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ORIGINAL ARTICLE

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Respiratory muscle training increases cycling endurance without affecting cardiovascular responses to exercise

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Abstract We tested whether the increased cycling endurance observed after respiratory muscle training (RMT) in healthy sedentary humans was associated with a training-induced increase in cardiac stroke volume (SV) during exercise, similar to the known effect of endurance training. Thirteen subjects underwent RMT by normocapnic hyperpnea, nine underwent aerobic endurance training (cycling and/or running) and fifteen served as non-training controls. Training comprised 40 sessions performed within 15 weeks, where each session lasted 30 min. RMT increased cycling endurance at 70% maximal aerobic power ($\dot{W}_{max}$) by 24% [mean (SD) 35.6 (11.9) min vs 44.2 (17.6) min, $P < 0.05$], but SV at 60% $\dot{W}_{max}$ was unchanged [94 (21) ml vs 93 (20) ml]. Aerobic endurance training increased both SV [89 (24) ml vs 104 (32) ml, $P < 0.01$] and cycling endurance [37.4 (12.8) min vs 52.6 (16.9) min, $P < 0.01$]. In the control group, no changes were observed in any of these variables. It is concluded that the increased cycling endurance that is observed after RMT is not due to cardiovascular adaptations, and that the results provide evidence for the role of the respiratory system as an exercise-limiting factor.

Keywords Endurance performance · Exercise-limiting factors · Respiratory muscle fatigue

Introduction

Until recently, the role of ventilation in limiting human performance was considered to be important only in highly trained athletes exercising at maximum aerobic power ($\dot{W}_{max}$, Dempsey 1986). For prolonged heavy exercise (60–85% of maximal oxygen uptake, $\dot{V}O_{2max}$) to exhaustion, it was argued that the elicited minute ventilation ($\dot{V}_E$) was not sufficient to induce exercise-limiting respiratory muscle fatigue. This argument was based mainly on the fact that even at exhaustion, both trained and sedentary subjects breathed well below their maximal voluntary ventilation (MVV) and were still capable of increasing their ventilation voluntarily.

In contrast with these views, several studies (Boutellier et al. 1992; Boutellier and Piwko 1992; Spengler et al. 1999) have shown that isolated respiratory muscle training (RMT) not only greatly increases respiratory muscle performance but also prolongs cycling endurance at constant submaximal workloads (i.e., below 85% $\dot{W}_{max}$). If it is assumed that no uncontrolled or side-effects of respiratory training (e.g., increased physical activity of the subjects during the RMT period, increased motivation of the subjects after training, or metabolic changes) were responsible for the longer cycling time, these previous findings imply that respiratory pump fatigue may indeed play a role in limiting human performance at such work intensities. For exercise above 80% $\dot{W}_{max}$, the occurrence of diaphragmatic fatigue has already been established (Johnson et al. 1993; Mador et al. 1993).

An alternative explanation that is more in line with the conventional view, is that the improved exercise times observed after RMT may be caused by concomitant cardiovascular adaptations to the specific type of RMT (i.e., normocapnic hyperpnea) used in these studies (Boutellier et al. 1992; Boutellier and Piwko 1992; Spengler et al. 1999). Acutely, hyperpnea causes large intrathoracic pressure swings that increase venous return to the heart (Willeput et al. 1984; Boutellier and Farhi 1986; Anholm et al. 1987; Coast et al. 1988) and may also increase ventricular afterload (Robotham et al. 1977). The normocapnic hyperpnea of the RMT may therefore be associated with a considerable increase in stroke work in addition to the increase in heart rate.

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From these acute effects, it may be inferred that repeated prolonged hyperpnea (30 min) at a higher level than normally occurs during exercise, performed several times per week, results in an increase in intrinsic myocardial contractility and maximal stroke volume (SV). If this were the case, the increased cycling endurance could beattributed to an increased myocardial performance, as observed after endurance training, and the respiratory system need not be considered to be implied as an exercise-limiting factor.

We therefore hypothesized that RMT by normocapnic hyperpnea leads to an increase in SV, determined at its presumed maximum. Thus, we assessed SV and cycling endurance in a group of healthy sedentary volunteers before, during and after a 15-week course of RMT. To compare SV changes with those expected from endurance training, we investigated two additional groups, one undergoing aerobic endurance training at a level that is expected to increase SV and cycling endurance, and one serving as a non-training control group with no expected changes.

If under these premises RMT neither increases SV nor lowers the heart rate during cycling, yet prolongs cycling endurance, then the prolongation can not be explained by cardiovascular effects. This would warrant the conclusion that in sedentary subjects, the exercise-limiting role of the respiratory pump during submaximal exercise is probably more important than hitherto assumed.

Methods

Subjects

The present study was approved by the Ethics Committee of the Institutes of Physiology and Pharmacology of the University of Zurich (Switzerland). Thirty-eight healthy, sedentary subjects entered the study after providing their written informed consent to participate. Two agreed to enroll first as controls and subsequently in one of the training groups. The subjects were then randomly assigned to either an RMT group ($n=15$), an endurance training group (ET, $n=10$) or a control group (C, $n=15$). Two subjects in the RMT group and one in the ET group did not complete the study. The age, height, body mass, vital capacity (VC), maximal voluntary ventilation (MVV), peak oxygen uptake ($\dot{V}O_{2peak}$) and $\dot{W}_{max}$ of the remaining subjects before training are listed in Table 1.

Table 1 Means (SD) of the subjects' characteristics, vital capacity (VC), maximal voluntary ventilation (MVV) and peak oxygen uptake ($\dot{V}O_{2peak}$) of the respiratory muscle training (RMT), the endurance training (ET) and the control (C) group before the training or control period

Characteristic	RMT	ET	C
Gender (female/male)	5/8	5/4	7/8
Age (years)	43 (7)	40 (10)	37 (9)
Height (cm)	170 (9)	172 (10)	170 (7)
Body Mass	67 (12)	73 (16)	68 (13)
VC (l)	4.7 (0.9)	4.7 (0.9)	4.8 (1.0)
MVV ($l \cdot min^{-1}$)	170 (49)	159 (46)	151 (37)
$\dot{V}O_{2peak}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	36 (11)	32 (9)	35 (9)

Equipment

VC, MVV, as well as ventilation and gas exchange during exercise were measured with an OxyconGamma unit (Jaeger, Würzburg, Germany). This system uses a turbine for ventilation measurement, a paramagnetic analyzer for oxygen measurement, an infrared absorption analyzer for carbon dioxide measurement, and a personal computer for data recording and monitoring.

All bicycle ergometer tests were carried out on an electromagnetically braked "Ergometrics 900S" bicycle ergometer (Ergoline, Bitz, Germany) that was connected to the OxyconGamma unit described above. Heart rates were recorded on PE4000 heart rate monitors (Polar Electro, Kempele, Finland) that were also connected to the OxyconGamma computer.

RMT was carried out with a self-developed device consisting of tubing (inner diameter of 19 mm) that connects a rebreathing bag with a mouthpiece at a 90° angle. In the middle of this connecting piece, a side-port (same diameter tube) is inserted. This side-port contains a 6-mm hole to allow inspiration from and expiration to ambient air; it also contains a valve. Subjects fill and empty the rebreathing bag completely while obtaining additional fresh air through the small hole during inspiration and breathing partially out through the small hole during expiration. To assure a constant tidal volume, the valve inserted in the side-portcloses when subjects have emptied the bag completely during inspiration and inspiratory air is passing purely through the side-port hole (with high flow). For the present study, the size of the bag was adjusted to 50–60% of the subject's VC, and breathing frequency was chosen such that $\dot{V}_E$ corresponded to 60% MVV (monitored while the training device was connected to the metabolic cart).

Subjects were instructed to fill and empty the bag completely while additional inspiratory and expiratory flow passed through a small hole in the tube to avoid an increase in arterial carbon dioxide partial pressure and a fall in oxygen saturation. Correct performance (i.e., the achievement of normocapnia and full arterial oxygen saturation) was checked in a preliminary session with the training device connected to the Oxycon Gamma. If necessary, the size of the hole in the tube was adjusted.

Cardiac output was assessed with the OxyconGamma unit, which uses a carbon dioxide rebreathing principle to determine mixed-venous carbon dioxide concentration and derives arterial carbon dioxide from end-tidal values. The plateau method (Collier 1956) was used to evaluate the rebreathing equilibrium. Cardiac output was estimated by using the indirect Fick equation corrected for hemoglobin concentration (Jones and Campbell 1982). Cardiac output and steady-state heart rate before rebreathing were then used to calculate SV.

Protocols

Before training was started, all subjects underwent three test sessions, which were carried out on separate days within 1–2 weeks. In the first session, lung function variables were measured according to the standard procedures of the American Thoracic Society (1995), and an incremental cycling test with simultaneous measurement of ventilation and gas exchange was performed. The initial workload was 60 W for female subjects and 80 W for male subjects; this was then increased by 20 W every 2 min until exhaustion. Pedaling frequency was kept constant at a self-chosen rate between 60 and 100 rpm. The highest workload sustained for at least 90 s was defined as $\dot{W}_{max}$, and the highest $\dot{V}O_2$ averaged over 30 s was defined as $\dot{V}O_{2peak}$. After recovery, the subjects were familiarized with the RMT device, as described above.

In the second session, cardiac output and SV were assessed while subjects cycled at 60% of their predetermined $\dot{W}_{max}$, the pedaling rate being the same as in the incremental test. Three cardiac output measurements were made within 20 min without intermittent recovery, and the median of these measurements was taken as the representative value. The median was selected to minimize the effect of potential outliers. However, final analysis revealed that the reliability of the measurements was good (average coefficient of variation 3.9%) and that outliers were virtually

nonexistent. Subsequently, the subjects were further familiarized with the RMT device until they were capable of breathing at a $\dot{V}_E$ corresponding to 70% MVV for more than 2 min. If this time was not achieved, the target $\dot{V}_E$ was reduced to 65% MVV.

In the third session, the subjects performed a breathing endurance test to exhaustion at the % MVV level established in the second session. Exhaustion was assumed when subjects stopped the test or when $\dot{V}_E$ dropped more than 10% below its target level. In those subjects who breathed for longer than 15 min, the test was interrupted because breathing load was considered to be too low. In this case, the test was repeated after a recovery period, applying a target $\dot{V}_E$ that was increased by 5% MVV. The mean $\dot{V}_E$ measured during the breathing endurance tests was similar in all three groups [mean (SD) RMT, 115 (28) l·min^{-1} or 69 (6)% MVV; ET, 104 (26) l·min^{-1} or 67 (11)% MVV; C, 105 (21) l·min^{-1} or 71 (10)% MVV]. After the breathing endurance test, a recovery time of 20 min was observed to ensure that no carry-over effect on the subsequent cycling test would ensue. This duration was based on the results of a previous study showing that exhaustive, normocapnic hyperpnea of 40 min duration that ended 15 min before an exhaustive cycling test, affected neither exercise time, metabolism nor ventilation during cycling compared to a cycling test without preceding voluntary hyperpnea (Spengler et al. 2000). In the present study, the cycling endurance test started with a 5-min warm-up at 35% $\dot{W}_{max}$, and was immediately followed by constant-load cycling at 70% $\dot{W}_{max}$. The pedaling rate was kept constant at the level chosen in the incremental test. Subjects were allowed to monitor their pedaling rate, but were not given any additional information or encouragement. Exhaustion was assumed when subjects stopped the test or when their pedaling rate dropped by more than 10% below target. Heart rate, ventilation and gas exchange were measured continuously.

The three test sessions were immediately followed by the training period, which lasted 15 (3) weeks, and comprised two times 20 training sessions, each of which was performed over 7 (2) weeks (range 4–8 weeks, depending upon subjects' availability of time), with a pause of 1–2 weeks (for testing in between, as described later). Each training session consisted of either 30 min RMT (RMT group), 30 min of endurance training (ET group), or no training (C group). The $\dot{V}_E$ for RMT was set initially at 60% MVV. For subsequent training sessions, subjects were encouraged to increase their breathing frequency or tidal volume as soon as they felt they could have continued for more than 30 min at the target $\dot{V}_E$. After an average of 30 training days, target $\dot{V}_E$ had already increased to 79% MVV. Endurance training consisted of strenuous, heart-rate-monitored running or cycling. The mean heart rate during training sessions was 104 (11) beats·min^{-1} [57 (6)% of peak heart rate] in the RMT group and 161 (8) beats·min^{-1} [88 (5)% of peak heart rate] in the ET group. The estimated training $\dot{V}_E$ of the ET group (estimated from $\dot{V}_E$ at the point where training heart rate was reached during the incremental test) resulted in an average of 34% MVV at the beginning and 46% MVV at the end of the training period. No additional RMT was included for training of the ET group. The C subjects performed no training. None of the subjects were allowed to perform any kind of additional exercise outside the training protocol and their usual activities. Most training sessions were carried out at home. To ensure full compliance and effort, subjects were obliged to save the heart-rate monitor readings of each training session and to record their training in a diary. These data were checked weekly by the investigators and showed that subjects followed their training schedule and kept their usual activities constant. Thus, compliance with the protocol was excellent. In addition, subjects in the RMT group periodically performed training sessions at the laboratory under direct supervision.

After 7 (2) weeks of training (20 training sessions), the cardiac output determination was repeated in exactly the same way as in the second session of the pre-training test series. The aim was to observe any early effects of training on SV.

When training was completed after a total of 15 (3) weeks, the initial three-session test series was repeated fully in an identical manner, with the following exceptions. Firstly, in the ET group only, the workload during the cycling endurance test was adapted proportionally to the post-training $\dot{W}_{max}$ as soon as the exhaustion time of the pre-training test was attained. The reason for this was to avoid excessively long cycling times after whole-body endurance training. Secondly, the post-training breathing endurance tests were terminated by the investigators after 40 min if no signs of exhaustion were present, again to avoid excessively long breathing times after training.

Statistical analysis

First, the test for normality of distribution by D'Agostino and Pearson (Zar 1996) was applied to all data. Normally distributed data were then analyzed statistically by one-way analysis of variance. Breathing endurance times, which were not normally distributed, were analyzed by the Kruskal-Wallis test. The Newman-Keuls test for normally distributed data and the procedure proposed by Dunn (Zar 1996) for breathing endurance data were used for post hoc multiple comparisons. All stated statistical significance refer to differences in response between the respective training groups (RMT and ET) and the C group. The level of statistical significance was set at $P < 0.05$. All statistical analyses were performed using StatView 4.5 software (Abacus Concepts, Berkeley, Calif., USA).

Results

Physical and respiratory performance

$\dot{V}O_{2peak}$ and $\dot{W}_{max}$ before and after training are shown in Table 2. No changes occurred in the RMT and C groups. In the ET group, the respective mean values increased by 19% and 22% ($P < 0.001$). Breathing endurance increased more than sixfold in the RMT group, from a median of 4.6 min (range: 2.0–10.2 min) to 40.0 min (15.4–40.0 min; $P < 0.001$), although the post-training tests were terminated after 40 min if no signs of exhaustion were present. Breathing endurance in the ET and C groups did not change significantly [mean (range) for ET: from 6.5 (1.8–15.8) min to 9.4 (1.4–40.0) min; C: from 5.2 (2.0–10.4) min to 3.9 (1.5–19.6) min)].

Table 2 Means (SD) of peak oxygen uptake ($\dot{V}O_{2peak}$), maximal aerobic power ($\dot{W}_{max}$) and cycling endurance of the respiratory muscle training (RMT), endurance training (ET) and control (C) groups before and after the training or control period

Variable	Group	Before training	After 15 weeks
$\dot{V}O_{2peak}$(l·min^{-1})	RMT	2.39 (0.76)	2.38 (0.77)
	ET	2.34 (0.66)	2.80 (0.85)***
	C	2.35 (0.60)	2.24 (0.55)
$\dot{W}_{max}$(W)	RMT	175 (57)	175 (55)
	ET	173 (42)	211 (62)***
	C	171 (43)	163 (35)
Cycling endurance (min)	RMT	35.6 (11.9)	44.2 (17.6)*
	ET	37.4 (12.8)	52.6 (16.9)[a],**
	C	32.8 (11.6)	31.4 (14.4)

[a]Workload increased when the end-time of the pre-training test was reached (see Methods)
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$ (compared to changes in the C group)

Cycling endurance times before and after the training period are also shown in Table 2. RMT increased mean cycling endurance time by 24% ($P < 0.05$), while there was no change in C group values. ET increased mean cycling endurance time by 41% ($P < 0.01$), but please note that the workload was partly adapted to the increased $\dot{W}_{max}$ after training, as described in the Methods section.

Cardiovascular adaptations

The responses of cardiac output, $\dot{V}O_2$ and heart rate, determined at 60% of the pre-training $\dot{W}_{max}$ after the attainment of a steady-state $\dot{V}O_2$ are shown in Table 3. These variables did not change in the RMT and C groups, whereas the ET group showed the characteristic heart rate reduction ($P < 0.001$).

The individual values for SV at the same $\dot{V}O_2$ before and after 7 and 15 weeks of training are plotted in Fig. 1. In the RMT group, the respective mean values were 94 (21) ml, 97 (22) ml, and 93 (20) ml. The C group values were similar [90 (25) ml, 94 (25) ml and 90 (23) ml]. There were no statistical differences between any of these values. In the ET group, SV increased from an initial 89 (24) ml to 112 (35) ml after 7 weeks ($P < 0.001$), and to 104 (32) ml after 15 weeks ($P < 0.01$). The downward trend from 7 weeks to 15 weeks was not significant. The heart rate during the cycling endurance test was compared before and after training for the constant-load period that could be sustained by all subjects of each group, and the results are shown in Fig. 2. Again, no changes were noted in the RMT and C groups, whereas the reduction observed in the ET group was significant ($P < 0.01$).

Metabolic adaptations

In neither the RMT group nor the C group was $\dot{V}O_2$ (Fig. 3) or substrate utilization – as measured using the respiratory exchange ratio (Fig. 4) – changed significantly during the constant-load period of the cycling endurance test performed after 15 weeks of respiratory training or after the control period. In the ET group, however, after the 15-week physical training period $\dot{V}O_2$ was significantly decreased, as was the respiratory exchange ratio ($P < 0.05$).

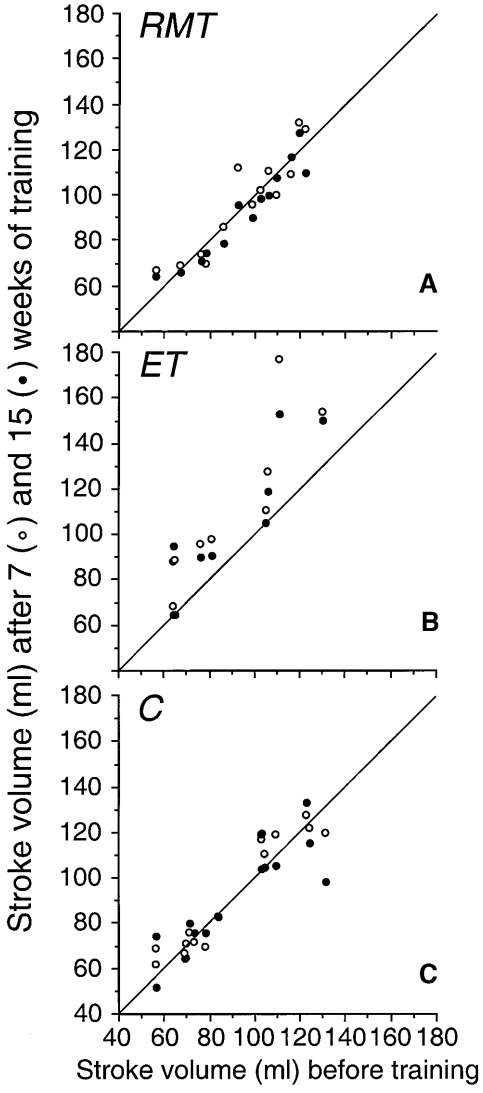

Fig. 1 Stroke volume at 60% maximal aerobic power ($\dot{W}_{max}$) of all subjects after 7 (2) weeks (○) and 15 (3) weeks (●) weeks of training, or after the control period (*ordinate*) is plotted against pre-training values (*abscissa*). The *diagonal line* represents the line of identity. Subjects were assigned to either a respiratory muscle training group (*RMT*, $n = 13$), an endurance training group (*ET*, $n = 9$), or a control group (*C*, $n = 15$). Stroke volume increased significantly in the ET group only ($P < 0.001$ compared to changes in the C group)

Table 3 Means (SD) of cardiac output, heart rate and oxygen uptake during cycling at 60% maximal aerobic power ($\dot{W}_{max}$) before, after 7 weeks and after 15 weeks of respiratory muscle training (RMT), endurance training (ET) or the control (C) period

Variable	Group	Before training	After 7 weeks	After 15 weeks
Cardiac output ($l \cdot min^{-1}$)	RMT	14.1 (3.1)	14.1 (3.5)	13.7 (3.1)
	ET	13.6 (3.2)	14.8 (3.4)	13.8 (3.1)
	C	13.7 (3.4)	14.1 (3.5)	13.8 (3.2)
Heart rate ($beats \cdot min^{-1}$)	RMT	150 (14)	146 (13)	149 (13)
	ET	155 (14)	135 (17)***	137 (17)***
	C	154 (13)	152 (11)	154 (12)
Oxygen uptake ($l \cdot min^{-1}$)	RMT	1.68 (0.48)	1.62 (0.47)	1.62 (0.45)
	ET	1.71 (0.45)	1.70 (0.41)	1.66 (0.32)
	C	1.63 (0.34)	1.63 (0.33)	1.64 (0.38)

***$P < 0.001$ (compared to changes in the C group)

Discussion

Our aim was to study the effects of RMT on SV and heart rate during submaximal heavy exercise in healthy sedentary humans in order to try to explain the increases

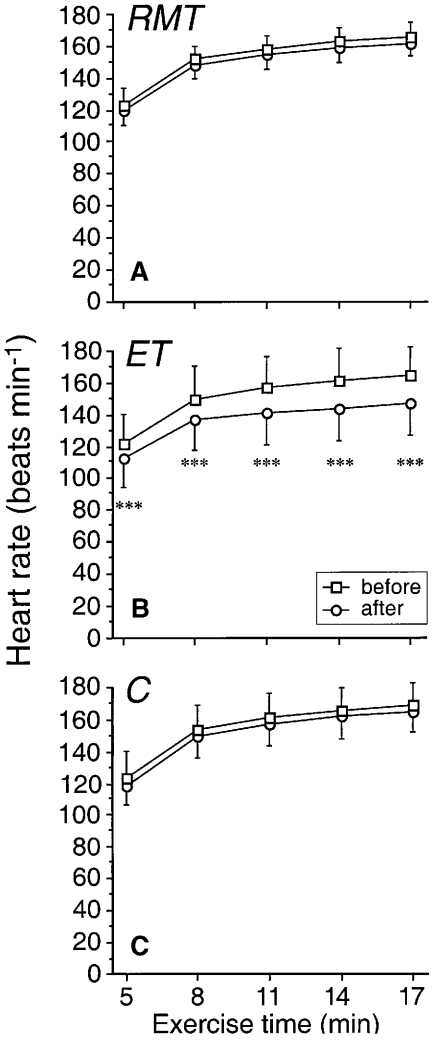

Fig. 2 Progression of heart rate during the cycling endurance test (70% $\dot{W}_{max}$) before (□) and after (○) 15 weeks of training or the control period is shown for the constant-load period that could be sustained by all subjects of each group (means ± SD). Subjects were assigned to either a respiratory muscle training group (*RMT*, $n = 13$), an endurance training group (*ET*, $n = 9$), or a control group (*C*, $n = 15$). Heart rate decreased significantly in the ET group only (***$P < 0.001$ compared to changes in the C group)

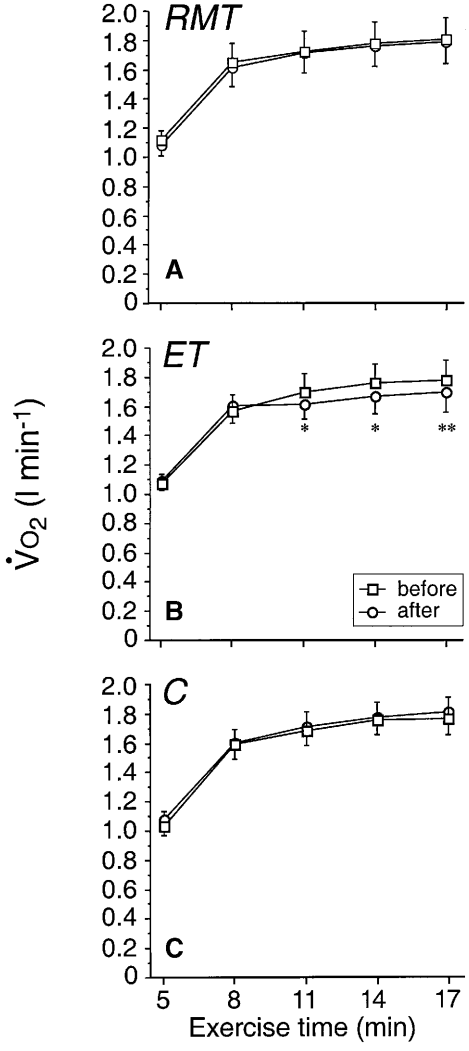

Fig. 3 Progression of oxygen consumption ($\dot{V}O_2$) during the cycling endurance test (70% $\dot{W}_{max}$) before (□) and after (○) 15 weeks of training or the control period is shown for the constant-load period that could be sustained by all subjects of each group (means ± SD). Subjects were assigned to either a respiratory muscle training group (*RMT*, $n = 13$), an endurance training group (*ET*, $n = 9$), or a control group (*C*, $n = 15$). $\dot{V}O_2$ decreased significantly in the ET group only (*$P < 0.05$, **$P < 0.01$ compared to changes in the C group)

in cycling endurance observed after RMT. We found that RMT carried out over a period of 15 weeks did not increase the SV determined at workloads that normally elicit maximal values, and that heart rate at the same absolute submaximal workloads remained unchanged.

Since our subjects were in a very low training state (mean $\dot{V}O_{2peak}$ was 30 ml·min^{-1}·kg^{-1} in the female and 38 ml·min^{-1}·kg^{-1} in the male subjects), even light exercise training was likely to induce cardiovascular adaptations. The fact that endurance training increased SV by 17% and reduced heart rate by 12% in the present study indicates that SV changes in the RMT group would not have been missed with the method used. Moreover, the absolute values obtained for cardiac output and SV were similar to those reported in the literature (Hartley et al. 1969; Hossack et al. 1981; Higginbotham et al. 1984). The results thus reliably indicate the absence of any cardiovascular training effects of RMT comparable to those of endurance training (Ehsani et al. 1978; Wolfe et al. 1979; Mier et al. 1997). The significant increase in cycling endurance after RMT can not therefore be attributed to the hypothesized cardiovascular adaptations. Thus, the possible acute effects of RMT, such as increases in venous return (Willeput et al. 1984; Boutellier and Farhi 1986; Anholm et al. 1987; Coast et al. 1988) and/or afterload (Robotham et al. 1977), appear to be insufficient to induce cardiovascular training effects.

Since our data reject the hypothesis of any cardiovascular effects of RMT, the increased cycling endur-

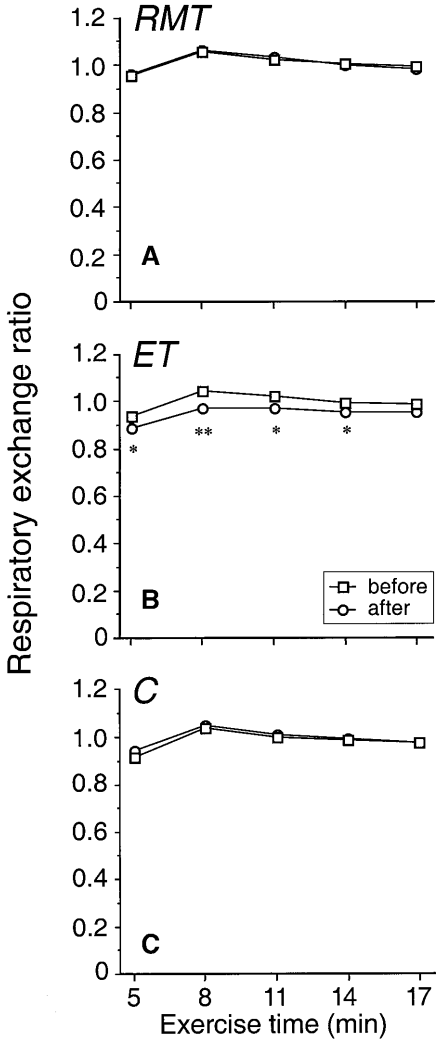

Fig. 4 Progression of the respiratory exchange ratio during the cycling endurance test (70% $\dot{W}_{max}$) before (□) and after (○) 15 weeks of training or the control period is shown for the constant-load period that could be sustained by all subjects of each group (means ± SD). Subjects were assigned to either a respiratory muscle training group (*RMT*, $n = 13$), an endurance training group (*ET*, $n = 9$), or a control group (*C*, $n = 15$). The respiratory exchange ratio decreased significantly in the ET group only (*$P < 0.05$, **$P < 0.01$ compared to changes in the C group)

ance after RMT may indeed originate from direct training effects on the respiratory system. Among such effects, delay of respiratory muscle fatigue may play a role (Dempsey 1986; Johnson et al. 1996; Boutellier 1998). Diaphragmatic fatigue has been demonstrated to occur during exhaustive exercise at workloads above 70% $\dot{W}_{max}$ (Johnson et al. 1993; Mador et al. 1993; Mador and Dahuja 1996), and expiratory muscle fatigue can also occur after exhaustive exercise (Fuller et al. 1996). These findings and the consistent effects of RMT on both breathing and cycling endurance (present study; Boutellier et al. 1992; Boutellier and Piwko 1992; Spengler et al. 1999) indicate that respiratory muscle fatigue may contribute to the limitation of cycling endurance at workloads that can be sustained for 15 min or more. In the light of these studies, our findings suggest that fatigue of the respiratory muscles might be reduced by RMT, allowing subjects to cycle for longer.

However, since respiratory function in the cycling-exhausted state was not assessed in the present study, it cannot be excluded that factors other than respiratory muscle fatigue may have been affected by the training and thus have caused the improvement of cycling endurance. For example, it may be surmised that RMT brings about a reduction of the blood flow required by the respiratory muscles due to increased respiratory muscle efficiency. This would tend to favor blood flow to the legs and help explain the increase in cycling endurance. For example, when Harms et al. (1998) reduced the work of breathing during maximal exercise by mechanical unloading, they showed that such a reduction resulted in a greater proportion of the total $\dot{V}O_2$ and cardiac output being utilized by the legs. This effect was accompanied by a reduction in total $\dot{V}O_2$ and cardiac output. In addition, Wetter et al. (1999) found a reduction in total $\dot{V}O_2$ with assisted breathing at submaximal workloads, but they did not find a concomitant change in leg blood flow or leg $\dot{V}O_2$. In the present study, which also tested submaximal exercise performance, neither $\dot{V}O_2$, cardiac output nor substrate utilization (respiratory exchange ratio) were reduced after RMT. Therefore, it appears unlikely that RMT decreased the blood flow or oxygen demand of the respiratory muscles during the submaximal exercise test, and the increased cycling times after RMT are not likely to be attributable to an increased blood supply to the leg muscles.

Another way by which RMT may influence cycling endurance is a reduction in the sensation of breathlessness at similar workloads. Since RMT does not alter chemoreceptor sensitivity (Markov et al. 1996), such an effect may be related either to a sensation of lower demand relative to the increased performance capacity of the respiratory muscles, or to a central nervous conditioning mechanism. Of course respiratory muscle fatigue and the sensation of breathlessness are not mutually exclusive factors, but they may interact and/or combine to limit exercise endurance. Further studies may help to determine whether delayed respiratory muscle fatigue or other factors related to the respiratory system (i.e., the sensation of breathlessness,or mechanical load) are responsible for the improvement of cycling endurance after RMT.

Conclusions

Fifteen weeks of RMT increased respiratory and cycling endurance but did not affect cardiac SV, $\dot{V}O_2$ or substrate utilization during exercise in healthy sedentary subjects. This indicates that the increased cycling endurance observed after RMT is not due to cardiac adaptations or changes in substrate utilization similar to those observed after endurance training, but that factors associated with the respiratory system are likely to limit

exercise endurance at submaximal intensities in healthy humans.

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References

American Thoracic Society (1995) Standardization of spirometry. Am J Respir Crit Care Med 152:1107–1136

Anholm JD, Johnson RL, Ramanathan M (1987) Changes in cardiac output during sustained maximal ventilation in humans. J Appl Physiol 63:181–187

Boutellier U (1998) Respiratory muscle fitness and exercise endurance in healthy humans. Med Sci Sports Exerc 30:1169–1172

Boutellier U, Farhi LE (1986) Influence of breathing frequency and tidal volume on cardiac output. Respir Physiol 66:123–133

Boutellier U, Piwko P (1992) The respiratory system as an exercise limiting factor in normal sedentary subjects. Eur J Appl Physiol 64:145–152

Boutellier U, Buchel R, Kundert A, Spengler C (1992) The respiratory system as an exercise limiting factor in normal trained subjects. Eur J Appl Physiol 65:347–353

Coast JR, Jensen RA, Cassidy SS, Ramanathan M, Johnson RL (1988) Cardiac output and O_2 consumption during inspiratory threshold loaded breathing. J Appl Physiol 64:1624–1628

Collier CR (1956) Determination of mixed venous CO_2 tensions by rebreathing. J Appl Physiol 9:25–29

Dempsey JA (1986) Is the lung built for exercise? Med Sci Sports Exerc 18:143–155

Ehsani AA, Martin III WH, Heath GW, Coyle EF (1978) Rapid changes in left ventricular dimensions and mass in response to physical conditioning and deconditioning. Am J Cardiol 42:52–56

Fuller D, Sullivan J, Fregosi RF (1996) Expiratory muscle endurance performance after exhaustive submaximal exercise. J Appl Physiol 80:1495–1502

Harms CA, Wetter TJ, McClaran SR, Pegelow DF, Nickele GA, Nelson WB, Hanson P, Dempsey JA (1998) Effects of respiratory muscle work on cardiac output and its distribution during maximal exercise. J Appl Physiol 85:609–618

Hartley LH, Grimby G, Kilbom A, Nilsson NJ, Astrand I, Njure J, Ekblom B, Saltin B (1969) Physical training in sedentary middle-aged and older men. III. Cardiac output and gas exchange at submaximal and maximal exercise. Scand J Clin Lab Invest 24:335–344

Higginbotham MB, Morris KG, Coleman RE, Cobb FR (1984) Sex-related differences in the normal cardiac response to upright exercise. Circulation 70:357–366

Hossack KF, Kusumi F, Bruce RA (1981) Approximate normal standards of maximal cardiac output during upright exercise in women. Am J Cardiol 47:1080–1086

Johnson BD, Babcock MA, Suman OE, Dempsey JA (1993) Exercise-induced diaphragmatic fatigue in healthy humans. J Physiol (Lond) 460:385–405

Johnson BD, Aaron EA, Babcock MA, Dempsey JA (1996) Respiratory muscle fatigue during exercise: implications for performance. Med Sci Sports Exerc 28:1129–1137

Jones NL, Campbell EJM (1982) Clinical exercise testing. Saunders, Philadelphia

Mador MJ, Dahuja M (1996) Mechanisms for diaphragmatic fatigue following high-intensity leg exercise. Am J Respir Crit Care Med 154:1484–1489

Mador MJ, Magalang UJ, Rodis A, Kufel TJ (1993) Diaphragmatic fatigue after exercise in healthy human subjects. Am Rev Respir Dis 148:1571–1575

Markov G, Orler R, Boutellier U (1996) Respiratory training, hypoxic ventilatory response and acute mountain sickness. Respir Physiol 105:179–186

Mier CM, Turner MJ, Ehsani AA, Spina RJ (1997) Cardiovascular adaptations to 10 days of cycle exercise. J Appl Physiol 83:1900–1906

Robotham JL, Rabson J, Permutt S, Bromberger-Barnea B (1977) Left ventricular hemodynamics during respiration. J Appl Physiol 47:1295–1303

Spengler CM, Roos M, Laube SM, Boutellier U (1999) Decreased exercise blood lactate concentrations after respiratory endurance training in humans. Eur J Appl Physiol 79:299–305

Spengler CM, Knöpfli-Lenzin C, Birchler K, Trapletti A, Boutellier U (2000) Breathing pattern and exercise endurance time after exhausting cycling or breathing. Eur J Appl Physiol 81:368–374

Wetter TJ, Harms CA, Nelson WB, Pegelow DF, Dempsey JA (1999) Influence of respiratory muscle work on $\dot{V}O_2$ and leg blood flow during submaximal exercise. J Appl Physiol 87:643–651

Willeput R, Rondeux C, DeTroyer A (1984) Breathing affects venous return from legs in humans. J Appl Physiol 57:971–976

Wolfe LA, Cunningham DA, Rechnitzer PA, Nichol PM (1979) Effects of endurance training on left ventricular dimensions in healthy men. J Appl Physiol 47:207–212

Zar JH (1996) Biostatistical analysis, 3rd edn. Prentice-Hall, Upper Saddle River, N.J.