Resistive respiratory muscle training improves and maintains endurance swimming performance in divers.

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Lindholm P, Wylegala J, Pendergast DR, Lundgren CEG. Resistive respiratory muscle training improves and maintains endurance swimming performance in divers. Undersea Hyperb Med 2007; 34(3):169-180. Respiratory work is increased during exercise under water and may lead to respiratory muscle fatigue, which in turn can compromise swimming endurance. Previous studies have shown that respiratory muscle training, conducted five days per week for four weeks, improved both respiratory and fin swimming endurance. This training (RRMT-5) consisted of intermittent vital capacity breaths (twice/minute) against spring loaded breathing valves imposing static and resistive loads generating average inspiratory pressures of ~ 40 cmH_2O and expiratory pressures of ~ 47 cmH_2O. The purpose of the present study (n=20) was to determine if RRMT 3 days per week (RRMT-3) would give similar improvements, and if continuing RRMT 2 days per week (RRMT-M) would maintain the benefits of RRMT-3 in fit SCUBA divers. Pulmonary function, maximal inspiratory (P_{insp}) and expiratory pressures (P_{exp}), respiratory endurance (RET), and surface and underwater (4 fsw) fin swimming endurance were determined prior to and after RRMT, and monthly for 3 months. Pulmonary function did not significantly improve after either RRMT-3 or RMMT-5; while P_{insp} (20 and 15%) and P_{exp} (25 and 11%), RET (73 and 217%), surface (50 and 33%) and underwater (88 and 66%) swim times improved. $\dot{V}O_2$, $\dot{V}_E$ and breathing frequency decreased during the underwater endurance swims after both RRMT-3 and RRMT-5. During RRMT-M P_{insp} and P_{exp} and RET and swimming times were maintained at post RRMT-3 levels. RRMT 3 or 5 days per week can be recommended to divers to improve both respiratory and fin swimming endurance, effects which can be maintained with RRMT twice weekly.

INTRODUCTION

In comparison to exercise on land, respiratory work during underwater exercise is increased due to the hydrostatic pressure differences across the chest as well as increased flow resistive respiratory work (1,2). 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 (2). The increased work of breathing is principally due to added airflow resistance from both the apparatus and increased gas density (1,3,4). This is likely to require augmented oxygen delivery via increased blood flow to respiratory muscles. It has recently been shown in healthy individuals that ventilatory limitations may cause a reduction of maximal exercise performance on land (5,6,7,8). The weakened exercise capacity has been attributed to a reduction in locomotor muscle oxygen transport secondary to diminished locomotor muscle blood flow (6,9,10). In several studies on land, respiratory muscle fatigue has been reported as a contributing factor to reduced maximal and endurance exercise performance (5,6,7,8,11,12,13). These same factors may also limit exercise performance in divers.

Leith and Bradley (14) were the first to demonstrate that respiratory muscle strength and endurance can be improved through specific respiratory muscle training (RMT). More recently, significant improvements in whole-body exercise endurance on land following specific respiratory muscle training have been documented in elite athletes (8,15,16,17,18,19). It has recently been shown in our laboratory that resistive RMT (RRMT) which is performed by vital capacity maneuvers against spring loaded breathing valves imposing about 50 cmH_20 inspiratory and expiratory opening pressures (which is 25 -50% of max pressures) five days per week for four weeks significantly improved swimming endurance at the surface and at 1.22 m under water (referenced to the membrane of a back-mounted breathing regulator) (20). These improvements were greater than those achieved by voluntary isocapnic hyperpnea which has been employed in many other land based studies (8,15,16,17,18,19). Training five days per week may be too intense to maximize improvements in respiratory and fin swimming muscles. We reasoned that reducing the number of training days to three may result in greater improvements in swimming performance as has recently been shown for locomotor muscles (21,22,23). On the other hand, three days per week for 4 weeks of RRMT may not provide a sufficient stimulus for adaptation and thus performance improvement may not occur, or be less that of RRMT-5.

The purpose of this study therefore, was to evaluate whether resistive respiratory muscle training three days per week for four weeks could improve respiratory function and surface swimming (with snorkel) and underwater swimming performance while utilizing scuba to the same degree as previously shown for a training schedule of five days per week for four weeks (20). In addition, we hypothesized that the improvements after RRMT-3 could be sustained over three months by RRMT twice per week (RRMT-M).

METHODS

The study protocol was approved by the Human Subjects Institutional Review Board of the University at Buffalo. Informed consent was obtained from the subjects prior to enrollment in the study. This study compared the effects resistance respiratory muscle training (RRMT) performed 3 days per week with RRMT five days per week, for 4 weeks, on respiratory and fin swimming performance in trained scuba divers. In addition, the potential usefulness of a two day per week RRMT (maintenance RRMT-M), after RRMT-3, was evaluated over a three month period.

Subjects

Twenty experienced and practicing SCUBA divers were recruited from the local diving community. The physical characteristics of the subjects in the RRMT-3 and RRMT-M were: age 22.9 ± 5.0 (SD) years, height 179.8 ± 28.0 cm, and weight 81.7 ± 12.7 kg, and for RRMT-5: age 25.0 ± 5.0 (SD) years, height 179.2 ± 5.1 cm, and weight 81.9 ± 7.7 kg.

The subjects were divided into two groups, one doing RRMT three days per week (RRMT-3) and one five days per week (RRMT-5). Both performed 4 weeks of fin swimming training followed by RRMT for 4 weeks. The RRMT-3 group also did RRMT-M.

Fin Training

To ensure that all subjects had uniform fitness for fin swimming, and that fitness would not influence the data collected pre- or post-RRMT, all subjects underwent fin training for four weeks (3 days/week) prior to participation in the RRMT. Fin training was conducted in an annular pool (60 m circumference) with the subjects' speed paced by a computerized underwater pace-light system using a training program previously shown to optimally improve $\dot{V}O_{2max}$ and fitness in swimmers (24). The same model of fins was worn by all subjects (US Divers-Blades, Aqua-Lung Corp, Vista, CA) for all swimming. Three 10-minute fin swimming periods, interspersed with 10-minute rest intervals were performed during each training session. The pace of each 10-minute swimming interval was established to require an effort of approximately 80%, 90%, and >95% of maximum heart rate, respectively. Heart rates were monitored with Polar heart rate monitors (Polar Electro Inc., Lake Success, New York). After the fin training period and during the 4 weeks of RRMT and during the three months of RRMT-M, all subjects participated in a maintenance swim program twice per week (three 10-minute swim periods, paced at 60-65% maximum heart rate, interspersed with 10 minute rest periods).

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 seconds (MVV), slow vital capacity (SVC), forced vital capacity (FVC), and forced expiratory volume in one second (FEV_1). All of these variables were recorded in accordance with ATS standards 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 the 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 (to maintain normocapnia) until they were unable to maintain the target ventilation presented to each subject on the computer display (20).

Maximal $\dot{V}O_2$ determined during Surface Swimming

Paced surface $\dot{V}O_{2max}$ tests were conducted prior to and after RRMT. Using fins, subjects swam at the surface following a monitoring platform that paced swimming speed and on which data were collected. The velocity was increased from 0.4 m/s in 0.1 m/sec increments every three minutes until the diver could no longer maintain the speed. Via a two-hose mouth piece expired gases were collected in "Douglas" bags during the last minute of each speed segment for determination of $\dot{V}O_2$, a venous blood sample was taken 5-7 min post-swim for lactate (anaerobic metabolism). Expired gas volume was measured with a 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). Standard equations were used to calculate $\dot{V}O_2$ and $\dot{V}CO_2$ and values were expressed at standard temperature, pressure dry gas (STPD).

Swimming Endurance at the Surface

Subjects swam with fins on the surface, paced by the underwater lights at a rate requiring an effort of approximately 70-75% of maximal heart rate, until they could no longer maintain the pace. Heart rates (HR) throughout and post-swim plasma lactate levels were determined as described above.

Swimming Endurance Underwater

Prior to the underwater endurance swim test, all subjects underwent a familiarization trial on the equipment. For the underwater fin-swim endurance test at a depth of 1.22 m (referenced to the membrane of a back-mounted breathing regulator) the subject maintained a prone position on a platform with shoulders against a padded harness. The platform could slide with very low friction on a frame fastened to the pool wall. A pulley system incorporated a weight which imposed a rearward pull on the diver via the platform. The weight was kept off the bottom of the pool as long as the subject's swimming effort generated enough forward thrust on the platform; his inability to keep the weight suspended marked the end of the endurance swim. The weight the subject had to keep suspended with his swimming effort was set to require a $\dot{V}O_2$ of 70-75 % (~ 2.0 l/min) of the subject's individual swimming $\dot{V}O_{2max.}$ The mean weight used by all subjects was 5.62 ± 1.35 kg.

The subject breathed from a two-hose/two-stage balanced regulator (Royal Aqua-Master #747709, Aqua Lung Corp, Vista, CA) supplied with breathing air from a standard tank (80 cu ft, 3000 psi). The breathing gear was adjusted to impose a breathing resistance equal to the highest acceptable flow resistance as recommended for scuba (10-15 cm negative static lung load) (1,2). Expired gases were collected by the two hoses of the regulator being attached via PVC pipes and valves (2 ½ in diameter)to a pressurized "bag in the box" containing a Douglas air bag. The box pressure was automatically equilibrated to the water pressure acting on the chest (2 psi) by a scuba breathing regulator placed under water at the proper depth relative to the subject's chest. 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. Expired gas was collected for one min, every fourth min, depressurized to one atmosphere, and analyzed for volume with a calibrated dry gas meter, temperature (Yellow Springs Instrument Co.), and CO_2 and O_2 fractions by a calibrated mass spectrometer (MGA1100, Perkin-Elmer, Pomona, CA). Standard equations were used to calculate $\dot{V}O_2$ (STPD) and $\dot{V}_E$ (BTPS). Heart rates were monitored every 4 minutes. Five minutes after the underwater endurance swim the divers completed pulmonary function testing as well as maximal P_{exp} and P_{insp}.

Resistive Respiratory Muscle Training (RRMT)

After completing all base line testing, subjects were randomly assigned to either RRMT-3 or RRMT-5. Training for all protocols was 30 min/day for 4 weeks. The training devices consisted of a nose clip and a mouthpiece with a pressure transducer, the output of which was registered on a laptop computer. The mouthpiece was fitted with spring loaded expiration and inspiration valves imposing opening pressures of 70.1 ± 16.1(SD) and 61.0 ± 9.6 cmH_2O and sustained pressures of 46.6 ± 4.8 and 40.1 ± 3.3 cm H_2O. Thus the training device generated a combination static/resistive load. The laptop computer was used to pace the breathing frequency and to record each RRMT session. A "timer" displayed on the computer screen, along with an audible tone, was used to prompt each training breath. At time zero, the subject expired to RV, put the mouth piece in the mouth and took a full vital capacity inspiration 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 sec for 30 min. Thus, the subject performed 60 vital capacity breaths against resistance during each training session.

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

STATISTICAL ANALYSIS

Pre- and post-RMT data for RRMT-3 and RRMT-5 data for surface endurance swims, pulmonary function tests, underwater endurance swim times and related variables were analyzed by a one-way ANOVA with repeated measures ($P \leq 0.050$). These variables included pulmonary function data, swim time, $\dot{V}O_2$, $\dot{V}_E$ (total ventilation), V_T, f_b, lactate and heart rate (HR) and are shown in Tables 1 to 3 as the absolute mean and standard deviations of the group data. Normalizing for differences in pre-RRMT data the relative improvement in swimming endurance for each subject was also calculated in percent and the means and standard deviations of those calculations are shown in Fig. 1.

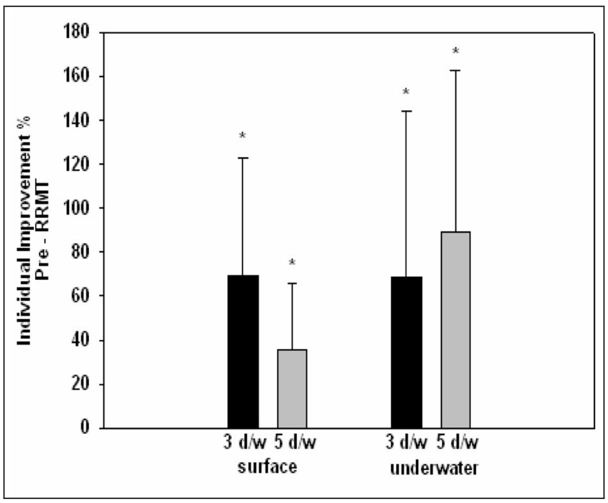

Fig. 1. The average percentage increases (±SD) Pre- to Post-RRMT in surface (left panel) and underwater swimming endurance (right panel) are plotted for RRMT-5 (5 d/w) and RRMT-3 (3 d/w). The * indicates a significant improvement from pre-RRMT. The % improvements in individual subjects were not different between RRMT-3 and RRMT-5.

RESULTS

All subjects in both groups complied with the protocol and all their data are included in the analysis.

Pulmonary function

The data for pulmonary function and respiratory endurance are shown in Table 1, and Figure 2. There were no significant changes in VC, FEV_1, and FVC for either RRMT-3 or -5, while MVV increased significantly only after RRMT-3 (18%). After RRMT-3 and RRMT-5, respectively, significant increases were recorded in P_{exp} (20% and 15%) and in P_{insp} (25% and 11%). In addition, respiratory endurance increased 73% after RRMT-3 and 217% after RRMT-5.

Pulmonary function		Pre-3	Post-3	Sign.	Pre-5	Post-5	Sign.
VC	(liters)	5.51	5.75	NS	6.10	6.22	NS
		0.92	1.16		0.7		
FEV_1	(l/sec)	4.66	4.89	NS	5.05	5.12	
		0.63	1.32		0.6		
FVC	(liters)	5.25	5.52	NS	5.83		
		1.00	1.18		0.70		
MVV	(liters)	166.0	195.9	*	213.6		
		20.31	30.27		35.3		
P_{exp}	(cm H_2O)	131	157	*	125	144	*
		11	14		25		
P_{insp}	(cmH_2O)	113	141	*	117	130	*
		23	27		24		
Respiratory endurance (RET)							
Duration	(min)	12.80	22.12	*	12.67		
		7.77	16.17		8.8		

Table 1. Comparison of respiratory performance pre- and post- RRMT-3 and RRMT-5. Values are mean ± SD for all variables. Significant differences between pre-RMT recordings are shown by the * for each group.

$\dot{V}O_2$max swim

Comparing pre to post-RRMT for either the 3 or 5 day RRMT during the progressive velocity surface swim tests there were no

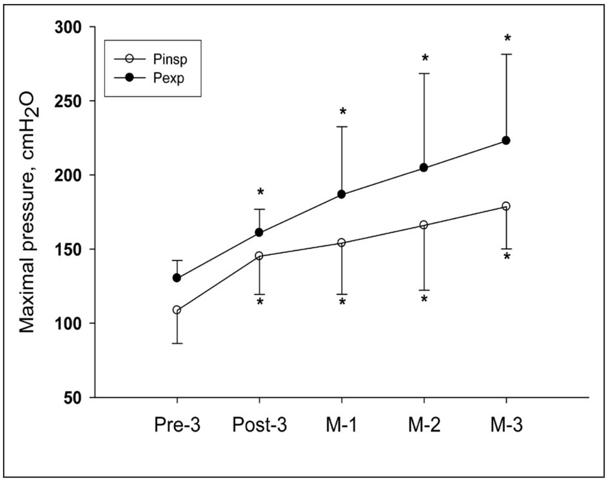

Fig. 2. The average (±SD) P_{exp} and P_{insp} after RRMT-3 and after one, two, and three month's maintenance RRMT-M. Significant differences form post-RRMT-3 are shown by *.

significant differences in maximal swimming speed (mean ± s.d. = 1.08 ± 0.08 m/sec, p = 0.08), $\dot{V}O_{2max}$ (2.54 ± 0.42 l/min, p = 0.56), maximal heart rate (172 ± 14 b/min, p = 0.33) or post swim lactate (6.54 ± 1.57 mM, P = 0.13). These data indicate that neither RRMT- 3 nor RMT-5 improve maximal oxygen transport.

Surface swim endurance

The gains in swimming time in the surface endurance swims at 70-75 % of $\dot{V}O_{2max}$ data are shown in Table 2 and Figure 3. For the group the swim duration increased 50% after RRMT-3 and 33% after RRMT-5. The increased endurance in both RRMT-3 and RRMT-5 occurred despite the lack of significant differences in heart rates during the swim. However, post- swim lactate was reduced 29% (RRMT-3) and 21% (RRMT-5), indicating a reduced anaerobic component to the swimming energetics after respiratory muscle training.

To demonstrate the potential enhancement in swimming endurance from performing RRMT an individual surface swimmer can expect the earlier mentioned normalization of individual results to pre-RRMT values was made, averaged and presented

		RRMT-3			RRMT-5		
Surface swim endurance		**Pre-**	**Post-**	**Sign.**	**Pre-**	**Post-**	**Sign.**
Duration	(min)	25.49	38.28	*	31.88	42.33	*
		9.98	17.62		6.71	8.84	
HRmax	(b/min)	161	159	NS	157	155	NS
		15	13		9	10	
HRaverage	(b/min)	146	145	NS	131	126	NS
		13	11		16	14	
Post-swim lactate (mM)		4.40	3.11	*	3.9	3.1	*
		2.23	1.52				
Underwater swim endurance							
Duration	(sec)	25.48	47.97	*	19.01	31.60	*
		7.12	31		10.65	11.69	
$\dot{V}O_2$	(l/min)	2.23	2.11	*	2.197	2.024	*
		0.48	0.47		0.38	0.42	
$\dot{V}_E$	(l/min)	64.36	55.11	*	62.5	55.8	*
		15.66	12.65		12.39	12.48	
VT	(liters)	2.22	2.12	NS	2.50	2.79	*
		0.46	0.57		0.58	0.69	
Vf	(br/min)	29	26	*	25	20	*
		5	8		6	4	
HR	(b/min)	162	151	*	131	126	NS
		11	15		16	14	
Post-swim lactate (mM)		3.84	3.34	NS	5.2	4.8	NS
		2.16	1.70		1.7	1.3	

* indicates significant difference from pre-RRMT.

Table 2. Comparison of fin swimming performance pre- and post- RRMT-3 and RRMT-5. Values are mean ± SD for all variables. Significant differences from pre-RRMT are shown by * for each group.

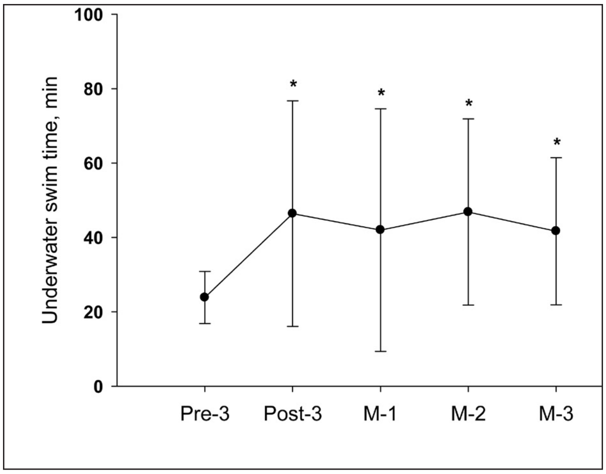

Fig. 3. The average (±SD) underwater swimming time after RRMT-3 and at one, two, and three month's maintenance RRMT-M. No significant differences were noted.

in Fig.1 As can be seen an improvement in surface swimming endurance of 36% (RRMT 5 days) to 69% (RRMT 3 days) can be expected.

Underwater swim endurance

These data for the groups are shown in Table 2. Endurance increased significantly i.e. by 88% after RRMT-3 and by 66% after RRMT-5. In spite of the longer swim times, $\dot{V}O_2$ decreased significantly by 5% and 8% and $\dot{V}_E$ significantly by 14% and 11% after RRMT-3 and RRMT-5, respectively. Heart rate during the endurance swim was significantly lower after RRMT-3 but not after RMT-5 . Post-swim lactate was not significantly different pre- to post-RRMT or between RRMT-3 and RRMT-5, although the swims were significantly longer post-RRMT than pre-RRMT. The reduced $\dot{V}_E$ after RRMT-3 was primarily due to a significant reduction in breathing frequency (10%), while after RRMT-5 frequency decreased significantly (20%), but in this case tidal volume increased significantly (11%), however the product of the two parameters resulting in an 11% lowering of $\dot{V}_E$ after RRMT-5.

To demonstrate the potential enhancement in underwater swimming endurance from performing RRMT an individual diver can expect the earlier mentioned normalization of individual results to pre-RRMT values was made, averaged and presented in Fig.1 As can be seen an improvement in swimming endurance (at 1.22 m of depth) of 69% (RRMT-3 days) to 88% (RRMT-5 days) can be expected.

Five minutes after the post-RRMT swim, compared to after the pre-RRMT swim, P_{exp} and P_{insp} were significantly higher in both groups (159 ± 20 vs 138 ± 15 cmH_2O for RRMT-3 and 144 ± 24 vs 125 ± 6 cm H_2O for RRMT-5, respectively). Other pulmonary function data measured post-swim were not affected by RRMT.

RRMT-Maintenance

The data from monthly testing post-RRMT-3 for maintenance effects (RRMT-M) are shown in Table 3 and Figs. 2 and 3. The VC, FEV_1 and FVC did not increase significantly by RRMT-3 and did not change during RRMT-M (Table 3). MVV increased significantly after RRMT-3 and remained elevated throughout RRMT-M. Maximal P_{exp} and P_{insp} were significantly increased by RRMT-3 and they continued to increase in RRMT-M reaching improvements of 71% and 64 %, respectively,

Pulmonary function	Post-3	RRMT-M-1	RRMT-M-2	RRMT-M-3
VC (liters)	5.8	5.6	5.6	5.5
	1.2	1.0	1.0	1.0
FEV_1 (l/sec)	4.46	4.58	4.53	4.48
	0.88	0.81	0.72	0.76
FVC (liters)	5.37	5.41	5.43	5.42
	1.02	1.10	1.02	1.11
MVV (liters)	192	194	198	197
	32	31	32	26

Table 3. Comparison of selected pulmonary function data post- RRMT-3 and RRMT-M one month (-1), two months (-2) and three months (-3). Values are mean ± s.d. for all variables. There were no significant differences between post- RRMT-3 and RRMT-M-1-3.

after the three months. Respiratory endurance also remained elevated and did not decrease from post-RRMT-3, during the RRMT-M (22.43 min. pre-RRMT vs. 23.37, 21.38, and 21.42 min. during RRMT-M-1 to -3, respectively).

The maximal swimming velocity did not increase after RRMT-3 but was maintained throughout the RRMT-M phase (1.07 ± 0.11 m/sec post-RRMT and 1.11 ± 0.07, 1.11 ± 0.07, and 1.07 ± 0.08 m/sec after the three RRMT-M periods, respectively). Maximal aerobic power ($\dot{V}O_{2max}$) was not affected by RRMT-3 and also remained constant throughout RRMT-M (2.55 ± 0.41 l/min post-RRMT vs 2.62 ± 0.41, 2.42 ± 0.35, and 2.31 ± 0.58 l/min RRMT-M-1 to -3). Similarly, maximal lactic acid after the $\dot{V}O_{2max}$ swim at the surface did not change significantly after RRMT-3, and remained constant throughout RRMT-M (6.5 ± 1.6 mM post-RRMT vs. 6.4 ± 1.9, 5.1 ± 1.5, and 5.5 ± 1.7 mM during the three RRMT-M periods, respectively).

Underwater endurance swim time increased 88% after RRMT-3 and remained elevated for the three months of the RRMT-M (76, 96, and 75%, respectively). Furthermore, the reduced ventilation after RRMT-3 was maintained during the 3 months of RRMT-M (77.62 ± 14.92 l/min post-RRMT vs. 84.70 ± 12.46, 74.34 ± 15.01, and 71.01 ± 15.59 l/min in the three RRMT-M periods, respectively); these levels of ventilation were generated while breathing frequency remained reduced (29 ± 7 breaths/min post-RRMT vs. 30 ± 12, 33 ± 8, and 30 ± 7 breaths/min in the three RRMT-M periods, respectively) and tidal volume increased (2.66 ± 0.64 post RRMT vs. 2.85 ± 1.14, 2.23 ± 0.47, and 2.39 ± 0.56 liters, respectively). Heart rate during the swims did not change significantly after RRMT-3 nor during the first month of RRMT-M, however, it was decreased after two months (162 ± 17 post-RRMT vs, 166 ± 13, 147 ± 9, and 150 ± 19 b/min in the three RRMT-M periods, respectively).

Five minutes after the post-RRMT swim P_{exp} and P_{insp} were significantly higher in both groups than pre-RRMT and remained so for each of the three month post-RRMT tests (165 ± 31, 185 ± 49, and 199 ± 67 cmH_2O for P_{exp} and 146 ± 26, 163 ± 35, and 179 ± 35, cmH_2O for P_{insp}, respectively) and the same was the case with MVV (203 ± 32, 199 ± 28, and 197 ± 35 l/min, respectively). Other pulmonary function data measured post-swim were not affected by RRMT over the three-months of RRMT-M.

DISCUSSION

The present study demonstrated that both RRMT-3 and RRMT-5 significantly improved respiratory muscle strength and also improved respiratory endurance. Both RRMT-3 and RRMT-5 resulted in a decreased frequency, reduced ventilation and oxygen consumption and prolonged endurance swim times. Furthermore RRMT-M for three months maintained the improvements observed after RRMT-3.

Fin training

To ensure that swim fitness was not a co-variate during RRMT, all subjects in this study underwent a four week fin-training protocol to ensure that their fitness levels ($\dot{V}O_{2max}$) and fin-kicking skills were optimized, as uniformly as possible, and maintained, throughout the RRMT and RRMT-M protocols. This was accomplished as the $\dot{V}O_{2max}$ test swim data did not change significantly during RRMT or RRMT-M. This is also evidenced by the observation that, in a previous study, using the same protocol a placebo group's swim fitness was unchanged pre- to post-RMT (20).

Respiratory muscle function after RMT

Pulmonary function

RRMT in this study primarily improved maximal inspiratory and expiratory pressures and respiratory endurance (RET).

The improvements in pressures in both RRMT-3 and RRMT-5 were less than observed by Leith and Bradley (14) as they used maximal resistance and this study only used ±50 cm H_2O (~40/% of max). RRMT-3 and -5 significantly increased RET (73 and 217%, respectively), which is in agreement with previous studies in divers (20). There were no significant changes in pulmonary function after 3 or 5 days per week of RRMT which is agreement with the observations by Leith and Bradley (14) and Wylegala et al (20). Studies that used voluntary isocapnic hyperpnea showed increased pulmonary function and RET, but not altered P_{exp} and P_{insp} (20). Based on these data, improving P_{exp} and P_{insp} (15%) and RET (73%) is sufficient to result in improvements in respiratory performance, as well as fin swimming endurance. The demonstration in the present study of an ergogenic effect of RRMT is in agreement with a previous study of fin swimming (20) and many studies of land exercise (8,15,16,17,22,25,26,27,28).

The underwater diving environment imposes increased respiratory loads on divers and thus challenges respiratory muscles. Respiratory muscle fatigue may result as a consequence of these challenges (4). The work of breathing increases as the density of the inhaled gases increases (1). Although our subjects were tested at a depth of only 1.22 m, limiting the increase in gas density to 13% (compared to surface conditions), it has been speculated that increases in lung volumes underwater would increase inspiratory flow rate, and force the inspiratory muscles to develop more tension. This is so because at the larger lung volumes a stronger recoil pressure from the chest-lung combination has to be overcome for inspiration. This could contribute to increased respiratory muscle energy utilization and respiratory muscle fatigue during underwater swimming with scuba. In addition to the increased work of breathing associated with high gas density underwater, a reduction of the end-expiratory lung volume will shorten the resting length of the diaphragm and consequently lower the point on the length-tension curve from which it operates. Reducing the resting length of a canine diaphragm to 70% of the optimal length lowered the maximal force generation at a stimulation frequency of 100 Hz by 40% (29). As exercise intensity and gas density increase, the added resistive work of breathing leeds to increases in both FRC and alveolar CO_2 tension (2,4). If resting length limits the ability of the respiratory muscles to generate force, compensation can be made temporarily by increasing the firing frequency, which however renders the diaphragm much more susceptible to fatigue (29).

Considering the hyperventilation at the end of the endurance swim seen pre-RRMT in most subjects in this study, it is reasonable to speculate that this was due to stimulation from lactate originating in respiratory and/or locomotor muscles. This might have led to respiratory muscle fatigue, generating reduced tidal volumes and increased frequency and consequently increased energy cost of respiration, respiratory muscle blood flow, and reduced blood flow and oxygen delivery to other exercising muscles. This cascade of events is likely to have led to the termination of exercise pre-RRMT and it is noteworthy that there was no paradoxical terminal hyperpnea post-RRMT whether the training had been conducted 3 or 5 days weekly.

Impact of RRMT on swimming Performance

Following RRMT, surface and underwater swimming times improved markedly after RRMT-5 and RRMT-3. The improvements in endurance performance were not due to changes in the aerobic fitness of the subjects as this was constant over the entire period (RRMT and RRMT-M). The improved swimming endurance was also, in all likelihood, not due to psychological factors as previous studies in divers have shown that placebo RMT did not have an impact on respiratory or fin swimming performance (20) and RMT studies on land have shown that control and placebo groups did not improve performance (8,15,16, 17,18,25,27,30).

One previous study failed to demonstrate an improvement in swimming performance after RMT (31). However, that study used very high intensity swimming at which an ergogenic effect of RMT should not be expected (31). Two studies (22,32) have reported lack of significant differences in performance pre- to post-RMT in cyclists but the overwhelming number of studies in cyclists, rowers and runners have shown improvement in respiratory and locomotor muscle performance on land using voluntary isocapnic hyperpnea (8,15,16,17,18 ,25,27,30).

The P_{max} and $P_{insp}max$ increased significantly after both RRMT-3 and RRMT-5, and appear to have led to increased tidal volumes during exercise (11 to 14% in conjunction with a 20-10% decrease in f_b for RRMT-5 and RRMT-3 respectively). Romer et al. (27) found that 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_T during land exercise that was maintained during the latter stages of incremental exercise, versus a more tachypneic pattern in the placebo group, as was also observed in the present study during the pre-RRMT testing. It is possible that the increased inspiratory strength and/or endurance can contribute to a shortened inspiration time, 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 a more optimized (increased) post-expiratory muscle length and lung volume making the muscles better capable of performing respiratory work as well as reducing flow resistance (due to the increased 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 swimming underwater decreased more than 10% and the steady-state $\dot{V}O_2$ decreased by 8%, as well. Given the energy cost of ventilation previously reported (5) it is attractive to propose that the post-RMT reduction in $\dot{V}O_2$ was due to the reduction in $\dot{V}_E$. This conclusion is consistent with reported increases in oxidative enzyme potentials (SDH, citrate synthase) in the diaphragm and intercostals muscles and increased proportion of Type I fibers in external intercostals following respiratory loading (similar to RRMT in the present study) in animal models (33,34,35).

The work of breathing during maximal and submaximal exercise is the primary determinant of respiratory muscle blood flow (6,9). Respiratory muscle $\dot{V}O_2$ increases linearly with ventilation, up to the ventilatory threshold, after which a marked increase in ventilation occurs. When exercise is performed (during terrestrial conditions) at 70% $\dot{V}O_{2max}$, the respiratory muscles require ~ 5%, and at maximal exercise ~10%, of the total $\dot{V}O_2$ (5). Due to the high ventilation during exercise above $\dot{V}O_{2max}$ the $\dot{V}O_2$ the higher resistive and elastic respiratory work may require nearly 15% of total O_2 (5). A high O_2 cost of ventilation may especially be the case in diving where trans-thoracic hydrostatic pressure differences (static lung loading), breathing gear resistance and gas density increase the work of breathing. During such increased work of breathing (36) and resultant high O_2 demands by the respiratory musculature its need for increased blood flow is likely to compromise the blood flow, and thus O_2 delivery, to the skeletal locomotor muscles (9). 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 via experimental congestive heart failure (37).

Training three days per week was as effective as five days per week suggesting that the more intense schedule may have caused overtraining. Studies of other skeletal muscles have shown that full strength gain could only be demonstrated after 4 days, as compared 2-4 days of rest from training (38,39). Thus, daily training may not allow sufficient recovery. Therefore, post training fatigue can give misleading information about the ability of RMT to enhance exercise endurance. This is illustrated by the outcome of a study which failed to show an ergogenic effect of RMT on terrestrial locomotion when tested one day after intense RMT (32). Additionally, it has been shown that testing about five days after RMT reveals greater improvement than testing one day after RMT (8,40). Other studies of high intensity aerobic training and resistance training (21,22,23) have shown that significant improvements can be made in four to five weeks, as has previously been demonstrated for surface swimming (24).

SUMMARY

The major findings of the present study were that 30 minutes of resistance respiratory muscle training carried out three or five days per week for four weeks substantially improved fin swimming endurance (at 70-75%$\dot{V}O_{2max}$) and that similar improvements in respiratory muscle performance were obtained. This study supports the results of a previous study (20) as both demonstrated increased tidal volume while $\dot{V}_E$ and frequency were reduced. Breathing underwater requires a greater generation of force by the inspiratory and expiratory muscles and, compared to voluntary isocapnic hyperpnea (improvement: 26% - 38%) (20), RRMT appears to be the method of choice (improvement: 66-75%) for enhancing swimming endurance. Interestingly, RRMT using maximal resistance has been found not to improve exercise endurance on land, in spite of large changes in inspiratory and expiratory pressures (16). Further studies are needed to determine the optimal resistance, duration, and frequency of training to maximize exercise endurance in divers. While the divers in the present study only were tested at 1.22 m of depth it is reasonable to hypothesize that there will be similar gains when swimming at deeper depths where the increased density of the breathing gas will cause the respiratory work to be further increased.

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