Noninvasive measurement of respiratory muscle performance after exhaustive endurance exercise

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ABSTRACT: The use of noninvasive techniques to measure respiratory muscle performance after different types of endurance exercise has not been entirely successful, as the results have not consistently indicated diminished performance for similar types of exercise. The aim of the present study was 1) to compare different, noninvasive methods to assess respiratory muscle performance before and after an exhaustive cycling endurance test (which has previously been shown to induce diaphragmatic fatigue) and 2) to determine which of the tests best reflect published results of measurements of diaphragmatic fatigue.

Twelve healthy subjects participated in the study and performed three different test series in a random order on three different days. These tests were performed before, and 5, 40 and 75 min after an exhausting task (a cycling endurance run at 85% of maximal oxygen uptake ($V'\text{O}_2\text{max}$)). The tests of the three test series were 1) breathing against a constant inspiratory resistance to task failure, 2) determination of 12-min sustained ventilatory capacity, and 3) spirometric and maximal inspiratory and expiratory mouth pressure measurements.

The only measurement that was affected by exhaustive cycling was the time to task failure breathing against inspiratory resistance. It was significantly reduced from (mean±sd) 364±88 s before exercise to 219±122 s at 5 min after cessation of exercise.

It is concluded that the constant-load resistive breathing test to task failure is the only noninvasive respiratory muscle performance test evaluated in this study which shows a decrease in respiratory muscle performance after exhaustive endurance exercise.

of endurance exercises of different types and duration. This might explain the contradictions in the results of the different studies. Alternately, these noninvasive measurements (force, endurance or maximal flow tasks) may not all be equally well suited to detecting reduced respiratory muscle performance occurring after intensive exercise. Therefore, the aim of the present study was to compare different, noninvasive tests of respiratory muscle performance (constant-load resistive breathing to task failure, SVC, MVV, vital capacity (VC), FVC, FEV1, peak expiratory flow (PEF), Pmax and Pe(max)) to assess respiratory muscle performance before and after cycling to exhaustion at a constant load corresponding to 85% V'02,max, an intensity previously shown to induce diaphragmatic fatigue by measurement of Pdi,sw [3, 4].

Material and methods

Study subjects

Twelve healthy, nonsmoking subjects (4 females, 8 males) participated in the study. Their average age was (mean±SD) 28±7 yrs, height 177±10 cm and weight 70±10 kg. The study was performed in accordance with the ethical standards of the Helsinki Declaration for experimentation on human subjects. Subjects were familiarized with the experimental procedures and informed consent was obtained.

Study design

Subjects carried out respiratory performance tests before, and 5, 40 and 75 min after a cycling endurance test at 85% V'02,max continued until exhaustion. The tests consisted of 1) breathing against a constant inspiratory resistance to task failure, 2) determination of the 12-min sustained ventilatory capacity or 3) spirometric measurements and determination of maximal inspiratory and expiratory mouth pressures. The test groups (1, 2, or 3) were performed on three different days in a random order.

Preliminary tests

On three different days, the following preliminary tests were performed.

Incremental breathing test. Subjects began by breathing against an inspiratory resistive load at a pressure corresponding to 60% Pmax (determined at residual volume). Expiration was unloaded and breathing frequency (fR) was set at 18 breaths-min⁻¹ and paced by a metronome. Every 3 min the resistive load was increased by 5% Pmax. The test continued until the subjects were no longer able to overcome the load. The inspiratory pressure (Pi) of the last step which the subjects were able to sustain for 3 min, was selected as the target pressure for the constant-load resistive breathing test (see below).

Two consecutive constant-load resistive breathing tests. On a different day, subjects performed two consecutive constant-load resistive breathing tests at a constant load corresponding to (mean±SD) 79±9% Pmax. The two tests were separated by a 15 min rest period. During each test, the subjects matched their inspiratory pressure to a pressure waveform (previously determined to be comfortable) displayed to them on an oscilloscope at an fR of 18 breaths-min⁻¹. The time to task failure (task failure) was defined as the time when the subjects were no longer able to achieve the target pressure. During this test, subjects were asked to rate their respiratory exertion on a modified Borg scale every minute.

Incremental cycling test. An incremental cycling test was performed to exhaustion in order to determine V'02,max. The work load on the cycle ergometer was set at 100 W and was increased by 30 W every 2 min. Pedalling frequency was maintained at a constant level throughout the test. Subjects chose their preferred frequency at the beginning of the test.

Main experiments

The following tests were performed at least once before the actual testing, and the main experiments consisted of the three test series, each one performed on different days separated by at least 48 h. Each test series began (t0) with one of the three respiratory muscle performance tests (see below). Fifteen minutes after the end of the respiratory muscle performance test, subjects started cycling at 85% V'02,max and continued until exhaustion. At 5 min (t5), 40 min (t40) and 75 min (t75) after the subjects stopped cycling, the respiratory muscle performance tests were repeated. These respiratory tests before and after cycling consisted of 1) measuring the time that the subjects could breathe against a constant inspiratory resistance (inspiratory resistance was individually determined, see above; average mean±SD) 79±9% Pmax, corresponding to -133±25 cmH2O) (Task failure-series), 2) determining the 12-min SVC (SVC-series) or 3) measurement of spirometric variables (VC, FVC, FEV1, PEF, MVV in 15 seconds (MVV15), Pmax and Pe(max) (Spiro-series). These three test series were performed in a randomized order. During the Task failure-series, subjects were asked to rate their perceived respiratory exertion every minute on a modified Borg scale. Before and after every respiratory muscle performance test-series, a 20 μL blood sample was taken from an earlobe to analyse for blood lactate concentration. Cycling endurance tests were started at 100 W, and the workload was increased in three equal increments of 2 min duration to reach 85% V'02,max within 6 min. The exact levels achieved were 78±3% of Wmax (245±50 W) corresponding to 86.9±4.6% V'02,max for the Task failure-series, 84.0±5.2% V'02,max for the SVC-series and 85.2±5.6% V'02,max for the Spiro-series.

Equipment

Spirometric variables (VC, FVC, FEV1, PEF, MVV15), SVC as well as ventilatory and gas exchange variables during cycling were determined with an ergo-spirometric device, (Oxycon Beta; Mijnhardt; Bunnik, Netherlands) using a turbine flow meter for volume measurements, a paramagnetic analyser for O2, and an infrared absorption
analysed for CO₂-measurements. For SVC-measurements, subjects were instructed to breathe maximally for a period of 12 min. The average minute ventilation for the entire 12 min was then calculated. To maintain isocapnia during the 12-min SVC-measurement, a partial rebreathing device was used. It consisted of a latex bag connected to a tube with inlet and outlet valves. The size of the bag was adjusted to be 50–60% of the subjects’ VC. Subjects were instructed to fill and empty the bag completely while sufficient inspiratory and expiratory flow through the valves was permitted to ensure isocapnia and full oxygen saturation. Minute ventilation was mainly varied by changing flow. In a preliminary session, subjects were trained to use this device. During the tests, the settings kept end tidal CO₂ in the normal range (SVC at t: 5.4±0.8 kPa (40.9±6.0 mmHg); SVC at t5: 5.1±0.7 kPa (38.0±4.9 mmHg); SVC at t40: 5.1±0.7 kPa (38.0±4.9 mmHg); SVC at t75: 5.0±0.7 kPa (37.9±5.4 mmHg). Measurement of $P_{\text{t}}$ (at residual volume) and $P_{\text{t,max}}$ (at total lung capacity) as well as constant-load resistive breathing were performed on a self-developed device (Tecuria, Chur, Switzerland). This device consists of a mouthpiece connected to a tube system including a flow sensor (163PC01D75; Honeywell Inc., Phoenix, AZ, USA) and a pressure sensor (143C05PCB; Sensym Inc., Milpitas, CA, USA). The tube system extends to two electronically controlled valves (inspiratory and expiratory). Breathing resistance increases proportionally to the voltage applied to the valves. The mouth pressure generated was displayed online on the screen of an oscilloscope on which the target pressure trace was outlined. Respiratory frequency and duty cycle were paced by the sweep time of the cathode beam. Cycling tests were performed on an electronically broken cycle ergometer (Ergometrics 800; Ergoline, Bitz, Germany). Blood samples were analysed enzymatically for blood lactate concentration by an ESA T 6661 analyser (Eppendorf, Hamburg, Germany). Subjects rated their perceived respiratory exertion on a modified Borg scale (0–10).

**Analysis**

For comparison of ventilatory variables during the constant-load resistive breathing tests, average values over the entire test-time were calculated. Ventilatory variables during the cycling tests were averaged during the constant-load period, with the first and last 1.5 min of this period being discarded to avoid the inclusion of any hyperventilation which may have occurred shortly before the end of exercise. To test for significant differences between the respiratory muscle performance tests at the four different times of one test-series, the nonparametric Friedman analysis of variance was used. If a significance was found a Wilcoxon and Wilcox comparison was used to locate the significant differences. The same statistics were used to test for significant differences between variables of different respiratory muscle performance test-series at equal time-points before or after exercise as well as between variables of the three cycling endurance tests. Values of the two preliminary consecutive resistive breathing tests were compared using the paired Wilcoxon’s signed rank test. Results are given as mean±SD. Values were considered to be significantly different if $p<0.05$.

**Results**

Time to task failure of the constant-load resistive breathing test was significantly reduced at 5 min after cessation of exercise (t5) compared to values before the exhaustive exercise (fig. 1). All other respiratory muscle performance tests were unaffected by prior exhaustive cycling (table 1). Average minute ventilation and breathing pattern were not significantly different during the constant-load resistive breathing tests at t5, t40 and t75 from t0 (table 2). Blood lactate concentrations before respiratory performance tests did not differ significantly between test series at t0 (1.5±0.6 (Task failure-series), 1.2±0.4 (SVC-series), 1.3±0.4 mmol·L⁻¹ (Spiro-series)), t5 (7.7±1.7, 7.4±1.8, 7.0±2.0 mmol·L⁻¹), t40 (2.0±0.6, 1.9±0.4, 1.9±0.7 mmol·L⁻¹) and t75 (1.3±0.4, 1.3±0.3, 1.5±0.5 mmol·L⁻¹). During the three exhaustive cycling tests, average minute ventilation, breathing pattern and times to exhaustion did not differ significantly either (table 3).

Average times to task failure in the two preliminary, consecutive constant-load resistive breathing tests were

![fig. 1](image-url)  

**Table 1.** Data from respiratory muscle performance tests

<table>
<thead>
<tr>
<th>Time</th>
<th>r0</th>
<th>t5</th>
<th>t40</th>
<th>t75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task failure s</td>
<td>364±88</td>
<td>219±122*</td>
<td>346±135</td>
<td>370±119</td>
</tr>
<tr>
<td>SVC L·min⁻¹</td>
<td>141±22</td>
<td>139±21</td>
<td>136±17</td>
<td>136±19</td>
</tr>
<tr>
<td>MVV15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L·min⁻¹</td>
<td>188±31</td>
<td>190±33</td>
<td>188±33</td>
<td>183±34</td>
</tr>
<tr>
<td>VC L</td>
<td>5.72±0.89</td>
<td>5.74±0.93</td>
<td>5.72±0.92</td>
<td>5.78±0.92</td>
</tr>
<tr>
<td>FVC L</td>
<td>5.58±0.84</td>
<td>5.56±0.82</td>
<td>5.49±0.77</td>
<td>5.51±0.80</td>
</tr>
<tr>
<td>FEV1 L</td>
<td>4.55±0.76</td>
<td>4.60±0.73</td>
<td>4.53±0.69</td>
<td>4.49±0.71</td>
</tr>
<tr>
<td>PEF L·s⁻¹</td>
<td>9.9±2.1</td>
<td>9.6±1.9</td>
<td>9.7±2.1</td>
<td>9.5±1.9</td>
</tr>
<tr>
<td>$P_{\text{t,max}}$ mbar</td>
<td>-169±25</td>
<td>-167±21</td>
<td>-160±22</td>
<td>-166±18</td>
</tr>
<tr>
<td>$P_{\text{t,max}}$ mbar</td>
<td>197±26</td>
<td>191±38</td>
<td>188±37</td>
<td>189±36</td>
</tr>
</tbody>
</table>

Absolute values (mean±SD) of time to task failure (task failure), sustained ventilatory capacity (SVC), maximal voluntary ventilation in 15 seconds (MVV15), vital capacity (VC), forced vital capacity (FVC), forced expiratory volume in one second (FEV1), peak expiratory flow (PEF), maximal inspiratory and expiratory mouth pressures ($P_{\text{t,max}}$ and $P_{\text{t,max}}$) before (r0) and (t5), 40 (t40) and 75 min (t75) after an exhaustive cycling endurance test (n=12). *: $p<0.01$. 1 mbar=0.1 kPa.
390±141 and 388±118 s, respectively. They were not significantly different. Also, minute ventilation (V′E: 15.1±3.6, 14.5±2.6 L·min⁻¹) and breathing pattern (inspiratory time (tI): 1.3±0.3, 1.3±0.3 s; expiratory time (tE): 2.0±0.2, 1.9±0.2 s; inspiratory flow (tidal volume (Vt)/tI): 0.7±0.2, 0.6±0.2 L·s⁻¹) did not differ significantly.

**Discussion**

The only test to show a decrease in respiratory muscle performance after exhaustive endurance exercise was the constant-load resistive breathing test leading to task failure. Neither SVC, measurements of lung function, i.e. VC, FVC, FEV₁, PEF and MVV₁5, nor Pmax and PEFmax were significantly reduced after cycling.

Possible factors other than any type of fatigue, which might have led to the reduced respiratory muscle performance during constant-load resistive breathing after exhaustive cycling need to be considered. In a subject-limited endurance test such as breathing to exhaustion against a resistance, subject's motivation is crucial. To avoid lack of motivation influencing the outcome of the study, only highly motivated subjects were chosen to participate. In fact, ratings of perceived respiratory exertion (table 2) which were similar at the end of all four constant-load resistive breathing tests, suggest that highly motivated subjects were successfully recruited and that they performed as hard as possible and to similar degrees of exertion at any time. In addition it is believed that, if motivation was a factor, reduced performance would also have occurred at t5 during the 12-min SVC-test as this test lasted longer than the constant-load resistive breathing test.

Alternatively, a change in minute ventilation and/or breathing pattern, as shown by CLANTON et al. [17], could have been responsible for a reduced endurance time during constant-load resistive breathing at t5 compared to t0. However, no significant changes were observed in minute ventilation and breathing pattern (table 2) after cycling compared to before. Thus changes of task failure cannot be attributed to changes in breathing pattern.

Further, one could argue that a reduction of task failure at t5 might be a consequence of pre-existing fatigue of the respiratory muscles due to breathing against resistance at t0 as LAGHE et al. [18] and TRAVALINE et al. [19] showed diaphragmatic fatigue to last for at least 24 h after subjects breathed against inspiratory resistive loads at 60% of maximal transdiaphragmatic pressure (Pd,max) for 33 min and at 80% Pd,max for 25 min. However, those loaded breathing tasks were substantially longer than the respiratory breathing test of the present study (average 6 min). In a preliminary test, respiratory muscle performance of the subjects was assessed in two subsequent constant-load resistive breathing tests until exhaustion with a 15 min rest in-between. In this setup, the second breathing test was of similar duration as the first one which suggests that the reduced time to exhaustion at t5 was not the result of the pre-cycling resistive breathing test at t0. In addition, if respiratory muscles were fatigued by the first test, a change in breathing pattern, similar to results of MADOR and ACEVEDO [20] would have been expected and possibly a change in endurance time during cycling [21]. This was not the case (table 3): breathing pattern as well as cycling times were similar during the three cycling endurance tests performed which also indicates that the reduced respiratory performance at t5 is unlikely to be the result of a different load on respiratory muscles during cycling in the Task failure-series compared to the SVC- or Spiro-series.

The possibility that central drive to respiratory muscles was reduced at t5 (Task failure-series) to protect respiratory muscles from fatigue during constant-load resistive breathing also needs to be considered. It may in fact be possible that subjects always stopped the resistive breathing test because of a "protective" reduction of central drive. In any case, this would suggest, it is believed, that respiratory muscles were more prone to fatigue or slightly fatigued at t5, thus "protection" was necessary earlier than during the test at t0. Also, this potential reduction of central drive would have occurred later during resistive breathing tests at t40 and t75, which could indicate that respiratory muscles recovered in-between.

Lastly, one could argue that lactic acidosis, known to impair muscle contractility, was increased during constant-load resistive breathing at t5 compared to t0 as a result of

**Table 2. – Data from the constant-load resistive breathing test**

<table>
<thead>
<tr>
<th>Variables</th>
<th>t0</th>
<th>t5</th>
<th>t40</th>
<th>t75</th>
</tr>
</thead>
<tbody>
<tr>
<td>V′E L·min⁻¹</td>
<td>15.0±2.4</td>
<td>15.8±3.1</td>
<td>14.1±2.1</td>
<td>14.5±1.9</td>
</tr>
<tr>
<td>tI s</td>
<td>1.32±0.28</td>
<td>1.30±0.28</td>
<td>1.38±0.25</td>
<td>1.30±0.27</td>
</tr>
<tr>
<td>tE s</td>
<td>1.92±0.26</td>
<td>1.98±0.28</td>
<td>1.91±0.24</td>
<td>1.93±0.29</td>
</tr>
<tr>
<td>V′E/tI L·s⁻¹</td>
<td>0.64±0.17</td>
<td>0.71±0.24</td>
<td>0.56±0.14</td>
<td>0.62±0.15</td>
</tr>
<tr>
<td>Respiratory exertion (first min)</td>
<td>5.2±2.4</td>
<td>6.1±2.4</td>
<td>5.5±2.5</td>
<td>5.5±2.5</td>
</tr>
<tr>
<td>Respiratory exertion (last min)</td>
<td>9.3±1.1</td>
<td>9.3±1.1</td>
<td>9.3±1.2</td>
<td>9.3±1.4</td>
</tr>
</tbody>
</table>

Absolute values (mean±SD) of minute ventilation (V′E), inspiratory time (tI), expiratory time (tE), inspiratory flow (ventilatory time (Vt)/tI), and time to exhaustion during the three cycling endurance tests (CET) in the Task failure-series, the SVC-series and the Spiro-series (n=12).

**Table 3. – Data from three cycling endurance tests**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Task failure-series</th>
<th>SVC-series</th>
<th>Spiro-series</th>
</tr>
</thead>
<tbody>
<tr>
<td>V′E L·min⁻¹</td>
<td>98.9±14.0</td>
<td>98.9±13.2</td>
<td>94.1±14.1</td>
</tr>
<tr>
<td>tI s</td>
<td>0.84±0.16</td>
<td>0.82±0.11</td>
<td>0.85±0.18</td>
</tr>
<tr>
<td>tE s</td>
<td>0.93±0.19</td>
<td>0.88±0.15</td>
<td>0.92±0.16</td>
</tr>
<tr>
<td>V′E/tI L·s⁻¹</td>
<td>3.45±0.51</td>
<td>3.38±0.44</td>
<td>3.26±0.52</td>
</tr>
<tr>
<td>Time to exhaustion min</td>
<td>25.7±6.6</td>
<td>25.5±6.7</td>
<td>26.0±9.8</td>
</tr>
</tbody>
</table>

Absolute values (mean±SD) of minute ventilation (V′E), inspiratory time (tI), expiratory time (tE), inspiratory flow (ventilatory time (Vt)/tI), and time to exhaustion during the three cycling endurance tests (CET) in the Task failure-series, the SVC-series and the Spiro-series (n=12).
prior cycling. Indeed, blood lactate concentration was significantly increased at t5 but similar increases were observed at t5 of the SVC- and Spiro-series; in fact, blood lactate concentrations at t5 were not significantly different between the three test series. Thus it is suggested that all respiratory tests performed at t5 should have been affected similarly if blood lactate concentrations of 7 mmol·L⁻¹ would have influenced respiratory muscle performance at this time.

The question remains as to why respiratory muscle performance was only reduced during the constant-load resistive breathing test. It is obvious that the different respiratory performance measurements tested for different properties of respiratory muscles: the maximal isometric force ($P_{\text{max}}$) and the ability to perform fast contractions with little development of force over a short period of time (FEV1, PEF, MVV) and over a longer period of time (SVC) remained unaffected by prior exercise while the ability to produce a high force with slow movement over an extended period of time was diminished. Why only this last type of respiratory performance was impaired after exercise remains to be addressed in further studies.

The aim of the present study was to apply different noninvasive techniques, commonly used in the literature to detect respiratory muscle fatigue [5, 8, 16], for the measurement of possible impairments of respiratory muscle performance after a type of exercise which was previously shown to induce diaphragmatic fatigue [2–4]. Also, the authors wanted to compare measures of reduced performance with the published data on reductions in $P_{\text{di,tw}}$. In the present study, respiratory muscle performance during constant-load resistive breathing was reduced by 43% at 5 min after the end of exercise (87% $V'_{O_2,\text{max}}$, corresponding to 78% $W_{\text{max}}$) while the decrease of $P_{\text{di,tw}}$ was 17% at 10 min after cycling (80% $W_{\text{max}}$) [2] and ranged from 8–32% immediately after cycling (85–95% $V'_{O_2,\text{max}}$) [4]. Since the exercise workload of the present study corresponded well to the workloads in the above mentioned studies, diaphragmatic fatigue was also likely to be present in the current subjects. If so, a possible explanation for the differences in the decrease of respiratory performance and the decrease of $P_{\text{di,tw}}$ might then be that during constant-load resistive breathing not only the diaphragm but also inspiratory ribcage muscle performance was tested. This can be inferred from a study suggesting that breathing against a threshold load preferentially fatigues ribcage muscles rather than the diaphragm [22]. In fact, McKenzie et al. [23] were unable to detect diaphragmatic fatigue in their subjects at the point of task failure after breathing against resistive loads. It is possible that, during cycling, rib cage muscles fatigue to a similar or larger extent than the diaphragm: this assumption is supported by Johnson et al. [4] who have shown that the relative contribution of the diaphragm to total respiratory motor output was progressively reduced with exercise. If ribcage muscles do fatigue during exercise, a task testing ribcage muscle performance as well as diaphragmatic performance would be affected to a larger extent by prior exercise than a test measuring diaphragmatic fatigue only.

While task failure at t5 was significantly reduced compared to t0, the differences were no longer significant at t40 (although 8/12 subjects had not yet attained control values), and at t75 baseline levels were reached. This pattern of recovery corresponds to the pattern of $P_{\text{di,tw}}$ recovery measured in previous studies where $P_{\text{di,tw}}$ returned to baseline values after 60 min [2] and 70 min [4] but the same pattern of recovery was also shown for ribcage muscles. Smilowski et al. [24] found that ribcage muscles fully recovered within 60 min of the fatiguing exercise. Since the time course of recovery was similar in the present study, it might be possible that constant-load resistive breathing does test for global inspiratory muscle fatigue.

In summary, the constant-load resistive breathing task to task failure applied in the present study seems to be a useful tool for detecting a reduction in respiratory muscle performance capacity due to prior respiratory muscle work. This test could be useful in assessing respiratory muscle performance of patients suffering from chronic obstructive pulmonary disease and cystic fibrosis since these patients also benefit from inspiratory resistive or threshold training [25]. The constant-load resistive breathing test could then be used to follow progress or reduction in respiratory muscle performance over time.

In conclusion, measures of vital capacity, forced vital capacity, forced expiratory volume in one second, peak expiratory flow, maximal voluntary ventilation in 15 seconds, maximal inspiratory and expiratory mouth pressures or sustained ventilatory capacity were not affected by exhaustive cycling at 85% maximal oxygen uptake. Thus, it is concluded that constant-load resistive breathing to task failure is the only noninvasive respiratory muscle performance test evaluated in this study that shows a decrease in respiratory muscle performance after exhaustive endurance exercise.

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References


