HIGHLIGHTED TOPIC | Fatigue Mechanisms Determining Exercise Performance

Exercise-induced respiratory muscle fatigue: implications for performance

Lee M. Romer1 and Michael I. Polkey2
1Centre for Sports Medicine and Human Performance, Brunel University, Uxbridge; and 2Respiratory Muscle Laboratory, Royal Brompton Hospital, and National Heart and Lung Institute, London, United Kingdom

Romer LM, Polkey MI. Exercise-induced respiratory muscle fatigue: implications for performance. J Appl Physiol 104: 879–888, 2008. First published December 20, 2007; doi:10.1152/japplphysiol.01157.2007.—It is commonly held that the respiratory system has ample capacity relative to the demand for maximal O2 and CO2 transport in healthy humans exercising near sea level. However, this situation may not apply during heavy-intensity, sustained exercise where exercise may encroach on the capacity of the respiratory system. Nerve stimulation techniques have provided objective evidence that the diaphragm and abdominal muscles are susceptible to fatigue with heavy, sustained exercise. The fatigue appears to be due to elevated levels of respiratory muscle work combined with an increased competition for blood flow with limb locomotor muscles. When respiratory muscles are prefatigued using voluntary respiratory maneuvers, time to exhaustion during subsequent exercise is decreased. Partially unloading the respiratory muscles during heavy exercise using low-density gas mixtures or mechanical ventilation can prevent exercise-induced diaphragm fatigue and increase exercise time to exhaustion. Collectively, these findings suggest that respiratory muscle fatigue may be involved in limiting exercise tolerance or that other factors, including alterations in the sensation of dyspnea or mechanical load, may be important. The major consequence of respiratory muscle fatigue is an increased sympathetic vasoconstrictor outflow to working skeletal muscle through a respiratory muscle metaboreflex, thereby reducing limb blood flow and increasing the severity of exercise-induced locomotor muscle fatigue. An increase in limb locomotor muscle fatigue may play a pivotal role in determining exercise tolerance through a direct effect on muscle force output and a feedback effect on effort perception, causing reduced motor output to the working limb muscles.

respiratory muscles; exercise; diaphragm; abdominals; magnetic stimulation; metaboreflex

THE PURPOSE OF THIS MINIREVIEW is to address the question of whether the respiratory demands of exercise contribute significantly toward exercise limitation, either directly through limitations of the respiratory muscle pump or indirectly through effects on limb blood flow and locomotor muscle fatigue. We describe the mechanical and metabolic costs of meeting the ventilatory requirements of exercise. We then ask whether the respiratory muscles fatigue with exercise, what factors contribute to any such fatigue, and what the implications of these factors are for exercise tolerance. Finally, we deal with the potential mechanisms by which respiratory muscle fatigue could compromise exercise tolerance and whether it is possible to overcome this potential respiratory limitation. Our review focuses on the healthy young adult exercising near sea level. However, we also consider special circumstances that determine the balance between metabolic demand and respiratory system capacity in the highly trained endurance athlete and the clinical implications for respiratory limitations to exercise in patients with chronic obstructive pulmonary disease (COPD) and chronic heart failure (CHF).

EXERCISE DEMANDS ON THE RESPIRATORY MUSCLES

The primary function of the respiratory control system during moderate exercise is to drive alveolar ventilation in proportion to metabolic requirements such that arterial blood-gas tensions and acid-base balance are maintained at or near resting levels. At work rates that engender a metabolic acidosis, there is the additional challenge of effecting compensatory hyperventilation to minimize the fall of arterial pH and prevent arterial hypoxemia. In addition to maintaining arterial blood-gas and acid-base homeostasis, ventilation and breathing pattern must be regulated precisely so that the work performed by the respiratory muscles is minimized. In the healthy subject, these ventilatory requirements are readily met because the respiratory muscles are anatomically suited to the increased ventilatory demands of exercise, and the neural regulation of breathing is optimal. The diaphragm, for example, has a high oxidative capacity, a short capillary-to-mitochondrial diffusion distance for O2, and a velocity of shortening between that of fast-twitch and slow-twitch muscles (91). Furthermore, with
progressively increasing exercise, activation of expiratory muscles, in the absence of expiratory flow limitation, reduces end-expiratory lung volume (EELV) below resting levels (44), helping to assist the inspiratory muscles in three ways. First, the reduced EELV enables increases in tidal volume to occur over the most linear portion of the respiratory system pressure-volume relationship such that respiratory system compliance remains high (99, 123). Second, the reduced EELV means that the diaphragm is lengthened, enabling this muscle to operate near its optimal length for force generation (101, 114). Third, the reduced EELV allows for storage of elastic energy in the chest and abdominal walls during expiration that can be used to produce a portion of the work required during the ensuing inspiration (5, 35), although it is also possible that inspiration is aided in this situation by passive descent of the diaphragm (35). Importantly, accessory respiratory muscles are progressively recruited with increasing ventilatory demand during exercise, thereby sharing the load needed to support the exercise hyperpnea (6). The unique structural characteristics of respiratory muscles combined with the precise neural regulation of breathing mean that the capacity of these muscles for pressure generation usually exceeds the demands placed on them. Thus, in most untrained healthy subjects, the pressures produced by the expiratory muscles during maximal exercise are well within the constraints for effective pressure generation, and the pressures produced by the inspiratory muscles are only 40–60% of maximum dynamic capacity (54). Furthermore, the metabolic requirements of the respiratory muscles are relatively low with the O₂ cost of breathing during maximal exercise averaging only 8–10% of total body O₂ consumption (3).

In contrast, the highly fit endurance athlete working at higher metabolic rate and ventilation may meet or exceed the capacity of the respiratory system. As exercise intensity and ventilation increase, airways undergo dynamic compression during expiration, flow limitation occurs, and EELV is forced upward so that flow can be increased further (56). At high operational lung volumes the inspiratory muscles have to overcome the added elastic load presented by the lung and chest wall (85). Furthermore, breathing at a higher lung volume means that the inspiratory muscles are shorter, with less force-generating capability (4). Accordingly, highly fit subjects exercising at maximum can increase expiratory pressures to levels that exceed the maximal dynamic pressure at which flow becomes limited, and peak dynamic inspiratory muscle pressures can be elevated to 90% of capacity or greater (54). To meet these ventilatory requirements the respiratory muscles require a substantial blood flow and O₂ supply. Data in highly fit subjects suggest that up to 16% of the total VO₂max and total cardiac output is devoted to inspiratory and expiratory muscles during maximum exercise (3, 40). These indirect estimates agree closely with those in running equines as measured directly with radiolabeled microspheres (75, 76).

**EXERCISE-INDUCED RESPIRATORY MUSCLE FATIGUE**

Muscle fatigue is defined as “a condition in which there is a loss in the capacity for developing force and/or velocity of a muscle, resulting from muscle activity under load and which is reversible by rest” (94). Fatigue is evident from a reduced force output relative to prior baseline values, where force output is objectively determined by electrically or magnetically stimulating the motor nerves to the muscle in question across one or more frequencies. Compared with limb muscles, it is difficult to objectively assess fatigue of the diaphragm because both the muscle and the motor nerves are relatively inaccessible. Thus force development across the muscle (i.e., transdiaphragmatic pressure) is estimated by measuring the pressure difference between gastric and esophageal pressures induced by stimulation of both phrenic nerves (9, 90, 97, 110). For the abdominal muscles, force output is estimated by measuring the gastric pressure response to magnetic stimulation of the thoracic nerve roots (61). For nerve stimulation to provide a valid measure of respiratory muscle fatigue it is important to carefully control for several potential sources of error, including supramaximal stimulation (20, 128), isovolumic conditions (47, 114), abdominal compliance (58, 73), and postactivation potentiation (71, 143).

Application of these nerve stimulation techniques to studies examining resistive breathing or voluntary hyperpnea has shown that fatigue can be induced in the human diaphragm (37, 93) and abdominal muscles (61). These techniques have also been used to show that whole body endurance exercise can induce fatigue of the diaphragm (11–14, 52, 72) and abdominal muscles (127, 133). In fit normal subjects exercising to exhaustion (8–10 min) at intensities that elicit at least 80–85% of VO₂max, reductions of 15–30% in the transdiaphragmatic pressure response to supramaximal stimulation of the phrenic nerves were consistently obtained within 10 min after exercise, and transdiaphragmatic pressures did not return to near preexercise values until 1–2 h postexercise (11–14, 52, 72). Interestingly, short-term incremental exercise to exhaustion did not alter stimulated transdiaphragmatic pressures (64, 106, 134), a phenomenon probably explained by the fact that exercise duration was too short for the cumulative work history of the diaphragm to reach fatiguing levels (106). This latter finding suggests not only that exercise intensity is important but also that exercise duration plays a role in diaphragm fatigue. More recent studies have reported postexercise declines of about 15–25% in the gastric pressure response to magnetic thoracic nerve stimulation at work rates eliciting >90% of VO₂max (127, 133), indicating that whole body exercise can also induce abdominal muscle fatigue.

To date, only changes in respiratory muscle force output have been assessed using nerve stimulation techniques. However, other changes in muscle function may occur with a reduction in force output, such as a change in the velocity of muscle shortening or in the ability to shorten under load. A major component of the exercise response involves high velocities of muscle shortening (i.e., high flow rates) in addition to increases in force output. Thus future studies are needed to determine the role these factors may play in the loss of function associated with fatigue.

**FACTORS CONTRIBUTING TO EXERCISE-INDUCED RESPIRATORY MUSCLE FATIGUE**

The cause of exercise-induced respiratory muscle fatigue is due, in part, to the high levels of respiratory muscle work that must be sustained throughout heavy exercise, as shown by the finding that diaphragmatic fatigue was prevented when diaphragmatic work during exercise was reduced by >50% using...
a mechanical ventilator (11). However, other factors besides respiratory muscle work must also be responsible for exercise-induced respiratory muscle fatigue, because fatigue did not occur when the resting subject mimicked the magnitude and duration of diaphragmatic work incurred during exercise (13). Indeed, fatigue did not occur until the pressures developed by the diaphragm were voluntarily increased twofold greater than required during whole body exercise at intensities that caused exercise-induced diaphragmatic fatigue (13). The probable explanation for why the fatigue threshold of force production for the diaphragm was so much lower during whole body exercise than at rest is that, at rest, the volitional increases in diaphragmatic work mean that large shares of the total cardiac output are devoted to the diaphragm, whereas during exercise the diaphragm must compete with locomotor muscles for its share of the available cardiac output (39, 40). Less blood flow to the diaphragm promotes inadequate O2 transport, increasing the likelihood of fatigue.

Collectively, these findings suggest that the development of diaphragmatic fatigue with exercise is a function of the relationship between the magnitude of diaphragmatic work and the adequacy of its blood supply: the less blood flow available, the less diaphragmatic work is required to produce fatigue. In healthy young adults of varying fitness, an imbalance of muscle force output versus blood flow or O2 transport availability to the diaphragm that favors fatigue appears to occur most consistently when the intensity of prolonged endurance exercise elicits at least 80–85% of VO2max (52) or arterial O2 saturation drops below ~85% (10, 135, 136).

FUNCTIONAL CONSEQUENCES OF RESPIRATORY MUSCLE FATIGUE

Several approaches have been used to determine whether respiratory muscle fatigue affects exercise tolerance. One such approach is to prefatigue the respiratory muscles at rest and observe whether subsequent whole body exercise performance is impaired. Fatigue of inspiratory or expiratory muscles can be produced using resistive loads, while global respiratory muscle fatigue can be achieved using voluntary hyperpnea. Prefatigue studies have shown either a significant decrease (69, 79, 132) or no change (24, 113, 118) in performance during subsequent heavy exercise. However, a problem with some of these studies is that respiratory muscle fatigue was not assessed (24, 79, 118) or was not quantified objectively using nerve stimulation techniques (69, 132). Consequently, some of the studies may have failed to induce significant levels of respiratory muscle fatigue before subsequent exercise or overestimated the normally occurring level of fatigue in response to whole body exercise. An additional limitation is that it is impossible to induce prior fatigue without subjects knowing and, hence, difficult to determine the contribution of subject expectation to changes in exercise tolerance. Another concern is that subjects may change their breathing pattern after prior fatigue of the respiratory muscles (68), such that any change in exercise tolerance may be due not only to a change in respiratory muscle fatigue but also to an increased intensity of dyspnea (67, 82). Last, it may be necessary to leave a sufficient interval between the fatiguing task and the subsequent exercise trial so as to separate the effects of long-lasting fatigue from general exhaustion or a time-dependent metaboreflex (see also Cardiorespiratory interactions).

Another approach to determine whether respiratory muscle fatigue (or the respiratory load) affects exercise tolerance is to partially unload the respiratory muscles during exercise by breathing a low-density gas mixture such as 79% helium-21% O2 (heliox). Heliox decreases the turbulent component of airflow at high levels of ventilation and may facilitate unloading of the respiratory muscles by way of reducing expiratory flow limitation and dynamic lung hyperinflation (80). Using this approach, time to exhaustion during constant-load exercise was increased at high work rates (>85–90% of VO2max) (51, 98, 141) but not at lower work rates (51). However, heliox does not simply unload the respiratory muscles but may also act by improving arterial oxygen saturation through the combined effect of an increase in alveolar ventilation and a decrease in the alveolar-to-arterial oxygen difference (19).

An alternative method of unloading the respiratory muscles is to use a mechanical ventilator. When a proportional assist ventilator was used to partially unload the inspiratory muscles during prolonged heavy exercise (>90% of VO2max), time to exhaustion was significantly increased, and the rates of rise of VO2 and perceptions of respiratory and limb discomfort during exercise were reduced (41) (Fig. 1). Not all studies have shown a benefit of mechanical unloading on exercise tolerance (30, 60, 77), but these studies were conducted at relatively lower exercise intensities (~70–80% of VO2max) in less-fit subjects. A potential limitation of this approach to unloading is that the pressures delivered by the ventilator during maximal exercise can be substantial and hence disruptive to subjects, even after thorough familiarization (41, 106). Another concern is that, with few exceptions (106), a placebo group is rarely incorporated into the experimental design. Studies without a placebo group can be criticized for having weak internal validity and for being vulnerable to the potential influence of subject bias. A limitation of all unloading studies is that it is difficult to determine whether the positive effect of reducing respiratory muscle work on exercise tolerance is attributable to the relief of respiratory muscle fatigue or whether this is simply a perceptual benefit obtained by relieving the discomfort attending high levels of respiratory muscle work. A further consideration is that inspiratory muscle unloading creates a less-negative intrathoracic pressure that, through a reduction in ventricular preload, reduces stroke volume and cardiac output (40, 89).

MECHANISMS BY WHICH RESPIRATORY MUSCLE FATIGUE COULD AFFECT EXERCISE TOLERANCE

Ventilation and dyspnea. Respiratory muscle fatigue could potentially limit exercise tolerance through an inadequate ventilatory response (i.e., relative alveolar hypoventilation), an alteration in breathing mechanics, an increased sensation of dyspnea, or a combination of these factors. Relative alveolar hypoventilation would be expected to occur if the respiratory muscles were unable to generate the required pressures or a tachypneic breathing pattern caused high dead space and, therefore, reduced alveolar ventilation. However, studies that have documented exercise-induced respiratory muscle fatigue showed that ventilation was generally appropriate for a given metabolic demand [i.e., end-tidal PCO2 (PETCO2) values less than 40 mmHg and O2 saturation near resting values] (11–14,
caused reductions in oxygen uptake (V\textsuperscript{\textcircled{}}\textsubscript{\textcircled{}}\textsubscript{\textcircled{}}\textsubscript{\textcircled{}}O\textsubscript{2}; 76% of trials by 1.3 normal work of breathing by 50% from control increased time to exhaustion in (see EXERCISE DEMANDS ON THE RESPIRATORY MUSCLES). The pro-
cress the metabolic and blood flow demands of these muscles
continues may distort the chest wall (34, 36), reduce the
increasing use of accessory respiratory muscles as exercise
the progressive hyperventilatory response (6, 12, 13, 52). The
inspiratory and expiratory muscles to be recruited to deliver
to total ventilation over time with a requirement for accessory
endurance exercise capacity at a work rate requiring
progressively increasing use of accessory respiratory muscles, as exercise
progressive recruitment of accessory respiratory muscles would be
expected to increase sensory input to the central nervous
system and, therefore, increase the intensity of dyspnea. Res-
piratory muscle fatigue per se may increase the intensity of dyspnea (31, 125, 126, 138), but this effect appears to be
specific to the accessory respiratory muscles because dia-
aphragm fatigue does not increase neural respiratory drive
assessed by diaphragm electromyogram (66), and specific
loading of the diaphragm does not increase the sensation of
inspiratory effort (18, 138). Factors independent of fatigue can
also modify dyspnea and potentially influence exercise toler-
ance. For example, increased tension in the respiratory mus-
cles, alterations in the pattern of tension development (velocity,
frequency, and duty cycle), and functional weakening of respi-
atory muscles, through a decrease in the operating length of
the muscles or an increase in the velocity of shortening, have a
potent influence on dyspnea (82).

Cardiorespiratory interactions. Perhaps a more likely aspect
of respiratory muscle work limiting exercise tolerance is
through a respiratory muscle fatigue-induced metaboreflex,
which increases sympathetic vasoconstrictor outflow and com-
promises perfusion of limb locomotor muscle, thereby limiting
its ability to perform work (Fig. 2). Evidence in animals
indicates that the diaphragm and other inspiratory and expira-
tory muscles, as in limb skeletal muscles, are richly innervated
with metaboreceptors (26). Diaphragm fatigue caused a time-
dependent increase in multunit activity in small-diameter
phrenic afferents in anesthetized cats (15, 49) and in single-unit
activity in group IV afferents in anesthetized rats (45). Fur-
thermore, when metaboreceptors in the diaphragm or expi-
atory muscles were stimulated electrically, pharmacologi-
cally, or with local lactic acid infusions, efferent sympa-
thetic nerve activity increased and vascular conductance
decreased in several vascular beds, including those in limb
muscle (48, 96, 102).

In humans, high-intensity voluntary contractions of the in-
spiratory or expiratory muscles against resistive loads to the
point of task failure or fatigue caused a time-dependent in-
crease in muscle sympathetic nerve activity in the resting leg,
despite a corresponding increase in systemic blood pressure
(22, 120). The gradual increase in muscle sympathetic nerve
activity was accompanied by a significant decrease in limb
vascular conductance and limb blood flow (108, 109). The
sympathetic and vascular responses that occur with high-
intensity dynamic contractions of the respiratory muscles are
similar to those that occur with fatiguing contractions of the
forearm musculature (108, 120).

During whole body exercise, the situation is more compli-
cated because any increase in muscle blood flow depends on
the opposing effects of strong local vasodilators and sympa-
thetic vasoconstrictor activity. What is still unclear is whether
the respiratory muscle metaboreflex is sufficiently powerful to
override the local vasodilator effects present in locomotor
muscles and redistribute blood flow to the respiratory muscle
vasculature. Data in fit human subjects performing maximal
cycle exercise indicate that reducing inspiratory muscle work
using a mechanical ventilator causes vascular conductance and
blood flow in the exercising limbs to increase (39). Conversely,
when the force output of the respiratory muscles was increased
by adding resistors to the inspirate, limb vascular conductance
and blood flow were reduced (39). It appears likely that the
local reductions in vascular conductance were sympathetically

Fig. 1. Effects of respiratory muscle unloading via mechanical ventilation on
endurance exercise capacity at a work rate requiring ~90% of maximal oxygen
uptake (V\textsubscript{\textcircled{}}\textsubscript{\textcircled{}}\textsubscript{\textcircled{}}\textsubscript{\textcircled{}}O\textsubscript{2}\textsubscript{\textcircled{}}\textsuperscript{\textsubcircled{}}}max\textsuperscript{\textcircled{}}} in trained male cyclists (n = 7). Group mean data are shown
for minutes 1–5 of exercise and at exhaustion. Absolute time to exhaustion
under control conditions averaged 9.1 ± 2.6 min (mean ± SD). Unloading the
normal work of breathing by 50% from control increased time to exhaustion in
76% of trials by 1.3 ± 0.4 min (14 ± 5%). Respiratory muscle unloading
caused reductions in oxygen uptake (V\textsubscript{\textcircled{}}\textsubscript{\textcircled{}}\textsubscript{\textcircled{}}\textsubscript{\textcircled{}}O\textsubscript{2}\textsubscript{\textcircled{}}} top\textsuperscript{\textcircled{}}} and the rate of rise in
perceptions of limb discomfort [leg ratings of perceived exertion (RPE);
middle\textsuperscript{\textcircled{}}} and respiratory discomfort (dyspnea; bottom) throughout the duration
of exercise. Data are from Harms et al. (41). *Significantly different from
control (P < 0.05).
mediated because these changes were inversely correlated with changes in norepinephrine spillover across the working limb (39). In canines exercising at moderate work intensities, a bolus infusion of lactic acid into either the phrenic artery or the deep circumflex iliac artery elicited a transient reduction in limb blood flow and vascular conductance (102). Again, these vascular responses appeared to be sympathetically mediated because they were prevented by pharmacological blockade of the adrenergic receptors (102).

Although the evidence appears to implicate a significant role of fatiguing respiratory muscle work in the sympathetically mediated vasoconstriction of exercising limb muscle vasculature, it is necessary to assert that additional respiratory influences on sympathetic vasoconstrictor outflow would likely be present during whole body exercise. These include an inhibitory effect of lung stretch (27, 107) and an excitatory effect of carotid chemoreceptor stimulation (115, 122). In addition, we assume that the reduction in limb blood flow with fatiguing respiratory muscle work is directed toward the respiratory muscles, but it is unclear whether the respiratory muscle vasculature also vasoconstricts in response to global sympathetic outflow. Likewise, we do not know how activation of the limb muscle metaboreflex affects blood flow to the inspiratory and expiratory muscles. In vitro studies of isolated arterioles have shown that α-adrenergic receptors in the diaphragm are less responsive to vasoconstrictor influences but equally sensitive to vasodilator influences compared with receptors in the limb vasculature (1, 2). Thus, at least theoretically, a global increase in sympathetic activity would result in greater vasoconstriction in the locomotor than respiratory muscle vasculature and in turn redirect blood flow to the respiratory muscles. Clearly, in vivo studies are needed to determine the relative responsiveness of the respiratory and locomotor muscle vasculatures to vasoconstrictor influences during whole body exercise.

Locomotor muscle fatigue. Reductions in limb blood flow and O₂ transport in response to fatiguing respiratory muscle work would be expected to impair limb locomotor muscle function. Indeed, when the inspiratory muscles were partially unloaded during heavy cycle exercise using a mechanical ventilator, the postexercise decrease in stimulated quadriceps force was attenuated by about one-third, and perceptual ratings of limb discomfort were reduced (103). Loading the respiratory muscles using inspiratory resistors exacerbated the severity of quadriceps fatigue by ~40% and increased the perceptions of limb discomfort compared with identical exercise with breathing unimpeled (Fig. 3). These findings, coupled with those from a previous study showing a significant relationship between changes in limb discomfort with inspiratory muscle unloading and improvements in exercise tolerance (41), suggest that locomotor muscle fatigue is exacerbated by the respiratory muscle work that accompanies sustained heavy exercise. We postulate that this extra fatigue plays a pivotal role in determining exercise tolerance both through its direct effect on muscle force output (i.e., peripheral fatigue) and through its feedback effect on effort perceptions, causing reduced motor output to the working limb muscles (i.e., central fatigue) (Fig. 4).

The effect of inspiratory muscle unloading on exercise-induced limb muscle fatigue likely underestimated what might be attributed to the total work of breathing (103). The normal work of breathing was reduced by only about one-half. In addition, unloading was confined to inspiration, which is important because recent evidence in humans indicates that the expiratory abdominal muscles are fatigable with heavy endurance exercise (127, 133) and that fatiguing expiratory muscle work elicits an increase in vasoconstrictive sympathetic nerve activity in resting limb muscle (22). Data in canines exercising at moderate intensity showed that activation of the respiratory muscle metaboreflex from the abdominal expiratory muscles by way of a bolus infusion of lactic acid into the deep circumflex iliac artery caused vasoconstriction in resting and exercising hindlimb muscle and reduced blood flow a small but significant amount despite increases in systemic blood pressure.
In health, it appears that the effects of respiratory muscle work on limb blood flow and fatigue occur during heavy sustained exercise only. Respiratory muscle work had to be increased to near fatiguing levels for muscle sympathetic nerve activity to be increased (22, 120), or for blood flow to be decreased in a resting (109) or an exercising limb (39, 59, 102, 139). Exercise in hypoxia would also be expected to exacerbate the effects of respiratory muscle work on limb fatigue and exercise tolerance. Recent evidence suggests that the increased work of breathing during acute moderate hypoxia (arterial O2 saturation 81%) accounts for at least one-third of the total limb locomotor muscle fatigue induced by exercise and a significant part of the hypoxia-induced reduction in exercise tolerance (8).

Clinically, respiratory muscle work may play a particularly important role in determining limb fatigue and hence exercise tolerance in patients with COPD or CHF. In patients with COPD, the limb muscles are more fatigable (70) and the O2 cost of breathing is higher (65) compared with healthy control subjects. In addition, a significant fraction of patients with severe COPD exhibit a plateau in leg blood flow and leg VO2 early during incremental exercise. Patients who exhibit a plateau in leg blood flow have higher levels of ventilation and dyspnea at submaximal exercise intensities compared with patients who do not exhibit a plateau (111), suggesting that blood flow may be redirected to the respiratory muscles in patients with the highest work of breathing. Patients with CHF also have an elevated ventilatory demand (53), as well as a blunted cardiac output and an exaggerated sympathetic response to exercise (112). Collectively, these factors could compromise limb blood flow and fatigue, even during submaximal exercise. A recent study using a canine model of heart failure showed that unloading the respiratory muscles using a mechanical ventilator increased stroke volume and limb blood flow even during moderate exercise (89). The effect was attributable to a reduced afterload on the left ventricle by way of less negative intrathoracic pressures and to relief of the inspiratory muscle metaboreflex through a reduced work of breathing (89).

In health, it appears that the effects of respiratory muscle work on limb blood flow and fatigue occur during heavy sustained exercise only. Respiratory muscle work had to be increased to near fatiguing levels for muscle sympathetic nerve activity to be increased (22, 120), or for blood flow to be decreased in a resting (109) or an exercising limb (39, 59, 102, 139). Exercise in hypoxia would also be expected to exacerbate the effects of respiratory muscle work on limb fatigue and exercise tolerance. Recent evidence suggests that the increased work of breathing during acute moderate hypoxia (arterial O2 saturation 81%) accounts for at least one-third of the total limb locomotor muscle fatigue induced by exercise and a significant part of the hypoxia-induced reduction in exercise tolerance (8). The effects of augmented respiratory muscle work in acute hypoxia on limb fatigue and exercise tolerance may be especially significant in chronic hypoxia during which the hyperventilatory response and work of breathing are greatly magnified (129).

Fig. 3. Summary of effects of increasing and decreasing inspiratory muscle work on quadriceps muscle fatigue (n = 8). Percent Δ twitch force (ΔQtw) represents the reduction in the average quadriceps force output determined across 4 stimulation frequencies (1–100 Hz) and compared between baseline (preexercise) and 2.5 min postexercise. Control vs. respiratory muscle unloading (via mechanical ventilation) effects on quadriceps muscle fatigue were compared at equal cycle ergometer work rates and durations (the durations being determined by the time to exhaustion under control conditions). Control vs. respiratory muscle resistive loading effects on quadriceps muscle fatigue were also compared at equal cycle work rates and durations (the duration being determined by the time to exhaustion under loaded conditions). Force output of the inspiratory muscles was measured as the time integral of the average esophageal pressure multiplied by breathing frequency and for the diaphragm was measured as the average transdiaphragmatic pressure time integral multiplied by breathing frequency. Differences in ΔQtw were significant (⁎ P < 0.01) between control and unload, and control and load. Data are from Romer et al. (103). [Reproduced with permission from Dempsey et al. (21a). Copyright Elsevier 2006.]

(102). Furthermore, expiratory flow limitation and prolonged expiratory time during heavy exercise often result in positive intrathoracic pressures that meet or exceed those at which dynamic compression of the airways occurs (54). Positive intrathoracic pressures will reduce ventricular transmural pressure, thereby decreasing the rate of ventricular filling during diastole, and reducing stroke volume and cardiac output (86, 121). Active expiration against positive resistance impedes femoral venous return, even in the face of an active “muscle pump” (87, 88). These extra expiratory effects may compromise systemic O2 delivery (7) and render the working limb musculature even more susceptible to fatigue.

**CONDITIONS UNDER WHICH RESPIRATORY MUSCLE WORK AFFECTS LIMB BLOOD FLOW AND FATIGUE**

In health, it appears that the effects of respiratory muscle work on limb blood flow and fatigue occur during heavy sustained exercise only. Respiratory muscle work had to be increased to near fatiguing levels for muscle sympathetic nerve activity to be increased (22, 120), or for blood flow to be decreased in a resting (109) or an exercising limb (39, 59, 102, 139). Exercise in hypoxia would also be expected to exacerbate the effects of respiratory muscle work on limb fatigue and exercise tolerance. Recent evidence suggests that the increased work of breathing during acute moderate hypoxia (arterial O2 saturation 81%) accounts for at least one-third of the total limb locomotor muscle fatigue induced by exercise and a significant part of the hypoxia-induced reduction in exercise tolerance (8). The effects of augmented respiratory muscle work in acute hypoxia on limb fatigue and exercise tolerance may be especially significant in chronic hypoxia during which the hyperventilatory response and work of breathing are greatly magnified (129).
OVERCOMING THE RESPIRATORY LIMITATIONS TO EXERCISE

Unloading the respiratory muscles during exercise may be a useful adjunct to the supervised rehabilitation of selected patients with increased work of breathing, dyspnea, or circulatory limitations. Heliox has been shown to be beneficial in relieving symptoms and improving exercise tolerance in patients with COPD (63, 100) or CHF (74). Mechanical ventilation during an acute bout of exercise has also been shown to reduce exertional symptoms and increase exercise tolerance in patients with COPD (62, 144) or CHF (95). When mechanical ventilation was used during routine exercise training, patients with advanced disease were able to exercise at higher intensities and for longer such that the training stimulus was increased to severely deconditioned locomotor muscles (32, 43, 130). When nonhypoxemic COPD patients breathed supplemental O\textsubscript{2} during exercise, dynamic hyperinflation and exertional dyspnea were reduced and exercise tolerance was improved (116).

It is neither feasible nor permissible for healthy athletes to use low-density gas mixtures, mechanical ventilators, or supplemental O\textsubscript{2} during competitive endurance events. Hence, alternative ways of overcoming the proposed respiratory limitations are needed. One approach could be to train the respiratory muscles (83). The basis for such training is that increasing the strength or endurance of the respiratory muscles would improve the fatigue resistance and mechanical efficiency of these muscles during whole body heavy exercise. Consequently, the fraction of total cardiac output required by the respiratory muscles during exercise would be less, and metabolites would not be accumulated as readily. Thus any potential reflex vasoconstrictive effects on the locomotor muscle vasculature would be prevented. Furthermore, if respiratory or locomotor muscle fatigue are prevented or delayed, this might blunt sensory input from the contracting muscles to the central nervous system (CNS), resulting in a reduced perception of respiratory and limb discomfort.

Studies that have specifically trained the respiratory muscles have reported either an improvement (16, 17, 28, 33, 78, 84, 119, 124, 131) or no change (25, 29, 38, 57, 92, 117, 140) in whole body exercise tolerance. A concern with all of these studies, however, is that endurance performance was evaluated using fixed work-rate tasks sustained to the limit of tolerance. Such tests do not accurately represent competitive endurance performance and are often unreliable (50). Another concern is that many of these studies have used small sample sizes. Unreliable performance tests, combined with small sample sizes, may explain in part why some studies have found improvements in exercise tolerance but failed to achieve statistical significance. In addition, most of the studies have not used a placebo group, rendering the findings difficult to interpret. More recent studies have used reliable and externally valid outcome measures (i.e., simulated time-trial performance) in conjunction with a placebo-controlled experimental design, and most (46, 55, 104, 137), but not all (117), findings from such studies indicate that respiratory muscle training has a small but likely significant effect on endurance exercise performance.

Despite a strong theoretical rationale for respiratory muscle training, few studies have specifically investigated the mechanisms by which such training exerts an ergogenic effect on exercise performance. The ergogenic effect could be due to relief of respiratory muscle fatigue (105, 131) or limb muscle fatigue (81), perhaps by attenuation of the respiratory muscle metaboreflex (142). However, the perceptual benefit obtained through relieving the discomfort associated with high levels of respiratory muscle work may also be responsible for at least some of the improvement in exercise performance (82). Clearly, further studies are needed to better understand the mechanisms by which respiratory muscle training improves exercise performance.

REFERENCES


87.


