post-RMT from post-fin training. *Black* represents pre-fin training, *light gray* post-fin training and *dark gray bars* represent post-RMT. PRMT is placebo-RMT, RRMT is resistance-RMT and ERMT is endurance-RMT

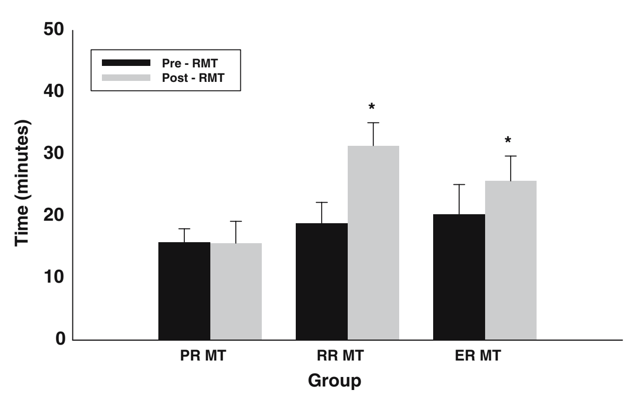


**Fig. 3** Mean (± SD) time (in min) to exhaustion for the underwater endurance fin swim is plotted for each RMT protocol pre-RMT and post-RMT. (*) indicates a significant difference compared to pre-RMT. *Black bars* represent pre-RMT and *gray bars* represent post-RMT. PRMT is placebo-RMT, RRMT is resistance-RMT and ERMT is endurance-RMT

Heart rates measured during underwater swim testing pre- and post-RMT, did not change and averaged approximately 133.11 ± 10.4 vs. 129.7 ± 13.0 beats/min in the PRMT group, approximately 131.4 ± 16 vs. 125.9 ± 13.6 beats/min in the RRMT group, and approximately 144.4 ± 17.0 vs. 142.3 ± 17.1 beats/min in the ERMT group.

### Tidal volume, frequency, and ventilation

During the underwater swim, tidal volume increased significantly after training in both the RRMT and ERMT protocols. Pre- and post-RMT tidal volumes averaged 2.5 ± 0.58 and 2.79 ± 0.69 l ($P = 0.004$) in the RRMT group. In the ERMT group, pre- and post-RMT tidal volumes averaged 2.57 ± 0.43 and 2.74 ± 0.54 l ($P = 0.027$), respectively. Breathing frequency decreased significantly only in the RRMT protocol, from 24.5 ± 5.7 to 19.9 ± 3.5, $P = 0.034$, pre- and post-RMT, respectively. Figure 4 illustrates the mean $\dot{V}_E$ as a function of endurance time. The pre-RMT data for all groups were averaged as there was no significant difference among the values. The post-RMT data for RRMT and ERMT are compared to those of the PRMT. The post-PRMT data were not significantly different from pre-RMT values for any time point. In fact, hyperventilation occurred at the 15 min. time point both pre- and post PRMT. The values for $\dot{V}_E$ in the ERMT group were lower post-RMT than pre-RMT and the hyperventilation, although similar to what was recorded for the pre- and post-PRMT occurred ten minutes later. For the RRMT group, $\dot{V}_E$ was lower throughout the test than during pre-RMT testing and this group did not demonstrate a hyperventilation at the end of the endurance swim. Furthermore, the $\dot{V}_E$ at the end of the swim was significantly lower than during the pre-RMT test, in spite of the increase in underwater swimming endurance time.

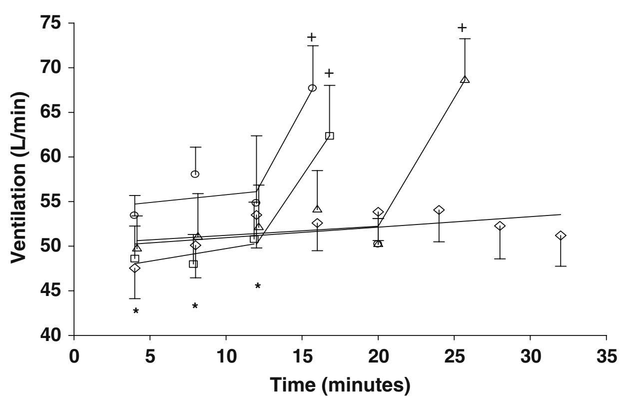


**Fig. 4** Ventilation during the underwater endurance test for subjects is plotted as follows: *circle* pre-RMT (all groups), *diamond* post-RRMT, *triangle* post-ERMT, *square* post-PRMT (abbreviations the same as in Fig. 2) and *solid line* is the line of best fit. Values are mean (± SD) and the (*) indicates a significant difference between post-RRMT and post-ERMT on the one hand and pre-RMT on the other, and (+) indicates significant increase from steady-state $\dot{V}_E$ under the respective conditions so marked

## Discussion

The present study demonstrated that both ERMT and RRMT significantly improved respiratory endurance and, additionally, RRMT improved respiratory muscle strength. These improvements were noted both within each group and compared to a placebo group (PRMT). Both ERMT and RRMT resulted in an increased tidal volume, decreased frequency, reduced total but not alveolar ventilations, reduced oxygen consumption and prolonged endurance swim time at the surface, and more so, underwater. RRMT enhanced swimming endurance significantly more that ERMT underwater did.

### Fin training

To ensure that swim fitness was not a co-variate during RMT, all subjects in this study underwent a 4-week fin-training protocol to ensure that their fitness levels ($\dot{V}O_{2max}$ and swim endurance) and fin-kicking skills were optimized, as uniformly as possible, and maintained throughout the RMT. This was accomplished by this program as evidenced by the observation that the placebo groups' swim fitness was unchanged pre- to post-RMT. This strongly suggests that the post-RMT changes observed in the RRMT and ERMT groups were not due to further increases in swim fitness, but rather were the result of the RMT these two groups underwent.

### Swimming endurance before RMT

Oxygen consumption and $\dot{V}_E$ (Fig. 4) did not change significantly during the endurance swims over the first 12.5 min, however at 15 min $\dot{V}_E$ significantly increased while $\dot{V}O_2$ remained constant, a pattern previously reported for cycling and running (Boutellier 1998; Boutellier et al. 1992; Boutellier and Piwko 1992). This increase in $\dot{V}_E$, above $\dot{V}O_2$ demands, is most likely the respiratory compensation for metabolic acidosis, in the presence of high respiratory and locomotor muscle lactate and has been suggested to be an indicator of respiratory muscle fatigue (Boutellier 1998; Boutellier et al. 1992; Boutellier and Piwko 1992). The subjects' stopped exercising at this point due to locomotor and/ or respiratory muscle fatigue.

The work of breathing during maximal and submaximal exercise has been reported to influence both respiratory muscle and locomotor muscle blood flow (Aaron et al. 1992; Harms et al. 1997; Wetter et al. 1999). Up to the point of the ventilatory threshold, where a marked increase in ventilation occurs, respiratory muscle $\dot{V}O_2$ increases linearly with ventilation. At exercise performed at 70% $\dot{V}O_{2max}$, the respiratory muscles require approximately 4.6% of the total $\dot{V}O_2$ (Aaron et al. 1992). During maximum exercise, the $\dot{V}O_2$ required by the respiratory muscles increases to approximately 10.1% (Aaron et al. 1992). These values may approach 15% of total $O_2$ consumption in the presence of extreme expiratory flow limitation (Aaron et al. 1992). As a consequence of such high $O_2$ demands by the respiratory musculature, respiratory muscle blood flow increases at the expense of blood flow to the locomotor skeletal muscles (Harms et al. 1997). Vasoconstriction in the active lower extremity musculature, along with a decrease in blood flow to the lower extremities, is directly related to an increase in the work of breathing during maximal exercise (Wetter et al. 1999). These vascular changes have been attributed to a stimulation of type III–IV afferent nerves in the diaphragm and other respiratory muscles, which when activated during maximal exercise, vasodilate vasculature in the respiratory muscles and cause a reflex vasoconstriction of the exercising limb vasculature (Harms et al. 1997; Weiss 1991). Increased diaphragmatic blood flow along with decreased limb locomotor blood flow during submaximal exercise have been reported after increasing the work of breathing in rats by experimental congestive heart failure (Musch 1993).

The underwater diving environment severely challenges respiratory muscles by imposing heavy respiratory loads, which may accelerate respiratory muscle fatigue (Thorsen et al. 1990). Pressure differences between the outside of the body and the gas pressure in the lungs can create a situation of negative pressure breathing or negative static lung loading (Lundgren 1984). A 10–15 cm negative static lung load was imposed on the subjects in the present study. Furthermore, compressed air breathed by subjects was delivered from gear adjusted to impose a breathing resistance equal to the highest acceptable flow resistance as recommended for UBA, thus adding potential for respiratory muscle fatigue (Lundgren 1984; Warkander et al. 1992).

The work of breathing increases as the density of the inhaled gases increases (Maio and Farhi 1967). The increased gas density creates increased airway resistance during both inspiration and expiration. Although our subjects were tested at a depth of only 4 ft, causing only a 13% increase in gas density (compared to surface conditions), additional respiratory resistance was imposed by the SCUBA apparatus. The fact that RRMT was more effective than ERMT in enhancing underwater swimming endurance deserves consideration. Some earlier studies in exercising divers (Derion et al. 1992; Thalmann et al. 1979) have shown reductions in expiratory reserve volume (ERV) in response to negative SSL of approximately 10–20 cm $H_2O$. The reductions amounted to about 0.5 l, less than what can be predicted from a standard pressure/volume diagram of the respiratory system. One potential explanation for this might be that under the conditions of the present type of experiments, the inspiratory muscles maintained a higher than normal tension, also at end expiration, which would increase the FRC. This, in turn, might confer two advantages reducing the tendency for respiratory muscle fatigue, namely that the inspiratory muscles can operate at a more advantageous part of their length/tension curve and that the increase in average lung volume reduces pulmonary flow resistance. The RRMT may have enhanced the ability to maintain basic inspiratory muscle tone in the submerged situation better than the ERMT. This interpretation is also in keeping with the fact that the RRMT did not offer an advantage relative to ERMT when swimming endurance was tested in surface swimming with a snorkel which involves less of an SLL challenge.

Based on the hyperventilation at the end of pre-RMT (Fig. 4), it is reasonable to speculate that this is due to lactate accumulation in locomotor and/or respiratory muscles, leading to respiratory muscle fatigue, including reduced tidal volume and increased frequency, thus to increased energy cost of respiration, respiratory muscle blood flow, and reduced blood flow and oxygen delivery to exercising muscle. This cascade of events is likely to have led to the termination of exercise.

## Respiratory muscle function after RMT

### *Pulmonary function*

RRMT in this study primarily improved maximal inspiratory and expiratory pressures, with an improvement noted also in respiratory endurance (RET), whereas ERMT improved RET, MVV, SVC, FVC, and $FEV_1$. Leith and Bradley (1976) examined the impact of strength and endurance training on respiratory muscle performance in humans. Both the strength (resistance) group and the endurance group trained 30 min/day, 5 days/week for 5 weeks. $P_{Emax}$ increased by 57 ± 9% and $P_{Imax}$ increased by 54 ± 16% in the strength-trained group, whereas in the endurance training group, 10 and 9% changes were noted for $P_{Imax}$ and $P_{Emax}$, respectively. The resistances used in that study (Leith and Bradley 1976) for the RRMT group were much greater than in the present study, thus the greater increases in maximal pressures; our increases in pressure were similar to what was observed in their (Leith and Bradley 1976) endurance group. The timed ventilatory test to exhaustion increased significantly by 15 ± 5% in the endurance group but did not significantly change in the strength group (Leith and Bradley 1976), whereas RET increased after both RRMT (31%) and ERMT (216%) and to a much greater extent. The 15 s MVV also significantly improved by 14 ± 4.7% in the endurance group, whereas there was no significant change in the strength group for the Leith and Bradley (1976) study and our results were similar.

## Impact of RMT on swimming performance

Following RRMT, surface swimming times improved 33% and underwater swimming times improved 66%. Following ERMT, surface swimming and underwater swimming times improved 38 and 26%, respectively. Results of this study suggest that the endurance performance improvements were not due to changes in the aerobic fitness of the subjects since it was unchanged throughout the study.

The improved swimming endurance was, in all likelihood, not due to psychological factors as the PRMT did not demonstrate improvements. This notion is further strengthened by the different effects on swimming endurance by ERMT and RRMT. The ERMT protocol employed in the present dive study utilized a voluntary isocapnic hyperpnea design. Improvement in endurance performance has previously been noted in cyclists and runners following such voluntary isocapnic hyperpnea (Boutellier 1998; Boutellier et al. 1992; Fairbarn et al. 1991; Markov et al. 2001; Romer et al. 2002). This type of training also improves ventilatory muscle endurance (Boutellier et al. 1992; Boutellier and Piwko 1992; Loke et al. 1982). The present results are consistent with those obtained in cyclists and runners (Markov et al. 2001). In our study, there were no significant differences in $\dot{V}O_2$ post fin-training between subjects randomly assigned to participate in the PRMT, RRMT, or ERMT group. This, coupled with the lack of significant change in heart rate, $\dot{V}O_{2max}$, $\dot{V}_E/\dot{V}O_2$ ratio, respiratory muscle endurance or strength following placebo RMT, supports the conclusion that the endurance performance improvements in the RRMT and ERMT groups were due to adaptation in respiratory muscles secondary to RMT.

Previous studies (Boutellier et al. 1992; Boutellier and Piwko 1992) have demonstrated results similar to ours using voluntary isocapnic hyperpnea (ERMT) on submaximal exercise at ~65% $\dot{V}O_{2max}$ cycling endurance which increased by 50% after RMT. This was associated with a breathing endurance increase of 268%, similar to our observation.

In contrast to the effects of the isocapnic hyperpnea protocol in our study, as well as some other studies (Boutellier et al. 1992; Boutellier and Piwko 1992), Sonetti et al. (2001) found no significant differences in performance pre- to post-RMT in cyclists in either an 8 km time trial or in a fixed work-rate cycling performance. Several factors may have contributed to the differences between our results and those of Sonetti et al. (2001). Whereas our subjects underwent either a protocol of resistive training or voluntary isocapnic hyperpnea, the subjects in the Sonetti study (Sonetti et al. 2001) utilized a RMT that combined resistance and endurance, which may not have allowed for optimal adaptation to either (McConnell and Romer 2004). More importantly, post-testing in the Sonetti study (Sonetti et al. 2001) occurred 24–48 h post-RMT, compared to 4–5 days in studies that showed improvement (Boutellier et al. 1992; Boutellier and Piwko 1992). The shorter rest period before the performance tests in the former study (Sonetti et al. 2001) apparently did not allow adequate time for full recovery of respiratory muscle function, a situation similar to what has previously been shown for other striated muscle after resistance training (Weiss 1991; Weiss et al. 2003).

Another study (Fairbarn et al. 1991) in highly trained cyclists who underwent a protocol of 16 sessions of isocapnic hyperpnea, which improved respiratory muscle endurance time by only 12%, failed to demonstrate an increase in cycling endurance time at 90% $\dot{V}O_{2max}$. However, this increase in respiratory endurance was modest and the exercise intensity high compared with the present and other studies.

A recent study using inspiratory and expiratory resistance training demonstrated that RMT resulted in improvements of respiratory muscle performance, including both conventional pulmonary function and respiratory muscle endurance (Wells et al. 2005). These improvements were similar to those observed in the present study. The former authors, however, concluded that the RMT did not significantly improve swimming performance in male and female adolescent competitive swimmers. It should be noted that there were 2 and 4% (significant) improvements in critical speed (aerobic) for men and women, respectively, that, as the authors point out, may be important in highly trained athletes. Using an incremental swimming test protocol, they found no improvements in maximal velocity. However, as these speeds were super-maximal they should not be expected to be improved by RMT. Furthermore, their subjects performed 9–11 training sessions per week for 12 weeks, with very high intensities in the second 6-week period, which, as recognized by the authors, may have led to chronic respiratory muscle fatigue that may have blunted and/or concealed potential performance improvements. This would particularly be the case if the testing was performed without sufficient recovery time (preferably 5–7 days—cf. discussion above) from this very intense RMT, something that was not addressed in the article.

Volianitis et al. (2001) investigated the effects of a resistive RMT protocol on rowing performance in competitive rowers. The experimental group showed an improvement of ~40% in $P_{\mathrm{Imax}}$, whereas the control group increased $P_{\mathrm{Imax}}$ only 4.6%. The time to complete 5,000 m on a rowing ergometer decreased 3.1% following RMT in the experimental group versus 0.9% in the control group, again demonstrating that the effects of RMT are not psychological.

### Improved pulmonary ventilation

The $P_{\mathrm{Imax}}$ and $P_{\mathrm{Emax}}$ increased significantly in the RRMT group, while pulmonary function (SVC, FVC, $\mathrm{FEV}_1$) improved after ERMT and RET improved in both, particularly in ERMT. Additionally, the tidal volume during exercise in the RRMT protocol increased by 11%, in conjunction with a 23% decrease in $f_{\mathrm{b}}$, while the ERMT groups had a 7% increase in TV and 15% decrease in $f_{\mathrm{b}}$. Romer et al. (2002) found training that incorporated 30 inspiratory efforts against a resistance ~50% of maximal inspiratory mouth pressure, similar to that used in the present study, resulted in a $V_{\mathrm{T}}$ that was maintained during the latter stages of incremental exercise versus a more tachypneic pattern in the placebo group, as was also observed in this study. In spite of the small decrease in $\dot{V}_{\mathrm{E}}$ the reduction in $f_{\mathrm{b}}$ and increased $V_{\mathrm{T}}$ allowed the alveolar ventilation to be maintained in both surface and underwater swimming. It is possible that the increased inspiratory strength and/or endurance can contribute to a shortened time of inspiration; however, this was not measured in the present study. Such a change, in conjunction with the increased strength and endurance of the respiratory muscles, might allow for a more effective regulation of resting muscle-length and lung-volume, thereby minimizing the work of breathing.

The adaptations described above may reduce the oxygen cost of ventilation. In the present study, total ventilation decreased about 10%, while alveolar ventilation was unchanged, after RMT and the steady-state $\dot{V}O_2$ decreased by 8%, as well. Given the energy cost of ventilation previously reported, it is attractive to propose that the post-RMT reduction in $\dot{V}O_2$ was due to the reduction in $\dot{V}_{\mathrm{E}}$. This conclusion is consistent with reported increases in oxidative enzyme potentials (SDH, citrate synthase) in the diaphragm and intercostal muscles (Akabas et al. 1989; Keens et al. 1977) and increased proportion of Type I fibers in external intercostals (Ramirez-Sarmiento et al. 2002) following respiratory loading in an animal model.

## Summary

The RRMT and ERMT significantly improved exercise endurance in subjects swimming both on the surface and underwater. These changes were associated with increased tidal volume while $\dot{V}_{\mathrm{E}}$ and frequency were reduced, and alveolar ventilation was maintained. The respiratory endurance increases following the ERMT and RRMT protocols reflect the specificity of training in that, respiratory endurance was improved significantly more after ERMT than RRMT; however, inspiratory and expiratory pressures were greater after RRMT. The ERMT protocol of voluntary isocapnic hyperpnea may more closely replicate exercise ventilation demands on land where they have shown greater exercise performance improvements than RRMT. Breathing underwater, however, requires a greater generation of force by the inspiratory and expiratory muscles. The improvements brought about by the RRMT protocol would thus help to explain the superior underwater swim endurance that followed the RRMT (66%), as opposed to that which followed the ERMT protocol (26%) and surface swimming (33–38%). Interestingly, RMT using maximal resistance has been found not to improve exercise endurance, in spite of large changes in inspiratory and expiratory pressures (Leith and Bradley 1976). Further studies are needed to determine the optimal resistance, duration, and frequency of training to maximize exercise endurance in divers, and to determine whether similar benefits would be observed at depths greater than 4 ft.

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