Respiratory Medicine (2006) **100**, 1117–1120

respiratoryMEDICINE

SHORT REPORT

Does training of respiratory muscles affect exercise performance in healthy subjects?

Francesco Gigliotti[a], Barbara Binazzi[b], Giorgio Scano[a,b,*]

[a]*Fondazione Don C. Gnocchi, IRCCS, Section of Respiratory Rehabilitation, Pozzolatico (Florence)*
[b]*Department of Internal Medicine, Section of Respiratory Disease, Clinica Medica 3, University of Florence, Firenze, Italy*

Received 29 April 2005; accepted 11 September 2005

Is there a physiologic rationale for respiratory muscle training effects on exercise performance?

Ventilatory demand during exercise is met by increased volume and airflow. They require higher negative pleural pressure (Pes) which peak ranges from 49% to 90% of maximal pressure generating capacity (Pcap) of the respiratory muscles during both incremental maximal[1,2] and endurance exercise.[3,4] In these conditions the diaphragm progressively reduces over time its relative pressure contribution (Pdi) to total inspiratory muscle output (Pdi/Pes).[3–5] Studies employing non-volitional methods have demonstrated that high-intensity whole body exercise endurance ($>$85% VO_2max) induces global respiratory muscle fatigue. In this context, the functional significance of improved respiratory muscle function with respiratory muscle training (RMT) would presumably be to prevent or delay the diaphragm fatigue that is known to occur during sustained high-intensity exercise.[3] Competition for blood flow distribution and/or acidification of the diaphragm via its uptake of circulating lactate in conjunction with a contracting diaphragm accounts for most of the exercise-induced diaphragm fatigue in healthy subjects.[6] To define the contribution of the work of breathing to diaphragm fatigue, Babcock et al.[7] were able to show that endurance exercise at 80–85% VO_2max (55 ml/kg/min) resulted in both high- and low-frequency diaphragm fatigue. Partial unloading of the diaphragm via pressure assist ventilation (PAV) reduced the work of breathing and total VO_2 and prevented diaphragm fatigue at all stimulation frequencies and after exercise. These findings are consistent with the contribution of work load per se to diaphragm fatigue.

Development of diaphragm fatigue during exercise is a function of the relationship between the magnitude of diaphragm work and adequacy of its blood supply: the less the blood flow available, the less the diaphragm work required to produce fatigue. Muscle force output vs blood flow imbalance of the diaphragm (which favors fatigue) may occur during endurance exercise only when the intensity of exercise exceeds 85% VO_2max or arterial hypoxemia is present.[8]

Recent evidence shows that inspiratory muscle fatigue causes a sympathetically mediated vasoconstriction of lower limbs. St Croix et al.[9] fatigued

*Corresponding author. Department of Internal Medicine, Section of Respiratory Disease, Clinica Medica 3, University of Florence, Viale Morgagni 85, Careggi 50134 Firenze, Italy. Tel.: +39 055 4296 414; fax: +39 055 422867.
E-mail address: gscano@unifi.it (G. Scano).

0954-6111/$ - see front matter
doi:10.1016/j.rmed.2005.09.022

the diaphragm by imposing high-intensity contraction and high duty cycle on healthy subjects. Fatigue caused a time-dependent increase in muscle sympathetic nerve activity (MSNA) in resting legs. MSNA is likely due to type IV nerve ending stimulation of the diaphragm. In a later study, MSNA was found to be accompanied by significant decreases in limb vascular conductance and limb blood flow along with increased mean arterial pressure and heart rate.[10] A high MSNA also results as a metabo-reflex during high-intensity and high-frequency contractions of the expiratory muscles.[11] In turn, Romer and Dempsey[12] postulated that reflex mechanisms of sympathoexcitation are triggered by metaboreceptors in the diaphragm as the muscle begins to accumulate metabolic end products during heavy exercise when cardiac output is insufficient to adequately meet the high metabolic requirements of both respiratory and limb musculature.

It appears therefore that respiratory muscle fatigue must occur for unloading to improve performances.[13,14] This might explain why other studies have not found a significant effect of respiratory muscle unloading on exercise capacity.[15] An important observation is that respiratory muscle fatigue during heavy exercise[6,7] could negatively impact limb work capacity due to blood flow redistribution even when cardiac output is not near maximal level.

Based on the above results it has been postulated that RMT might improve exercise capacity as follows: (i) by preventing or delaying respiratory muscle fatigue and its effect on blood flow distribution, (ii) by causing less recruitment of accessory respiratory muscles, and therefore (iii) by increasing efficiency and decreasing blood flow requirements of respiratory muscles during exercise,[12] (iv) by reducing the amount of sympathetically induced reflex vasoconstriction in response to isometric exercise.[16,17]

RMT effects on exercise response

Several studies in recent years have examined the effects of specific respiratory muscle endurance training on the performance of both respiratory muscles and exercise performance itself. However, the effects of RMT on exercise performance in healthy subjects are controversial. As shown in Table 1, 25–50% improvement in endurance exercise performance has been reported by some,[18–27] but not by others.[28–34] A reduction in exercise ventilation[18,19] and blood lactate[20,21,27]

Table 1 Effects of RMT on whole body endurance capacity in healthy subjects.

Endurance improvement		VE			VO_2max		Blood lactate reduction	
Yes	Not	Reduction	No changes	Increase	Increase	No changes	Yes	Not
18*,19†,20*,21ǂ,22ǂ,23†, 24†,25ǂ, 26ǂ,27ǂ,28ǂ,40*	29ǂ,30ǂ,31*, 32ǂ,33ǂ,34ǂ	18,19,40	23,24,26,28,30–34	20–22,25,27,29	27	26,28–31,40	18,20,21,28	25,26,33

RMT: respiratory muscle training; VE: minute ventilation; VO_2: oxygen uptake.
*Trained subjects.
†Sedentary subjects.
ǂ Athletes.

has been reported as evidence of the effect of training on respiratory muscles. The two studies by Boutelier and Piwko[18] and Boutelier et al.[19] are exceptions in that endurance performance at about 75–80% of VO_2max was increased by 38% in non-athletes and 50% in athletes. These changes were accompanied by substantial but highly variable reductions in ventilatory responses to exercise. No reduction in ventilation[23,24,26,28,32–34] and even its increase[20–22,25,29] was reported in other studies whereas aerobic capacity resulted either unchanged[29–31] or improved.[28] The discrepancies among studies may reflect differences in exercise intensities and durations used for testing and the markedly different experimental designs of the studies. Sonetti et al.[33] have recently stressed the probable reasons for discrepancies (subjective nature of the performance tests, variation in the relative intensity and duration of exercise, fitness level of subjects, inclusion and exclusion of control groups), and two major confounding effects: (1) use of a fixed work rate performance test which has little relevance to the subject's competition experience, and does not usually yield reproducible results[35]; (2) absence of a legitimate placebo group (most of the performance outcomes tested volitional effort and therefore on the subject's expectation and motivation).

After the seminal paper by Harms et al.[36] showing that mechanical unloading of the respiratory muscles with PAV during maximal whole body exercise resulted in 5–7% blood flow increase in leg muscles, and 14% increase in endurance capacity, with no changes in circulating lactate, and decrease in VO_2, cardiac output, dyspnea and leg effort, it seems inconceivable that the effect of RMT could surpass those seen with PAV. Sonetti et al.[33] do not suspect this to be the case since they observed a similarly large performance improvement which was not due to RMT but primarily to a significant placebo plus familiarization effect for fixed work rate exercise. They also maintained that specific RMT in highly fit competitive subjects may influence peak exercise performance to a very limited extent and most of this influence can be explained by a placebo (expectation) effect. Some studies[32] used "minimal exercise" placebo that may not be sufficient to activate placebo factors such as expectation.[36] These data strengthen the need for applying the criteria suggested by Ojaunen[37] for a true placebo: (1) the placebo needs to be inert (no effect on ventilation, and carbon dioxide tension), (2) it should generate expectations, involvement, subjective utility and be meaningful to the subjects.

Is the present method for RMT useless in healthy subjects? Recent data by De Palo et al.[38] argue against this possibility. Based on the observation of diaphragm recruitment and Pdi increase with non-respiratory manoeuvres, De Palo et al.[38] show that strength training of non-respiratory manoeuvres may strengthen the respiratory muscles in healthy subjects by increasing maximal Pdi, maximal inspiratory (MIP) and expiratory (MEP) muscle pressures, and maximal gastric pressure after 16 weeks of training. Because diaphragm thickness also increased, it was unlikely that the effects were due to training. Whether and to what extent non-respiratory manoeuvres also affects exercise performance remains to be defined.

Conclusions

Recent studies provide evidence that RMT improves exercise performance in well-controlled and rigorously designed studies utilizing exercise tests with the lowest coefficient of variation for repeated testing, appropriate outcome measures, and fitness of the participants.[28,39,40] Further studies, however, are needed to define the mechanisms by which RMT improves exercise performance.

> No amount of experimentation can prove me right; a simple experiment may at any time prove me wrong (A. Einstein).

References

1. El-Manshawi A, Killian KJ, Summers E, Jones NL. Breathlessness during exercise with and without resistive loading. *J Appl Physiol* 1986;**61**:896–905.
2. Johnson BD, Saupe KVC, Dempsey JA. Mechanical constraints on exercise hyperpnea in endurance athletes. *J Appl Physiol* 1992;**73**:874–86.
3. Johnson BD, Babcock MA, Suman OE, Dempsey JA. Exercise induced diaphragmatic fatigue in healthy humans. *J Physiol (London)* 1993;**469**:385–405.
4. Mador MJ, Magalan UJ, Rodis A, Kufel TJ. Diaphragm fatigue after exercise in healthy human subjects. *Am Rev Respir Dis* 1993;**148**:1571–5.
5. Aliverti A, Cala SJ, Duranti R, et al. Human respiratory muscle action and control during exercise. *J Appl Physiol* 1997;**83**:1256–69.
6. Babcock MA, Pegelow DF, McClaran SR, Suman OE, Dempsey JA. Contribution of diaphragmatic power output to exercise-induced diaphragm fatigue. *J Appl Physiol* 1995;**78**:1710–9.
7. Babcock MA, Pegelow DF, Harms CA, Dempsey JA. Effect of respiratory muscle unloading on exercise-induced diaphragm fatigue. *J Appl Physiol* 2002;**93**:201–6.
8. Babcock MA, Johnson BD, Pegelow DF, Suman OE, Griffin D, Dempsey JA. Hypoxic effects on exercise-induced diaphragmatic fatigue in normal healthy humans. *J Appl Physiol* 1995;**78**:82–92.

9. St Croix CM, Morgan BJ, Wetter TJ, Dempsey JA. Fatiguing inspiratory muscle work causes reflex sympathetic activation in humans. *J Physiol* 2000;**529**:493–504.
10. Sheel AW, Derchak PA, Morgan BJ, Jacques AI, Dempsey JA. Fatiguing inspiratory muscle work causes reflex reduction in resisting leg blood flow. *J Physiol* 2001;**537**:277–89.
11. Derchak PA, Sheel AW, Morgan BJ, Dempsey JA. Effects of expiratory muscle work on muscle sympathetic nerve activity. *J Appl Physiol* 2002;**92**:1539–52.
12. Romer LM, Dempsey JA. The work of breathing during exercise: implications for performance. In: Aliverti A, Brusasco V, Macklem PT, Pedotti A, editors. *Mechanics of breathing: pathophysiology, diagnosis and treatment*. Milano: Springer; 2004.
13. Harms CA, Babcock MA, McClaran SR, et al. Respiratory muscle work compromises leg blood flow during maximal exercise. *J Appl Physiol* 1997;**82**:1573–83.
14. Harms CA, Wetter TJ, McClaran SR, et al. Effects of respiratory muscle work on cardiac output and its distribution during maximal exercise. *J Appl Physiol* 1998;**85**: 609–18.
15. Marciniuk D, McKim D, Sanii R, Younes M. Role of central respiratory muscle fatigue in endurance exercise in normal subjects. *J Appl Physiol* 1994;**76**:236–41.
16. Mostoufi-Moab S, Widmaier EJ, Cornett JA, Gray K, Sinoway LI. Forearm training reduces the exercise pressor reflex during ischemic rhythmic handgrip. *J Appl Physiol* 1998;**84**: 277–83.
17. Somers VK, Leo KC, Shields R, Clary M, Mark AL. Forearm endurance training attenuates sympathetic nerve response to isometric handgrip in normal humans. *J Appl Physiol* 1992;**72**:1039–43.
18. Boutellier U, Piwko P. The respiratory system as an exercise limiting factor in normal sedentary subjects. *Eur J Appl Physiol Occup Physiol* 1992;**64**:145–52.
19. Boutellier U, Büchel R, Kundert A, Splenger C. The respiratory system as an exercise limiting factor in normal trained subjects. *Eur J Appl Physiol Occup Physiol* 1992;**65**: 347–53.
20. Spengler CM, Roos M, Laube SM, Boutellier U. Decreased exercise blood lactate concentrations after respiratory endurance training in humans. *Eur J Appl Physiol Occup Physiol* 1999;**79**:299–305.
21. Kohl J, Koller EA, Brandenberger M, Cardenas M, Boutellier U. Effects of exercise-induced hyperventilation on airway resistance and cycling endurance. *Eur J Appl Physiol* 1997;**75**:305–11.
22. Volianitis S, McConnell AK, Koutedakis Y, McNaughton L, Backx K, Jones DA. Inspiratory muscle training improves rowing performance. *Med Sci Sports Exerc* 2001;**33**(5): 803–9.
23. Stuessi C, Spengler CM, Knöpfli-Lenzin C, Markov G, Boutellier U. Respiratory muscle endurance training in humans increases cycling endurance without affecting blood gas concentrations. *Eur J Appl Physiol* 2001;**84**:582–6.
24. Markov G, Spengler CM, Knöpfli-Lenzin C, Markov G, Boutellier U. Respiratory muscle endurance training in humans increases cycling endurance without affecting cardiovascular responses to exercise. *Eur J Appl Physiol* 2001;**85**:233–9.
25. McMahon M, Boutellier U, Smith RM, Spengler CM. Hyperpnea training attenuates peripheral chemosensitivity and improves cycling endurance. *J Exp Biol* 2002;**205**:3937–43.
26. Romer LM, McConnell AK, Jones DA. Effects of inspiratory muscle training on time-trial performance in trained cyclists. *J Sports Sci* 2002;**20**:547–62.
27. Holm P, Sattler A, Fregosi RF. Endurance training of respiratory muscles improves cycling performance in fit young cyclists. *BMC Physiol* 2004;**4**:9.
28. Romer LM, McConnell AK, Jones DA. Effects of inspiratory muscle training upon recovery time during high intensity, repetitive sprint activity. *Int J Sports Med* 2002;**23**:353–60.
29. Morgan DW, Kohrt WM, Bates BJ, Skinner JS. Effects of respiratory muscle endurance training on ventilatory and endurance performance of moderately trained cyclists. *Int J Sports Med* 1987;**8**:88–93.
30. Fairban MS, Coutts KC, Pardy RL, McKenzie DC. Improved respiratory muscle endurance of highly trained cyclists and the effects on maximal exercise performance. *Int J Sports Med* 1991;**12**:66–70.
31. Hanel B, Secher NH. Maximal oxygen uptake and work capacity after inspiratory muscle training: a controlled study. *J Sports Sci* 1991;**9**:43–52.
32. Imbar O, Weiner P, Azgad Y, Rotstein A, Weinsteine Y. Specific inspiratory muscle training in well-trained endurance athletes. *Med Sci Sports Exerc* 2000;**32**:1233–7.
33. Sonetti DA, Wetter TJ, Pegelow DF, Dempsey JA. Effects of respiratory muscle training versus placebo on endurance exercise performance. *Respir Physiol* 2001;**127**:185–99.
34. Williams JS, Wongsathikun J, Boon SM, Acevedo EO. Inspiratory muscle training fails to improve endurance capacity in athletes. *Med Sci Sports Exerc* 2000;**32**:1233–7.
35. Jeukendrup A, Saris WHM, Brouns F, Kester ADM. A new validated endurance performance test. *Med Sci Sports Exerc* 1996;**28**:266–70.
36. Harms CA, Wetter TJ, St.Croix CM, Pegelow DF, Dempsey JA. Effects of respiratory muscle work on exercise performance. *J Appl Physiol* 2000;**89**:131–8.
37. Ojaunen M. Can the true effects of exercise on psychological variables be separated from placebo effects? *Int J Sports Psychol* 1994;**25**:63–80.
38. De Palo VA, Parker AL, Al-Bilbeisi F, McCool D. Respiratory muscle strength training with non-respiratory maneuvers. *J Appl Physiol* 2004;**96**:731–4.
39. McConnell AK, Romer LM. Respiratory muscle training in healthy humans: resolving the controversy. *Int J Sports Med* 2004;**25**(4):284–93.
40. Gething AD, Williams M, Davies B. Inspiratory resistive loading improves cycling capacity: a placebo controlled trial. *Br J Sports Med* 2004;**38**:730–6.