Aerobic fitness effects on exercise-induced low-frequency diaphragm fatigue

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Babcock, Mark A., David F. Pegelow, Bruce D. Johnson, and Jerome A. Dempsey. Aerobic fitness effects on exercise-induced low-frequency diaphragm fatigue. J. Appl. Physiol. 81(5): 2156–2164, 1996.—We used bilateral phrenic nerve stimulation (BPNS; at 1, 10, and 20 Hz at functional residual capacity) to compare the amount of exercise-induced diaphragm fatigue between two groups of healthy subjects, a high-fit group (maximal O2 consumption (V\textsubscript{\text{O2max}}) = 69.0 ± 1.8 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}, n = 11) and a fit group (V\textsubscript{\text{O2max}} = 50.4 ± 1.7 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}, n = 13). Both groups exercised at 88–92% V\textsubscript{\text{O2max}} for about the same duration (15.2 ± 1.7 and 17.9 ± 2.6 min for high-fit and fit subjects, respectively, P > 0.05). The supramaximal BPNS test showed a significant reduction (P < 0.01) in the BPNS transdiaphragmatic pressure (Pdi) immediately after exercise of −23.1 ± 3.1% for the high-fit group and −23.1 ± 3.8% (P > 0.05) for the fit group. Recovery of the BPNS Pdi took 60 min in both groups. The high-fit group exercised at a higher absolute workload, which resulted in a higher CO2 production (+26%), a greater ventilatory demand (+16%) throughout the exercise, and an increased diaphragm force output (+28%) over the initial 60% of the exercise period. Thereafter, diaphragm force output declined, despite a rising minute ventilation, and it was not different between most of the high-fit and fit subjects. In summary, the high-fit subjects showed diaphragm fatigue as a result of heavy endurance exercise but were also partially protected from excessive fatigue, despite their ventilatory requirements, because their hyperventilatory response to endurance exercise was reduced, their diaphragm was utilized less in providing the total ventilatory response, and possibly their diaphragm aerobic capacity was greater.

METHODS

Subjects. Twenty-four subjects (20 men and 4 women) gave informed consent to participate in the study. All procedures were approved by the Institutional Review Board of the University of Wisconsin-Madison. These subjects had participated in one of three previous studies on the effects of exercise-induced diaphragm fatigue in our laboratory (2, 3, 18). These data were combined in the present study to provide a larger sample size for analysis of fitness effects on exercise-induced diaphragm fatigue.

BPNS. The BPNS procedure has been described previously (5, 18); therefore, only a brief description follows. Two balloon-tipped catheters were passed intranasally: one was positioned in the stomach to measure gastric pressure (P\text{ga}), and one was positioned in the lower one-third of the esophagus to measure esophageal pressure (Pes). The algebraic sum of P\text{ga} and Pes gave transdiaphragmatic pressure (Pdi). Surface electromyogram electrodes were placed over each hemidiaphragm in the sixth or seventh intercostal space near the costal margin to record the compound muscle action potential (M wave) resulting from phrenic nerve stimulation. After location and marking of the surface stimulation site on the neck, ~2 cm above the clavicle, the maximal M wave was determined by increasing the stimulation current until no change in M wave amplitude was found. To ensure supramaximal stimulation, the current of both stimulators was increased a further 50% above this level. This procedure was carried out before each BPNS data collection during preexercise control and 6–12, 30, and 60 min after exercise. Lung volumes were continuously monitored throughout the stimulation tests by connecting the subject to a wedge spirometer via a mouthpiece that was occluded before stimulation and providing the subject with visual feedback by means of an oscilloscope display of the lung volume.

During each BPNS session, 9–12 repeats of “twitch” stimulation at functional residual capacity (FRC) and 3–5 repeats of...
strikings at 10 and 20 Hz at FRC with the mouthpiece occluded were completed, and the resultant Pes, Pga, Pdi, and M waves were collected on computer and magnetic tape for later analysis. The 10- and 20-Hz stimulations were delivered using a constant 400-ms train, so that four stimuli were given at 10 Hz and eight stimuli were given at 20 Hz. A particular stimulation was repeated if 1) the M wave amplitude changed by greater than ±15% of the maximal value, 2) the stimulated BPNS Pdi was ±10% from the maximal stimulated value, or 3) the measured lung volume varied by greater than ±10%.

The stimulated BPNS Pdi values were analyzed for peak pressure, contraction time, and half-relaxation time (RT ½). The peak pressure was defined as the maximum increase in tension from the Pdi baseline at the onset of the stimulation. Contraction time represented the time interval from the initiation of the stimulation until Pdi reached its peak value. RT ½ was the time required for the Pdi to decline from peak pressure to one-half of the peak pressure. A fatigue index was calculated using the mean percent change in the BPNS Pdi at each stimulation frequency (twitch, 10 Hz, and 20 Hz) and then computing the arithmetic mean of these three values.

We have calculated two types of within-subject coefficient of variation (CV): 1) CV for Pdi amplitude within a single trial of 7–10 repeated stimulations (average CV = 5.4 ± 0.6%) and 2) CV for Pdi amplitude and M wave amplitude between two mean values before and after subjects changed position (CV for M wave = 15% and CV for Pdi = 10%). The latter values were intended to test reproducibility of the BPNS technique under conditions that required repositioning of the stimulating electrode and reestablishment of lung volume, as would occur before vs. after exercise.

Potential complications of the BPNS technique include twitch potentiation, changes in diaphragm length, changes in chest wall-lung configuration and compliance after exercise, and maintenance of supramaximal phrenic nerve stimulation. We have dealt with these problems previously (2, 3, 18; see RESULTS).

Pulmonary function tests. Vital capacity and inspiratory capacity were determined using a Collins 13.5-liter water-sealed spirometer. Thoracic gas volume and FRC were determined using the Collins Bodyplethysmograph. Maximal voluntary ventilation (MVV) was measured using a 12-s test, and the fit group MVV thanthefitgroup.

The level of inspiratory Pes (Pdi) and the mean time integral of the inspiratory Pes (J(Pdi)) were calculated over the 20- to 30-breath sample by the computer. Each of the time integrals was multiplied by the breathing frequency (f) to provide results of force output of the diaphragm (J(Pdi)-f) and all the inspiratory muscles (J(Pes)-f).

Statistical analyses were performed using the statistical program Systat. Values are means ± SE. One-way analysis of variance with repeated measures was used to determine differences in mean values over the duration of the exercise and recovery periods. Student's paired t-test was used to detect differences between mean values of the high-fit and fit groups. The level of significance was set at P < 0.05.

RESULTS

The subjects were divided into two groups on the basis of a VO2max of 60 ml·kg⁻¹·min⁻¹ (Table 1). The high-fit group VO2max (n = 11) ranged from 61.1 to 78.6 ml·kg⁻¹·min⁻¹, and the fit group VO2max (n = 13) ranged from 39.5 to 58.6 ml·kg⁻¹·min⁻¹. The results of the routine pulmonary function tests are also reported in Table 1. There was no difference between the high-fit and fit groups, except the high-fit group had a higher MVV than the fit group.

Response to BPNS. At 6–12 min after whole body endurance exercise, high-fit and fit groups showed a significant fall (P < 0.05) in the BPNS Pdi at all stimulation frequencies (Fig. 1). The mean BPNS Pdi remained below control values at 30 min into recovery.
except in the fit group at 20 Hz. After 60 min of recovery the BPNS Pdi values at all frequencies of stimulation were still reduced but were not different from control values for both groups. Immediately after exercise the mean percent change in the BPNS Pdi averaged for the three stimulation frequencies (i.e., diaphragm fatigue index) was $-23.7 \pm 3.1\%$ in the high-fit group and $-23.1 \pm 3.8\%$ in the fit group ($P > 0.05$). All but 3 of 24 subjects showed a $>15\%$ decrease in the diaphragm fatigue index after endurance exercise at an intensity $>90\%\text{VO}_{2\text{max}}$.

The percent change in the BPNS Pdi at 6–12 min after exercise at each of the three stimulation frequencies is shown for all subjects in Fig. 2 as a function of their $\text{VO}_{2\text{max}}$. The magnitude of the reduction in BPNS Pdi after exercise varied between subjects and with different stimulation frequencies. However, at any given BPNS stimulation frequency, the exercise-induced decrease in BPNS Pdi was not systematically different among subjects with different $\text{VO}_{2\text{max}}$.

The group mean values for the supramaximal BPNS Pdi and the relative contributions of Pga and Pes to Pdi at each stimulation frequency are shown in Table 2. No changes were found after exercise in the amplitude of the left or the right M wave; nor were there changes in the lung volume at which the stimulations were done (data not shown). The fall in the BPNS Pdi after the endurance exercise was due to a greater decrease in the absolute Pes component, but the relative contribution of Pes to Pdi remained constant at all three stimulation frequencies, as did the Pga-to-Pdi ratio (Table 2). The ratios reported here were similar to reports in the literature obtained in control conditions and after inspiratory resistive loading to the point of task failure (31). Changes in the time to peak tension and RT, of the “twitch” after exercise were small and not significant.

Ventilatory response to exercise. The mean values for ventilation and metabolic rate during exercise in high-fit and fit groups are shown in Table 3 (over the final 3 min of exercise) and in Fig. 3 throughout exercise. Both groups exercised at a similar average intensity of 92% of $\text{VO}_{2\text{max}}$ (88.8% at start of exercise and 97.8% at end of exercise). There was also no difference in exercise duration between the two groups: the high-fit group exercised for 15.2 ± 1.7 min and the fit group for 17.9 ± 2.6 min ($P > 0.40$). Even though the high-fit and fit groups exercised at the same relative intensity (percentage of $\text{VO}_{2\text{max}}$), the absolute O₂ consumption and CO₂ production ($\text{VCO}_{2}$) were 25.6 and 26.7% higher, respectively, in the high-fit group ($P < 0.05$). The higher metabolic cost of the exercise for the high-fit group required a 16% higher minute ventilation ($\text{Ve}$; $P < 0.05$). Both groups showed an increase in $\text{Ve}$-to-$\text{VCO}_{2}$ ratio with time during exercise, although the mean $\text{Ve}$-to-$\text{VCO}_{2}$ ratio (Fig. 3B) averaged 20% lower in the high-fit group throughout exercise ($P < 0.05$). At the end of exercise the rating of perceived exertion, on a 10-point Borg scale, was 9.8 ± 0.1 for the high-fit group and 9.9 ± 0.1 for the fit group.

### Table 1. Descriptive statistics for high-fit and fit groups

<table>
<thead>
<tr>
<th></th>
<th>High Fit</th>
<th>Fit</th>
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<tr>
<td>n</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Age, yr</td>
<td>30.0 ± 3.0</td>
<td>34.0 ± 3.0</td>
</tr>
<tr>
<td>Height, cm</td>
<td>175.3 ± 2.5</td>
<td>175.3 ± 2.5</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>66.9 ± 1.3</td>
<td>69.4 ± 3.3</td>
</tr>
<tr>
<td>$\text{VO}_{2\text{max}}, \text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$</td>
<td>69.0 ± 1.8</td>
<td>50.4 ± 1.7*</td>
</tr>
<tr>
<td>$\text{Ve}$, l/min</td>
<td>144.8 ± 3.8</td>
<td>121.6 ± 7.9</td>
</tr>
<tr>
<td>FRC, liters</td>
<td>3.43 ± 0.2</td>
<td>3.30 ± 0.2</td>
</tr>
<tr>
<td>IC, liters</td>
<td>3.61 ± 0.2</td>
<td>3.21 ± 0.2</td>
</tr>
<tr>
<td>TLC, liters</td>
<td>7.04 ± 0.2</td>
<td>6.51 ± 0.3</td>
</tr>
<tr>
<td>MEF50, l/s</td>
<td>5.8 ± 0.8</td>
<td>4.8 ± 0.8</td>
</tr>
<tr>
<td>FEV1.0, %FVC</td>
<td>86.8 ± 2.0</td>
<td>82.7 ± 1.1</td>
</tr>
<tr>
<td>MVV, l/min</td>
<td>156.2 ± 8.8</td>
<td>130.1 ± 8.1*</td>
</tr>
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Values are means ± SE; n, no. of subjects. $\text{VO}_{2\text{max}}$, maximal O₂ consumption; $\text{Ve}$, minute ventilation; FRC, functional residual capacity; IC, inspiratory capacity; TLC, total lung capacity; MEF50, maximum expiratory flow at 50% of TLC; FEV1.0, forced expiratory volume in 1 s; MVV, maximum voluntary ventilation. *Significantly different from high-fit group ($P < 0.05$).
Inspiratory muscle force output during exercise. Exercise effects on the time integrals for Pes and for Pdi are shown for the fit and high-fit groups throughout exercise in Fig. 3, and mean values for the last 3 min of exercise are summarized in Table 3. The mean $\int_{t=0}^{t} P_{\text{di}} \cdot f$ in both groups throughout exercise, but it was substantially greater in the high-fit group throughout the exercise time. $\int_{t=0}^{t} P_{\text{di}} \cdot f$ was greater in the high-fit group than in the fit group up to 60% of the total exercise time. Thereafter $\int_{t=0}^{t} P_{\text{di}} \cdot f$ declined with time in the high-fit group but remained constant in the fit group, so that mean values over the final 40% of the exercise duration were not different between groups.

Figure 4 shows $\int_{t=0}^{t} P_{\text{di}} \cdot f$ during tidal breathing vs. $V_{\text{O}2_{\text{max}}}$, for each subject at the beginning, in the middle, and at the end of exercise. We found significant correlations of force output with $V_{\text{O}2_{\text{max}}}$ over the time course of the exercise. These plots, across the continuum of $V_{\text{O}2_{\text{max}}}$, emphasize the substantial overlap in $\int_{t=0}^{t} P_{\text{di}} \cdot f$ among subjects throughout the duration of exercise. Also five of the high-fit subjects experienced exceptionally high $\int P_{\text{di}} \cdot f$ over the latter 40% of the exercise. These same five subjects did not show any greater diaphragm fatigue than the other high-fit or fit subjects (Fig. 2).

Flow- and pressure-volume relationship. Figure 5 shows the mean flow-volume and Pes-volume relationships during exercise for the high-fit and fit groups. The high-fit group was progressively more flow limited during expiration throughout the exercise [8.0% of tidal volume ($V_{T}$) flow limited at 3 min vs. 50.8% at the end of exercise]. These subjects also reached or slightly exceeded their maximal effective inspiratory pressure generation over 50% of their expired $V_{T}$ during the last

Table 2. BPNS Pdi and Pga-to-Pdi and Pes-to-Pdi ratios for three stimulation frequencies before exercise and during recovery period for both groups combined

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Twitch</th>
<th>10 Hz</th>
<th>20 Hz</th>
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<tbody>
<tr>
<td>Pdi/cmH2O</td>
<td>24.5 ± 1.5</td>
<td>19.3 ± 1.8</td>
<td>20.1 ± 1.4</td>
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<tr>
<td>Pga/Pdi, %</td>
<td>38.7 ± 2.2</td>
<td>40.5 ± 2.3</td>
<td>36.1 ± 2.1</td>
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<tr>
<td>Pes/Pdi, %</td>
<td>62.1 ± 2.2</td>
<td>59.6 ± 2.1</td>
<td>65.2 ± 2.2</td>
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Table 3. Comparison of selected parameters between high-fit and fit groups over last 3 min of exercise

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Fit (n = 11)</th>
<th>Fit (n = 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exercise intensity, % $V_{\text{O}2_{\text{max}}}$</td>
<td>92.3 ± 3.8</td>
<td>92.4 ± 2.0</td>
</tr>
<tr>
<td>Exercise time, min</td>
<td>152.2 ± 1.7</td>
<td>179.2 ± 2.6</td>
</tr>
<tr>
<td>$V_{\text{O}2}$/l/min</td>
<td>4.40 ± 0.2</td>
<td>3.26 ± 0.2*</td>
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<tr>
<td>$V_{\text{E}}$/l/min</td>
<td>145.5 ± 6.7</td>
<td>121.7 ± 7.9†</td>
</tr>
<tr>
<td>$P_{\text{di}} \cdot f$, cmH2O s·min$^{-1}$</td>
<td>571.2 ± 78.3</td>
<td>418.3 ± 35.0†</td>
</tr>
<tr>
<td>$P_{\text{es}} \cdot f$, cmH2O s·min$^{-1}$</td>
<td>824.7 ± 77.8</td>
<td>562 + 43.8*</td>
</tr>
<tr>
<td>$P_{\text{di}}$/Pes</td>
<td>0.74 ± 0.08</td>
<td>0.79 ± 0.09</td>
</tr>
<tr>
<td>$V_{\text{I}}$/lCO2</td>
<td>31.9 ± 1.0</td>
<td>40.3 ± 3.3</td>
</tr>
<tr>
<td>EELV, %TLC</td>
<td>47.6 ± 2.1</td>
<td>51.4 ± 2.1</td>
</tr>
<tr>
<td>EILV, %TLC</td>
<td>87.7 ± 2.7</td>
<td>87.7 ± 2.7</td>
</tr>
<tr>
<td>PI/Pcap, %</td>
<td>90.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Pcap, cmH2O</td>
<td>-91.6</td>
<td>-53.3</td>
</tr>
<tr>
<td>Flow limitation, %</td>
<td>50.8</td>
<td>0.0*</td>
</tr>
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</table>

Values are means ± SE; $n$, no. of subjects; $V_{\text{O}2}$, absolute $O_{2}$ consumption; $V_{\text{O}2_{\text{max}}}$, maximal $O_{2}$ consumption; $V_{\text{E}}$, minute ventilation; $P_{\text{di}}$, diaphragm force output; $P_{\text{es}}$, force output of all inspiratory muscles; $V_{\text{CO}2}$, CO2 production; EELV and EILV, end-expiratory and end-inspiratory lung volume; PI, inspiratory pressure; Pcap, dynamic capacity of inspiratory muscles to generate Pes; $V_{T}$, tidal volume. *Significantly different from high-fit group (P < 0.05). †P < 0.07. ‡P < 0.06.
3 min of exercise. In the fit group V\textsubscript{T} was not flow limited during expiration throughout exercise.

The high-fit group reached 31% (at the beginning of exercises), 49% (in the middle of exercise), and 90% (in the last 3 min of exercise) of their dynamic P\textsubscript{cap I} during tidal inspiration at peak Pes and at high lung volumes. In the fit group, peak inspiratory Pes reached during exercise were 37% (beginning), 38% (middle), and 40% (end) of P\textsubscript{cap I}.

**DISCUSSION**

Our data showed that the high-fit group was not protected by an increased aerobic capacity from exhibit-
ing exercise-induced low-frequency diaphragm fatigue after intense whole body endurance exercise. This is in contrast to other reports that showed no changes in maximal volitional tests of inspiratory muscle force output (6, 11) in highly trained athletes compared with untrained subjects after severe exercise to exhaustion. On the basis of this evidence, we had hypothesized that the high-fit group would not have exhibited a substantial amount of low-frequency diaphragm fatigue after intense whole body endurance exercise. We reject this hypothesis now, because the high-fit and fit groups experienced similar amounts of exercise-induced low-frequency diaphragm fatigue at all stimulation frequencies immediately after whole body endurance exercise.

Why were the high-fit subjects able to exercise at a higher absolute workload and a resultant greater ventilatory requirement and not incur a greater level of low-frequency diaphragm fatigue? We know that the \( \int P_{di} \cdot f \) increased four to five times above rest values in the first few minutes after exercise onset (2, 3, 18); as exercise continued the \( \int P_{di} \cdot f \) declined slightly, despite further time-dependent increases in \( V_{E} \) and \( \int P_{es} \cdot f \). The group mean data for \( \int P_{di} \cdot f \) during exercise showed that the high-fit group produced more force (+28%) during the first 60% of the exercise time, but over the last 40–50% of the exercise diaphragm force production was not different from the fit group (Figs. 3 and 4). Thus the higher ventilatory demand in most high-fit subjects was (with some notable exceptions, see below) dependent on increased recruitment of accessory inspiratory muscles as exercise time progressed. Because force development by the diaphragm is an important determinant of exercise-induced diaphragm fatigue (3), this apparent sparing of \( \int P_{di} \cdot f \) in many highly fit subjects would be expected to alleviate some of the fatigue, despite a higher ventilatory requirement.

We also emphasize that the ventilatory output in the high-fit subjects was not increased in proportion to their higher absolute work rate and \( V_{CO_2} \). That is, the \( V_{E} \)-to-\( V_{CO_2} \) ratio remained lower throughout exercise in the high-fit group. This reduced ventilatory requirement means that the requirement for force output by all the inspiratory muscles would also not be increased in proportion to their higher exercise \( V_{CO_2} \) in the highly trained subject. Our study does not address the cause of this reduced \( V_{E} \)-to-\( V_{CO_2} \) ratio in the high-fit athletes,
although a similar finding has been reported with short-term heavy exercise and attributed to reduced levels of metabolic acidosis (21).

What does this leveling off of the $\int P_{di} \cdot f$ mean? It may be indicative of a changing recruitment pattern of the inspiratory muscles during intense endurance exercise in response to the onset of diaphragm fatigue. Sieck and Fournier (28) found that the recruitment pattern of the diaphragm muscle fibers followed the size principle, inasmuch as the most fatigue-resistant type I fibers were recruited at low ventilatory loads and moderately fatigue-resistant type IIa fibers were recruited at moderate loads. The least fatigue-resistant type IIb fibers were only recruited for nonventilatory behaviors such as sneezing or gagging. Thus the very high ventilatory requirements during exercise requiring greater and greater force development from the diaphragm might make this muscle more susceptible to fatigue and compromise its role as the major inspiratory muscle (see below). It is appropriate, then, that diaphragm force production is inhibited perhaps by feedback inhibition (17) and accessory inspiratory and expiratory muscles are recruited during prolonged exercise. Similar patterns of selective recruitment of accessory muscles and derecruitment of the diaphragm have been observed in animals undergoing severe resistive loading (4). Furthermore, during prolonged exercise, the diaphragm (along with the accessory inspiratory muscles) may act as a significant force generator to displace the lungs and chest wall, but the diaphragm, with its longer fibers, mixed fiber types, convex shape, and high aerobic capacity, is ideally suited to serve as a major generator of high velocities of shortening and flow rates. Hence, during the latter stages of the endurance exercise, the diaphragm may actually further increase its velocity of shortening and make greater contributions to increasing flow rate at a time when its relative contribution to force development is decreasing.

Does the diaphragm force production level off in prolonged exercise because the diaphragm cannot produce more force or because it will not produce the force it is capable of producing? Theoretically, at the higher flow rates achieved during exercise, the velocity of shortening of the diaphragm would also be quite high and thus would compromise the muscle’s capability for force production (1). However, we think this is unlikely, because we have shown (3) that resting subjects were able to volitionally increase and maintain diaphragm force production 78% above the levels needed during endurance exercise and to sustain this force for the same time period as the exercise. Therefore, the diaphragm was capable of producing and sustaining a force production and velocity of shortening at rates that were well above those experienced during exercise without experiencing task failure. Whether the diaphragm force production could be increased and sustained this much during whole body exercise when other fatiguing influences are present (3) remains to be determined.

We emphasize that our supramaximal BPNS test does not evaluate all the important characteristics of diaphragm fatigue. Fatigue has been defined as a reduction in the force-generating capacity of the muscle resulting from activity under load that is reversible by rest (22a). By this definition, most high-fit and fit subjects have clearly shown low-frequency exercise-induced diaphragm fatigue. However, the BPNS technique does not provide information on the velocity of shortening, inasmuch as all stimulations are done at fixed lung volumes and are assumed to be “quasi-isometric” contractions. Therefore, any changes in the velocity of shortening of the diaphragm resulting from the whole body endurance exercise remains to be determined, as do any changes in this important characteristic of “fatigue” between subjects of different aerobic capacity.

Response of the diaphragm to whole body exercise training. A second explanation as to why the high-fit group could exercise at a higher absolute workload and exhibit the same level of low-frequency diaphragm fatigue as the fit group may be an enhanced diaphragmatic aerobic capacity in the high-fit group. This explanation might apply especially to those five high-fit subjects who clearly generated greater force output of the diaphragm over most of the duration of the endurance exercise and yet experienced the same amount of diaphragm fatigue (Fig. 2). We would predict that the high-fit subjects also had a greater $P_{di}$ relative to their absolute available capacity to generate $P_{di}$ throughout heavy exercise, because the capacity for force development (at any given lung volume or velocity of shortening) was similar in the high-fit and fit subjects, and during tidal breathing in exercise the lung volumes were similar and the inspiratory flow rates were higher in the high-fit group.

Evidence has accumulated in animal models that supports the idea that the aerobic capacity of the diaphragm does increase with intense and prolonged physical training. Three types of changes in response to whole body physical training have been documented to occur in the diaphragm: 1) increased oxidative enzyme activity (14, 16, 24), 2) decreased diffusion distance from capillaries to muscle due to decreased cross-sectional area of type I and type IIa muscle fibers (14, 24, 25, 30), and 3) increased capillary density (15). Whether the human diaphragm responds in the same way to whole body physical training or to increased aerobic capacity has not been documented. The human studies have shown improvements in volitional ventilatory muscle endurance performance after whole body physical training, as shown by increased maximal sustainable ventilation (10, 27) and greater MVV in trained than in untrained subjects (8–10, 13). On the other hand, in the present study and in others, no changes were found between normal-fit and high-fit subjects in maximal inspiratory pressure generation at a fixed lung volume (10, 23) or in the pressure-generating capacity of the inspiratory muscles at any given flow rate (19).
We are uncertain whether increased aerobic capacity of the diaphragm alone can explain our findings of similar diaphragm fatigue, despite elevated $\int P_{di} \cdot f$ in many of the high-fit subjects, because we know that more than just $\int P_{di} \cdot f$ per se causes exercise-induced diaphragm fatigue (3). Other factors such as blood flow distribution to diaphragm vs. locomotor muscle during endurance exercise and circulating metabolites produced by the locomotor muscles also contribute, and these factors might also very well be different in the highly fit subject.

Pulmonary system limitations in the high-fit group: demand vs. capacity. Key determinants of the pulmonary system’s capacity for maximum gas transport during exercise include alveolar-capillary diffusion surface, the flow-volume maximum envelope, and aerobic capacity of the respiratory muscles. All these functions are placed under considerable stress during heavy exercise in the high-fit subjects but appear to have quite different susceptibilities to reaching limitation because of their different capacities and degree of malleability in response to physical training. In the case of diffusion limitation, many very highly fit humans (1.5–2 times normal $V_{\text{O}2\text{max}}$) show significant exercise-induced hypoxemia, presumably because their extraordinary demand for $O_2$ transport is not matched by enhanced diffusion surface area in the lung (12). This hypoxemia presents a significant limitation to systemic $O_2$ transport and to $V_{\text{O}2\text{max}}$ (26). Similarly, the maximum flow-volume envelope is also unaltered in most highly fit subjects (19). Accordingly, with their high metabolic and ventilatory requirements, the highly fit individuals experience significant expiratory flow limitation and increased ventilatory work, even in moderately heavy exercise (Fig. 5), and many subjects will show complete mechanical flow limitation to ventilation at maximum exercise (19). Incurring these high mechanical loads during exercise may contribute to exercise limitation in the high-fit subjects, perhaps via high metabolic and blood flow requirements by the respiratory muscles or by mechanical constraint on alveolar ventilation. However, the actual contribution of these factors to exercise and ventilatory limitation remains controversial and unresolved.

Exercise-induced diaphragm fatigue as a third potential pulmonary system limitation presents quite differently in these comparisons of demand to capacity than do the diffusion or flow-volume limitations. First, healthy young adult subjects of all fitness levels and $V_{\text{O}2\text{max}}$ tested to date experienced significant exercise-induced diaphragm fatigue (as shown by a reduced force production in response to BPNS), so long as exercise was of sufficient intensity and duration (Fig. 2). In other words, there was no specific threshold of $V_{\text{O}2\text{max}}$, ventilatory requirement, or $\int P_{di} \cdot f$ during the heavy endurance exercise below which diaphragm fatigue did not occur in healthy subjects (Fig. 1). In a sense then, the demand for sustained force output by the diaphragm during exercise exceeded the muscle’s aerobic capacity in all healthy subjects. However, this reduction in force output of a single, albeit primary, inspiratory muscle clearly did not cause global respiratory muscle task failure or inadequate alveolar ventilation (2, 3, 18).

In a recent study in which the inspiratory muscles were partially, mechanically unloaded, no differences were found in $V_{\text{E}}$ or exercise performance time between normal and unloaded endurance exercise (22). Assuming that this partial unloading may have alleviated diaphragm fatigue, the authors interpreted these data to show that inspiratory muscle fatigue had no effect on the ventilatory response or breathing pattern during heavy endurance exercise. We agree and would speculate that the significant consequence of the exercise-induced diaphragm fatigue might be in providing a reordering of the pattern of respiratory muscle recruitment.

Finally, the fact that the diaphragm and inspiratory muscles do show significant increases in aerobic capacity in response to physical training also distinguishes the chest wall from the lung in terms of malleability. These chronic adaptations mean that the ratio of demand to capacity in the diaphragm (during exercise) remains about the same in trained and untrained subjects. Training effects on the respiratory muscles may also be important in preventing a more marked exercise-induced respiratory muscle fatigue and perhaps even task failure, especially given the very high ventilatory requirements faced in the highly trained during high-intensity endurance exercise.

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