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The respiratory system as an exercise limiting factor in normal trained subjects

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Summary. Recently, we have shown that an untrained respiratory system does limit the endurance of submaximal exercise (64% peak oxygen consumption) in normal sedentary subjects. These subjects were able to increase breathing endurance by almost 300% and cycle endurance by 50% after isolated respiratory training. The aim of the present study was to find out if normal, endurance trained subjects would also benefit from respiratory training. Breathing and cycle endurance as well as maximal oxygen consumption ($\dot{V}O_{2max}$) and anaerobic threshold were measured in eight subjects. Subsequently, the subjects trained their respiratory muscles for 4 weeks by breathing 85–160 l·min^{-1} for 30 min daily. Otherwise they continued their habitual endurance training. After respiratory training, the performance tests made at the beginning of the study were repeated. Respiratory training increased breathing endurance from 6.1 (SD 1.8) min to about 40 min. Cycle endurance at the anaerobic threshold [77 (SD 6) % $\dot{V}O_{2max}$] was improved from 22.8 (SD 8.3) min to 31.5 (SD 12.6) min while $\dot{V}O_{2max}$ and the anaerobic threshold remained essentially the same. Therefore, the endurance of respiratory muscles can be improved remarkably even in trained subjects. Respiratory muscle fatigue induced hyperventilation which limited cycle performance at the anaerobic threshold. After respiratory training, minute ventilation for a given exercise intensity was reduced and cycle performance at the anaerobic threshold was prolonged. These results would indicate the respiratory system to be an exercise limiting factor in normal, endurance trained subjects.

Key words: Respiratory muscle training – Breathing endurance – Cycle endurance – Maximal oxygen consumption – Anaerobic threshold

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Introduction

Recently, we found in four normal sedentary subjects that an untrained respiratory system can limit endurance exercise (Boutellier and Piwko 1992). These subjects were able to increase breathing endurance by almost 300% and cycle endurance by 50% after isolated respiratory training of 4 weeks duration. Vital capacity, peak flow, forced expiratory volume in 1 s, specific airway conductance and maximal voluntary ventilation were not influenced by respiratory training. During the endurance cycling test, minute ventilation increased continuously – after a fast initial rise to about 65 l·min^{-1} – to reach finally 96.9 (SD 23.6) l·min^{-1} in the respiratory untrained state. It was shown that the subjects did hyperventilate. After respiratory training, no hyperventilation occurred and minute ventilation remained at the same level (around 64 l·min^{-1}) during the entire endurance cycling test. We explained the increase of cycle endurance by 50% by the absence of the fatiguing hyperventilation. Considering the remarkable increase of cycle endurance in sedentary subjects after isolated respiratory training, the question arises if trained subjects may also benefit from additional respiratory training.

Standard endurance conditioning has been shown also to train the respiratory muscles and lower the ventilatory response to exercise (Gimenez et al. 1982; Casaburi et al. 1987). Therefore, endurance trained subjects could be expected also to have well-trained respiratory muscles. Surprisingly, additional respiratory training (Morgan et al. 1987; Fairbarn et al. 1991) has been found to improve dramatically the breathing endurance of moderately or highly trained cyclists. However, this successful respiratory training had no effect on cycle endurance measured at 90% of maximal power output or 95% of maximal oxygen consumption ($\dot{V}O_{2max}$). As performances near $\dot{V}O_{2max}$ can only be sustained for a few minutes, these exercise intensities do not correspond to those of so-called endurance events. Therefore, in the present study, we used the exercise intensity corresponding to the anaerobic threshold (Th_{an}) to investigate the effects of respiratory training on cycle endurance.

Special attention had to be paid to the overall level of activity of the subjects. A more intensive or a more extensive training would interfere with the effects of respiratory training. Whereas it was easy to maintain conditions for the sedentary subjects at the same level throughout the study (no additional physical activity), this was more difficult with respect to the conditioned subjects. The trained subjects agreed to train moderately and regularly without intensive workouts.

The aim of the study was to investigate whether additional respiratory training could improve cycle endurance at Th_{an} in trained subjects.

Methods

Subjects. Eight healthy trained subjects (one woman and seven men) participated in the study. The subjects' characteristics are listed in Table 1. Only persons performing at least 3 h of endurance training a week and taking part regularly in competitions were accepted as subjects. They were informed in detail about the study and agreed to stabilize their endurance training at a constant level 2 weeks before, 4 weeks during, and 1 week after respiratory training. In addition, we have included some findings on a cross-country skier (PS, age 22 years, height 172 cm, and body mass 63 kg).

Equipment. Vital capacity, peak flow, forced expiratory volume in 1 s, and 20 s maximal voluntary ventilation (MVV) were measured by an ultrasound flowmeter (Buess et al. 1986). A special device was developed to train respiration and to measure breathing endurance. It was similar to the device described in detail elsewhere (Boutellier and Farhi 1986). The device consisted of a gas mixing unit and indicators for respiratory frequency and tidal volume. Because the subjects were asked to hyperventilate, it was necessary to add CO_2 to the inspired air to maintain normocapnia. Air was continuously withdrawn from the mouthpiece and CO_2 was measured by an infrared method (medical gas analyser LB-2, Beckman Instruments Inc., Fullerton, Calif., USA). The CO_2 concentrations inspired were adjusted manually with the gas mixing unit to maintain end-tidal CO_2 concentrations at 5.4%. Air flow was measured by a pneumotachograph (Fleisch, no. 3, Metabo SA, Epalinges, Switzerland) and transduced into an electrical signal. This signal was integrated and then displayed to the subject using a horizontal series of 35 green light-emitting diodes (LED). Before every respiratory training session or endurance breathing test, the system was set with the help of a syringe so that each LED represented $\frac{1}{35}$th of the desired tidal volume. Three red LED at the end of the scale warned the subject that the breath exceeded the requested one. A metronome indicated the set frequency.

A cycle ergometer (Ergo-metrics 800S or 900, Ergoline, Bitz, FRG) was used to measure cycle endurance and $\dot{V}O_{2max}$. During cycling, respiratory variables were measured automatically either with an Oxymed (Isler Bioengineering, Zürich, Switzerland) or with an Oxyconbeta (Mijnhardt BV, Bunnik, Netherlands); both are so-called open systems. The principle of the Oxymed is described in detail elsewhere (Norton et al. 1989), except that the Oxymed in addition measures minute ventilation at the air inlet with a pneumotachograph. The Oxyconbeta measures ventilation breath by breath using fast responding gas analysers and a flow turbine device. To reduce the scatter, ventilation was averaged over 30 s with both systems. Heart rate (PE3000, Polar Electro OY, Kempele, Finland) was recorded in parallel with respiratory variables using both systems.

Blood lactate concentrations were measured with an automatic analyser (lactate analyser 23L, Yellow Springs Instrument Co. Inc., Yellow Springs, Ohio, USA) using blood taken from a fingertip or an earlobe. In this study only the increase in blood lactate concentrations is given, i.e. the concentration at the end of a test minus the resting value measured before the test.

Protocol. Two weeks before respiratory training started, the subjects began to fill out standardized training protocols. To compare the weekly training time of swimming, running and cycling, converting factors were calculated according to Stegemann (1984). First, the subjects familiarized themselves with the different devices before vital capacity, peak flow, forced expiratory volume in 1 s, MVV, and breathing endurance were measured. Breathing endurance was determined by voluntarily breathing with individually adjusted frequencies (42–48 $\cdot$ min^{-1}) and tidal volumes (2.50–3.25 l) both chosen such that exhaustion occurred within 10 min. The clock was stopped at the moment at which the subjects could not follow the preset respiratory frequency or tidal volume any longer. Two days later, Th_{an} and $\dot{V}O_{2max}$ were measured. The subjects started pedalling at 100 W and the intensity was increased by 30 W every 2 min until the subjects were exhausted. The Th_{an} was determined by a modified heart rate deflection method (Conconi et al. 1982) and by a ventilation threshold method (Wasserman and McIlroy 1964). After 2 more days, cycling endurance was measured at an exercise intensity corresponding to Th_{an}. Pedal frequency was chosen by each subject between 70 and 100 rev $\cdot$ min^{-1} and then kept constant in all tests. Before and after the determination of $\dot{V}O_{2max}$ and cycle endurance, blood lactate concentrations were measured. During the two tests, respiratory variables and heart rate were recorded continuously.

After the completion of these measurements, 4 weeks of respiratory training followed. The subjects trained their respiration daily for 30 min five times a week. Initial tidal volumes and breathing frequencies were set according to the results of the endurance breathing test. As soon as the subject was able to follow the set ventilation for 30 min, either breathing frequency or tidal volume was increased the next day to train the respiratory muscles as hard as possible. Table 2 indicates the minute ventilations of

Table 1. Subjects' characteristics

Subject	Sex	Age (years)	Height (cm)	Body mass (kg)	Discipline
RB	Male	23	171	61	triathlon
TD	Male	18	179	62	cycling
AE	Male	27	180	71	cycling, running
MH	Male	18	180	63	cycling
AH	Male	18	180	78	cycling
NK	Male	40	172	71	running
JS	Female	22	164	51	triathlon
VT	Male	19	168	61	triathlon

Table 2. Voluntary minute ventilation ($\dot{V}_E$) at the end of each week during respiratory training

Subject	$\dot{V}_E$ ($l \cdot min^{-1}$)			
	1st week	2nd week	3rd week	4th week
RB	99	105	115.5	124
TD	90	100	105	115.5
AE	130	149.5	154	157.5
MH	100	110	115.5	126
AH	110	115.5	121	126
NK	100	105	120	135
JS	95	100	105	115.5
VT	110	115.5	126.5	129
Mean	104	113	120	129
SD	12	16	16	13

the subjects on the last day of each week. Tidal volumes were between 2.25 and 3.5 l, breathing frequencies between 38 and $46 \cdot min^{-1}$.

Immediately after the end of the respiratory training period, the whole set of measurements, carried out at the beginning of the study, was repeated with an identical schedule. Because subject JS was breathing $115.5\ l \cdot min^{-1}$ at the end of the respiratory training for 30 min, we decided that she should repeat the endurance breathing test with $115.5\ l \cdot min^{-1}$ instead of the initial $105\ l \cdot min^{-1}$ and that she could stop the test after 40 min. The last criterion was applied to all subjects even if they could still follow the set ventilation without any signs of exhaustion.

For technical reasons, subjects TD and JS had to switch from the Oxymed to the Oxyconbeta for the $\dot{V}O_{2max}$ determination after respiratory training. Minute ventilation in subject AH showed such an unrealistically large scatter during the endurance cycling test after respiratory training that the values had to be disregarded.

To investigate the influences of respiratory training on ventilation during the endurance cycling test, two values of minute ventilation were compared before and after respiratory training:

1. Minute ventilation at the end of the shorter test ($\dot{V}_{E(t)}$ in Table 3) and
2. Minute ventilation at the end of both tests irrespective of the duration ($\dot{V}_{Emax}$ in Table 3).

For the $\dot{V}O_{2max}$ test, a similar procedure was applied, except that minute ventilation at the end of the last completed exercise intensity of the shorter test was compared before and after respiratory training ($\dot{V}_{E(t)}$ in Table 4).

Study with subject PS. Due to lack of time, PS performed the respiratory endurance training over 3 instead of 4 weeks, i.e. 20 daily sessions without a pause. Subsequently, he repeated the endurance breathing test. The next day, he performed the endurance cycling test. He had physically not trained – except the respiratory muscles – for 3 days before the endurance cycling test and he was highly motivated for this test. We repeated the endurance cycling test 5 days later. Between the two tests, he was running or cycling daily but abstained from any respiratory training with resultant tired legs. Therefore, he was not very optimistic about the outcome of the second endurance cycling test.

Statistics. The significance of differences between the values before and after respiratory training was tested by the paired Wilcoxon test. The analysis of variance introduced by Friedman was used to compare the weekly training times. Correlations were calculated using a linear regression analysis. A P-value lower than 0.05 was considered statistically significant. All statistical procedures applied are described by Sachs (1984).

Table 3. Minute ventilation during the endurance cycling test before and after 4 weeks of respiratory training

Subject	$\dot{V}_{E(t)}$ ($l \cdot min^{-1}$)		$\dot{V}_{Emax}$ ($l \cdot min^{-1}$)	
	Before	After	Before	After
RB	117	*134*	127	134
TD	*84*	82	84	96
AE	*105*	102	105	108
MH	*140*	133	140	143
NK	*159*	100	159	160
JS	*93*	77	93	77
VT	*119*	90	119	105
Mean	117	103	118	118
SD	26	23	26	29

$\dot{V}_{E(t)}$, minute ventilation corresponding to the end of the *shorter test*; $\dot{V}_{Emax}$, minute ventilation at the end of both tests, irrespective of the duration

Table 4. Minute ventilation during the maximal oxygen consumption test before and after respiratory training of 4 weeks

Subject	$\dot{V}_{E(t)}$ ($l \cdot min^{-1}$)		$\dot{V}_{Emax}$ ($l \cdot min^{-1}$)	
	Before	After	Before	After
RB	*116*	116	131	142
TD	105	*125*	122	125
AE	122	*133*	138	137
MH	139	*143*	172	155
AH	126	*141*	178	144
NK	145	*177*	178	184
JS	102	*131*	124	131
VT	*140*	147	140	147
Mean	124 *	139	148	146
SD	16	18	24	18

$\dot{V}_{E(t)}$, minute ventilation corresponding to the end of the last completed work load of the *shorter test*; $\dot{V}_{Emax}$, minute ventilation at the end of both tests, irrespective of the duration; * $P<0.05$

Results

All the experiments were performed without any major difficulties. The subjects complained sometimes about stitches in the side and about soreness of the muscles involved in heavy breathing, especially the abdominal muscles. Subject TD got hurt during a competition and pupil VT had too much homework to do. Therefore, these two subjects had to reduce their habitual endurance training for 4 days and 3 weeks, respectively; nevertheless, respiratory training was continued without interruption.

The effectiveness of respiratory training was demonstrated by a significant increase ($P<0.01$) of breathing endurance from 6.1 (SD 1.8) min before to about 40 min after respiratory training (Fig. 1). Seven of eight subjects reached the preset break-off level of 40 min without any signs of exhaustion. Subject JS was breathing $115.5\ l \cdot min^{-1}$ after respiratory training instead of the initial $105\ l \cdot min^{-1}$. She reached 40 min despite this "handicap". Average minute ventilation of the endurance breathing test amounted to 133 (SD 17) $l \cdot min^{-1}$, corresponding to 70 (SD 5) % MVV. Vital capacity [5.54 (SD 0.72) vs 5.35 (SD 0.62) l], peak flow [10.6 (SD 2.0) vs 10.8 (SD 1.7) $l \cdot s^{-1}$], and forced expiratory volume in 1 s [4.20 (SD 0.54) vs 4.20 (SD 0.51) l] were not influenced by respiratory training. The MVV increased significantly ($P<0.05$) from an initial 191.9 (SD 31.4) to 203.4 (SD 27.4) $l \cdot min^{-1}$ after respiratory training.

Cycle endurance at Th_{an} increased significantly ($P<0.01$) by 38% after respiratory training (Fig. 2). While the subjects cycled for 22.8 (SD 8.3) min at 258 W [corresponding to 77 (SD 6) % $\dot{V}O_{2max}$] before respiratory training, they could tolerate the same exercise intensity for 31.5 (SD 12.6) min after respiratory training. The

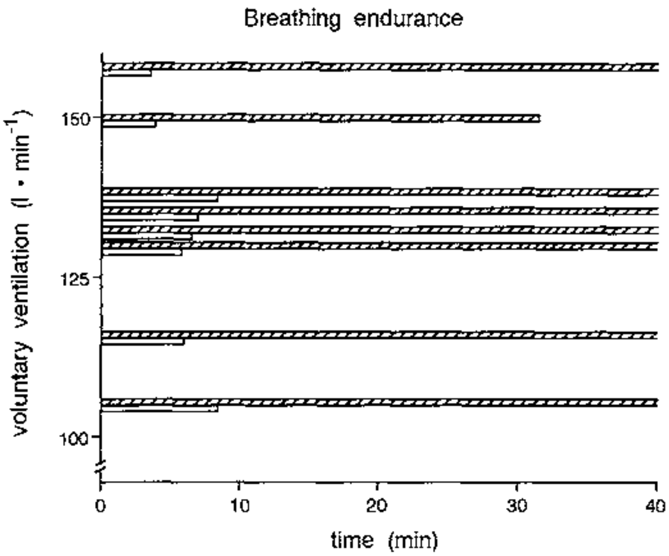

Fig. 1. Breathing endurance of eight subjects before and immediately after a 4-week respiratory training period. ▨ after; ☐ before

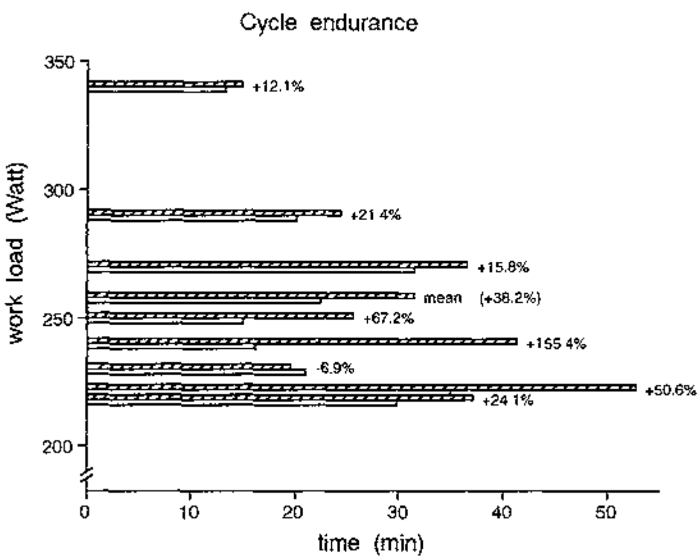

Fig. 2. Cycle endurance at the anaerobic threshold of eight subjects and their mean values before and immediately after a respiratory training period of 4 weeks. ▨ after; ☐ before

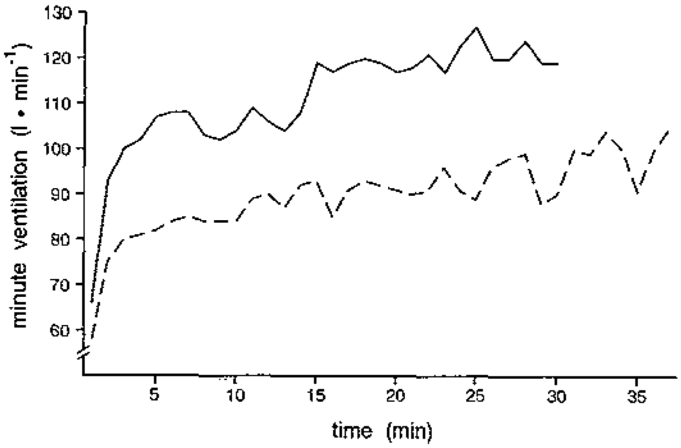

Fig. 3. Minute ventilation of subject VT during the endurance cycling test before and immediately after a 4-week respiratory training period —— before; --- after

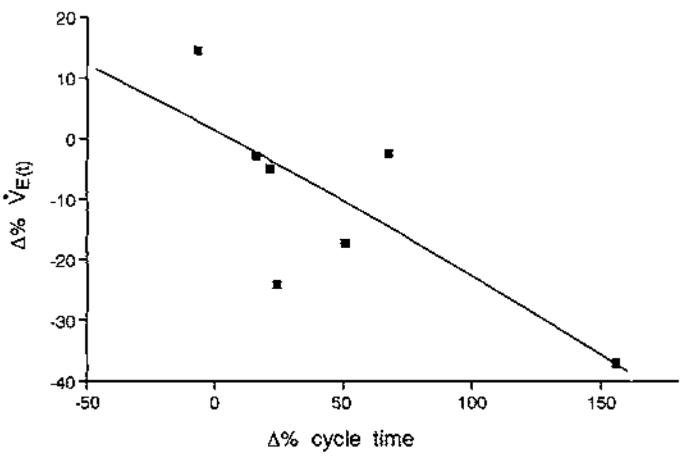

Fig. 4. Correlation between the percentage change of endurance and $\dot{V}_{E(t)}$ (for definition see Tables 3, 4) of the endurance cycling test in seven subjects after a 4-week respiratory training period: $y = -0.241x + 0.633$; $r = 0.762$ ($P < 0.05$)

corresponding oxygen consumption ($\dot{V}O_2$) amounted to 3.3 (SD 0.5) $l \cdot min^{-1}$ before and to 3.4 (SD 0.5) $l \cdot min^{-1}$ after the respiratory training. The increase in blood lactate concentrations above the resting values at the end of the endurance cycling tests was the same [2.2 (SD 1.4) vs 2.7 (SD 1.4) $mmol \cdot l^{-1}$] before and after respiratory training, in spite of an almost 9-min longer cycling duration after respiratory training.

The weekly endurance training times 2 weeks before, during and 1 week after respiratory training declined slowly with time but the reduction did not reach the level of significance (results not shown). The Th_{an} was essentially the same before and after respiratory training, irrespective of the method applied [calculated from heart rate: 258 (SD 50) vs 250 (SD 42) W or from minute ventilation: 265 (SD 36) vs 250 (SD 32) W]. Also $\dot{V}O_{2max}$ [4.4 (SD 0.5) vs 4.2 (SD 0.4) $l \cdot min^{-1}$] and the blood lactate increase during the determination of $\dot{V}O_{2max}$ [5.6 (SD 2.3) vs 5.2 (SD 2.4) $mmol \cdot l^{-1}$] had a tendency to decline without reaching statistical significance.

Respiratory training influenced minute ventilation during the endurance cycling and the $\dot{V}O_{2max}$ test in opposite directions. Whereas minute ventilation was decreased during the endurance cycling test in six of seven subjects after respiratory training (Table 3, Fig. 3), it was significantly increased ($P < 0.05$) during the determination of $\dot{V}O_{2max}$ (Table 4). The percentage change of cycle endurance correlated significantly ($P < 0.05$) with that of minute ventilation at the end of the shorter endurance cycling test (Fig. 4).

The endurance cycling tests of PS are presented in Fig. 5. Immediately after respiratory training, he performed an endurance cycling test which was reduced to 18.3 min (before respiratory training 28.9 min) despite

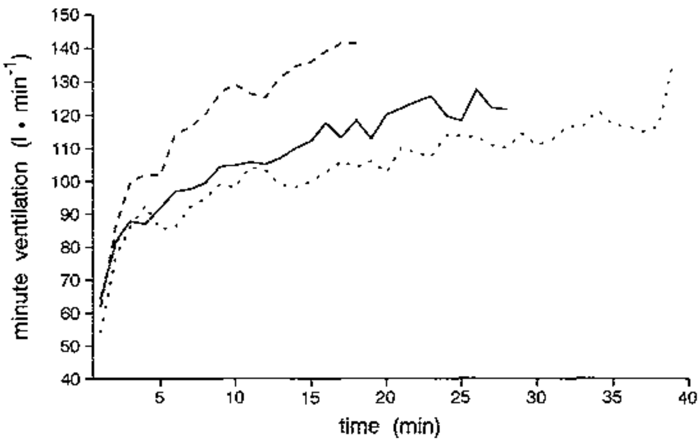

Fig. 5. Minute ventilation of subject PS during the endurance cycling test (280 W) before and twice after a 3-week respiratory training period ——before; --- after 1; ····· after 2

successful respiratory training. He had improved the endurance breathing test from 7.2 to 40 min without becoming exhausted. He repeated the endurance cycling test 5 days later. He cycled for 39.1 min. Figure 5 shows that the longest ride coincided with the lowest minute ventilation at a given time.

Discussion

Respiratory training increased the breathing endurance remarkably in endurance trained subjects. The progress in breathing endurance was already obvious during the training period as the subjects increased the set minute ventilation two to three times a week. In contrast to sedentary subjects (Boutellier and Piwko 1992), the trained subjects were competitive and trained their respiratory muscles close to their limits every day. Seven of the eight subjects reached 40 min during the endurance breathing test without showing any signs of exhaustion. Because we stopped the test after 40 min, we could not calculate the percentage improvement of breathing endurance achieved with respiratory training. However, an improvement from below 10 min to 40 min was remarkable and demonstrated that breathing endurance was not well developed even in endurance trained subjects. Our results are in accordance with two other studies (Morgan et al. 1987; Fairbarn et al. 1991). Not surprisingly, these investigators and others (Keens et al. 1977) could not find any change in breathing endurance without respiratory training in control persons. Respiratory training had no influence on vital capacity, peak flow, and forced expiratory volume in 1 s as in other studies (Leith and Bradley 1976; Belman and Gaesser 1988; Boutellier and Piwko 1992). The MVV has been shown to improve (this study; Leith and Bradley 1976; Morgan et al. 1987; Belman and Gaesser 1988) or not (Leith and Bradley 1976; Keens et al. 1977; Boutellier and Piwko 1992) according to the effectiveness of respiratory training in increasing breathing endurance.

Respiratory training increased cycle endurance at Th_{an} in trained subjects by 38%. This number compares well with the 50% found in untrained subjects (Boutellier and Piwko 1992). These findings are new and so far not confirmed by others. In two similar studies (Morgan et al. 1987; Fairbarn et al. 1991) cycle endurance was measured at 90% of maximal power output or 95% $\dot{V}O_{2max}$. The endurance cycling tests lasted less than 10 min and respiratory training had no influence on the outcome of these tests. As respiration does not normally limit $\dot{V}O_{2max}$ (for discussion see Boutellier and Piwko 1992), it is unlikely that a more trained respiratory system would have been advantageous at these high exercise intensities. Because efforts around $\dot{V}O_{2max}$ can only be tolerated for a short period of time, $\dot{V}O_{2max}$ has not been found to be a good indicator of aerobic performance or cycle endurance (Gimenez et al. 1982). The $\dot{V}O_{2max}$ indicates the limit an athlete may theoretically reach but $\dot{V}O_2$ at racing pace in endurance events is more than 10% below $\dot{V}O_{2max}$ except in world class athletes. Therefore, Th_{an} has been said to be a better indicator of aerobic performance than $\dot{V}O_{2max}$ (Allen et al. 1985; Joyner 1991). Furthermore, Gleser and Vogel (1973) have described endurance capacity by the equation:

$$\log(t) = -A \cdot L_r + B,$$

where t represents the time of the endurance cycling test and L_r the work load divided by $\dot{V}O_{2max}$. As the L_r values remained constant in our study as well as in the two other studies mentioned (Morgan et al. 1987; Fairbarn et al. 1991), maximal L_r did not change. The increase in endurance time at an unchanged, given, L_r can only be explained by a change of the slope A and the intercept B. The closer to $\dot{V}O_{2max}$ the exercise intensity is, the smaller the improvement of cycle endurance duration will be and it might not reach statistical significance as was seen in the studies of Morgan et al. (1987) and Fairbarn et al. (1991). In contrast to these studies, we measured endurance cycling duration at a lower exercise intensity [77 (SD 6) % $\dot{V}O_{2max}$] corresponding to the Th_{an}. At this level, respiratory training improved cycle endurance by 38%.

It was important for the estimation of the respiratory training effects that the habitual training did not interfere with the respiratory conditioning. Therefore, the study was undertaken in the autumn at the end of the outdoor season. The subjects agreed to prolong their season and to maintain regular endurance training 2 weeks before, during and 1 week after respiratory training - a promise they almost kept. In fact, the weekly training time tended to decline towards the end of the 7 weeks. Concomitantly, $\dot{V}O_{2max}$ and Th_{an} were slightly reduced after respiratory training. However, none of the decreases reached statistical significance. Therefore, the improvement of cycle endurance could not be explained by an increase of the overall endurance training. Also other factors such as conditioning of the heart or of peripheral skeletal muscles could not have been the cause of the increased cycle endurance after respiratory training. As we have discussed in detail in the case of sedentary subjects (Boutellier and Piwko 1992), respiratory training conditions neither the heart nor the peripheral skeletal muscles. This must apply even more to trained subjects who have already conditioned their hearts as well as their skeletal muscles. Finally, we are left with a better endurance of the respiratory muscles to explain the better response in the endurance cycling test after respiratory training.

As in sedentary subjects (Boutellier and Piwko 1992), an increase in breathing endurance reduced minute ventilation during steady-state cycling after respiratory training (Fig. 3). In the trained subjects, this reduction was less impressive than in the sedentary subjects. The percentage change of minute ventilation correlated significantly with that of cycle endurance (Fig. 4). This would suggest but does not prove the following interpretation: the less the respiratory muscles are trained, the higher is minute ventilation during exercise and the shorter is the cycle time. Therefore, an untrained respiratory system can limit endurance exercise. In addition, it is important to bear in mind that fatigue of the respiratory muscles increased ventilation during exercise in the normal subjects, although one would have expected a decrease. Respiratory training caused a reduction of minute ventilation during the endurance cycling test in most subjects and delayed the pre-exhaustion ventilatory increase in some of them. At the end of both tests, minute ventilation was the same, irrespective of the duration of the endurance cycling test. If hyperventilation occurred it was due to an increase of respiratory frequency. Why respiratory muscle fatigue yielded a higher breathing frequency remains obscure (Mador and Acevedo 1991a).

Contrary to the endurance cycling test, minute ventilation was higher during the $\dot{V}O_{2\max}$ test after respiratory training than before it. This surprising result was not due to technical problems because we used two different respiratory analysis systems which measured minute ventilation differently. The findings were identical, independent of the system used. A recent experience with a well-trained cross country skier (PS) may provide a clue. When he performed the endurance cycling test immediately after respiratory training of 3 weeks, his cycling endurance was reduced from 28.9 to 18.3 min (Fig. 5). This reduction occurred despite an optimal preparation with moderate physical activity 3 days before the test and a high motivation for the test. The following 4 days he was running or cycling daily but abstained from any isolated respiratory training. Before the test, he was not very optimistic that he would perform well due to tired legs. Despite subjectively worse conditions than 5 days before, he cycled for 39.1 min. The time differences between the three tests are too great to be explained by variations in daily form. Figure 5 shows that the longest ride coincided with the lowest minute ventilation at a given time. Therefore, we argue that the poor performance immediately after respiratory training was due to still tired respiratory muscles. Tired respiratory muscles seemed to increase minute ventilation during exercise. After the respiratory muscles had recovered, cycle endurance improved by 20.8 min. Comparing the endurance cycling test before with the second test after respiratory training, one can conclude that respiratory training increased cycle endurance of PS by 35%.

The three endurance cycling tests of PS demonstrated what an important role respiratory muscle fatigue played in limiting endurance exercise. Also others (Martin et al. 1982; Mador and Acevedo 1991b) but not all (Dodd et al. 1989) have found a reduced performance after respiratory muscle fatigue. In the present study, we obviously underestimated the tiredness of the respiratory muscles after respiratory training. It is very likely that 2 days were not sufficient for the respiratory muscles to recover after respiratory training and the endurance breathing test. This would explain the increased minute ventilation during the $\dot{V}O_{2\max}$ determination after respiratory training. A period of 2 more days of recovery were sufficient to reduce respiratory muscle fatigue with the result that minute ventilation was lower during the endurance cycling test after respiratory training. One can speculate that more recovery time could have reduced minute ventilation further during the endurance cycling test after respiratory training. This applies especially to RB and to subjects with only a small reduction in minute ventilation after respiratory training. A lower minute ventilation would have increased the duration of the endurance cycling test (Fig. 4). Therefore, fully recovered respiratory muscles might have yielded a higher improvement of cycle endurance by respiratory training in trained subjects than the 38% found. Nevertheless, 38% increase of cycle endurance time was a strong argument for the respiratory system being regarded as a limiting factor in endurance exercise.

There was also subjective evidence that respiratory muscle fatigue did limit exercise. The subjects reported that respiratory training eliminated the feeling of breathlessness even during uphill running or cycling. The problem with this was that they had felt very good at the beginning of a race or in an uphill run and then lost control of their potential: they started too fast with resultant acidotic legs. The same thing occurred with running or cycling uphill too fast. This was a new experience for the subjects and they had to find "pacers" other than ventilation. They reported improved performances after an optimal establishment of new pacers such as, for example, the heart rate or the lap time, which they followed strictly. That the elimination of breathlessness or hyperventilation with respiratory training can increase the average racing speed underlines the argument that the respiratory system is an exercise limiting factor. However, respiratory training increased neither the Th_{an} nor $\dot{V}O_{2\max}$ but it enabled the subjects to maintain a given speed for a longer time.

If additional respiratory training can also improve endurance in world class athletes remains to be answered. Joyner (1991) has examined current concepts concerning "limiting" factors in human endurance performance by modelling marathon running times. The analysis has suggested that substantial improvements in marathon performance are "physiologically" possible or that current concepts regarding limiting factors in endurance running need further refinement and empirical testing. It might be that respiratory training is a factor so far neglected. But it could also be that world class athletes already condition their respiratory endurance sufficiently (Anholm et al. 1989), for instance with interval or uphill training. However, the intensive training necessary to reach a minute ventilation as high as during isolated respiratory training, to train fully the respiratory muscles, is unpleasant, time-consuming and associated with a high risk of injuries. If respiratory training does not improve performance of world class athletes it may help to reduce the quantity of intensive training.

Conclusions

We have identified the respiratory system to be an exercise limiting factor in normal trained subjects also. After respiratory training, minute ventilation was reduced during an endurance cycling test at Th_{an}. The duration of this test was significantly prolonged by 38%, whereas Th_{an} and $\dot{V}O_{2max}$ remained at the same level.

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