Recovery of Gas Exchange Variables and Heart Rate After Maximal Exercise in COPD*

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Studies of the limited exercise capacity in patients with COPD have not assessed the recovery phase, although the phenomenon of increased oxygen uptake after exercise has been thoroughly investigated in normal subjects. Therefore, we compared the recovery of gas exchange variables and HR after maximal cycle ergometry in 16 patients with varying severities of airflow obstruction and ten aged control subjects. Aerobic capacity was reduced in the patients with COPD, and the rates of recovery of VE, V̇O₂, V̇CO₂, excess V̇CO₂ and HR were all significantly slower in the patients with COPD than in the controls. When expressed as the half-time for recovery, patients with COPD had values which were approximately twice that of control subjects for gas exchange and HR. The extent of recovery was similar in patients and controls. We conclude that in patients with COPD, postexercise relative hyperpnea and hypermetabolism are significantly prolonged. In addition, impaired elimination of increased body stores of carbon dioxide may contribute to impaired adjustment to acid-base disorders in these patients. (Chest 1990; 97:276-79)

RER = respiratory exchange ratio

In patients with COPD, exercise performance is limited by reduced ventilatory capacity.1-3 Although many studies have documented the correlation between reduced work capacity and spirometric indices of airflow obstruction,4,5 recovery from exercise has received little attention in COPD. The metabolic cost of exercise involves not only the performance of external work, but the demands of the oxygen transport system itself, including the work performed by the muscles of respiration, and persistent hypermetabolism during recovery.6 In normal subjects after maximal exercise, V̇O₂ during recovery declines in a biexponential manner6,7 and reaches near baseline values in approximately five to ten minutes. We hypothesized that patients with COPD have more prolonged hyperpnea after exercise than normal subjects due to airflow limitation and reduced rate of elimination of excess carbon dioxide formed during exercise. The clinical implications of prolonged hyperpnea after exercise in patients with COPD may include greater metabolic demand for a given task and reduced resistance to fatigue, particularly for repetitive tasks. In addition, delayed elimination of increased body stores of carbon dioxide would impair the ability to adjust to alterations of acid-base status in these patients.

**MATERIALS AND METHODS**

Patients with COPD (n = 16) were recruited from the outpatient department of the Albuquerque VA Medical Center for participation in this study. All were clinically stable and had not had an exacerbation of their disease for at least six weeks prior to study. In all patients, arterial blood gas analysis at rest revealed oxygen tensions greater than 55 mm Hg (range, 57 to 66 mm Hg) and normal carbon dioxide tensions (range, 32 to 37 mm Hg). Electrocardiograms revealed normal sinus rhythm in all patients; right axis deviation was present in six, right ventricular hypertrophy in one, and right atrial enlargement in two patients.

The control group (n = 9) consisted of normal aged subjects who volunteered to participate in a study of blood donation in the elderly. The present study was performed before blood donation. Subjects were accepted for inclusion in the study on the basis of absence of clinical evidence of cardiopulmonary disease and normal findings on electrocardiography and echocardiography.

All participants gave informed consent, and the study was approved by the Human Research and Review Committee of the University of New Mexico and the Research Committee of the Albuquerque VA Medical Center.

Spirometry was performed using a heated pneumotachograph (Pneumotest Erich Jaeger, Boeckford, IL). Predicted values were those of Morris et al.8

Graded ergometry was performed on an electrically braked cycle (Erich Jaeger, Boeckford, IL). All subjects selected pedal frequencies of 40 to 60 cycles per minute. This cycle maintains a constant workload for pedal frequencies of 40 to 100 cycles per min. All patients and control subjects maintained a constant pedal frequency within this range throughout the exercise and recovery phases. Respiratory gas exchange variables, V̇E, V̇O₂, V̇CO₂, RER, and excess V̇CO₂ were determined as previously described9 using 15-s timed collections of expired air (Incacorpulmin). Excess V̇CO₂ is defined as the V̇CO₂ attributable to nonmetabolic sources (buffering of lactic acid) and is calculated by the following equation:

\[ \text{Excess VCO}_2 = (\text{RER} - \text{RER}_{\text{mean}}) \cdot \text{VCO}_2 \]

where RER is the RER at any time during exercise or recovery.

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Gas Exchange Variables and Heart Rate After Exercise (Chick et al)
Table 1—Demographic, Spirometric, and Maximal Exercise Data*

<table>
<thead>
<tr>
<th>Data</th>
<th>Control</th>
<th>COPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>62 ± 6</td>
<td>69 ± 5</td>
</tr>
<tr>
<td>Height, in</td>
<td>68 ± 3</td>
<td>69 ± 3</td>
</tr>
<tr>
<td>Weight, lb</td>
<td>169 ± 25</td>
<td>162 ± 14</td>
</tr>
<tr>
<td>FVC, percent of predicted</td>
<td>116 ± 11</td>
<td>79 ± 16</td>
</tr>
<tr>
<td>FEV₁, percent of predicted</td>
<td>123 ± 14</td>
<td>43 ± 15</td>
</tr>
<tr>
<td>FEF25-75, L/min†</td>
<td>132 ± 20</td>
<td>24 ± 13</td>
</tr>
<tr>
<td>VO₂max, ml/kg/min</td>
<td>27.4 ± 6.3</td>
<td>15.9 ± 3.3</td>
</tr>
</tbody>
</table>

*Values are means ± SD.
†Instantaneous forced expiratory flow after 50 percent of FVC has been exhaled.

RERmax is the RER value obtained in the third minute of warm-up pedaling (discussed subsequently), and VO₂ is the VO₂ at any time during exercise or recovery. The RERmax was 0.86 ± 0.07 (mean ± SD) for the group with COPD and 0.84 ± 0.06 for the control group (NS).

After a three-minute warm-up period of 0-W pedaling, the workload was increased 10 W/min for the patients with moderate to severe COPD and 15 W/min for the patients with mild COPD. In the control subjects the workload increments were 15 W/min for subjects weighing less than 68.1 kg (150 lb) and 20 W/min for subjects weighing more than 68.1 kg. Using standard encouragement, exercise was continued to the point of volitional fatigue. All of the patients with COPD stopped exercise due to breathlessness, whereas the control subjects stopped because of leg fatigue. At the termination of exercise, the cycle workload was returned to 0 W, and the subject continued pedaling for ten minutes of active recovery.

Recovery half-times were reported as the minutes required for return of a variable to 50 percent of the difference between the maximal value attained during exercise and the value during the unloaded pedaling warm-up period before exercise. The percentage of recovery of Vₑ, for example, is calculated by the following equation:

\[
\% \text{ recovery} = 100\left(\frac{\bar{\text{V}}_{\text{Emax}} - \bar{\text{V}}_\text{E}}{\bar{\text{V}}_{\text{Emax}} - \bar{\text{V}}_{\text{E}}}\right)
\]

where \(\bar{\text{V}}_{\text{E}}\) is the maximal \(\bar{\text{V}}_{\text{E}}\) during exercise, \(\bar{\text{V}}_{\text{E}}\) is the \(\bar{\text{V}}_{\text{E}}\) at any time during recovery, and \(\bar{\text{V}}_{\text{E}}\) is the mean \(\bar{\text{V}}_{\text{E}}\) during the third minute of the warm-up period. In the event of incomplete recovery within 10 min, the recovery half-time was recorded as 10 min.

Statistical Methods

Data were entered into a microcomputer data base and analyzed with a commercial statistical package (Systat). Group differences in continuous variables were analyzed by the unpaired Student's t-test. Linear regression was used to examine the relationship between

![Figure 1](http://journal.publications.chestnet.org/pdaccess.ashx?url=/data/journals/chest/21606/ on 04/29/2017)

**Figure 1.** Percentage of recovery of \(\bar{\text{V}}_{\text{E}}\) (± SD) in control subjects.

![Figure 2](http://journal.publications.chestnet.org/pdaccess.ashx?url=/data/journals/chest/21606/ on 04/29/2017)

**Figure 2.** Percentage of recovery of \(\bar{\text{V}}_{\text{O}_2}\) (± SD) in control subjects.

![Figure 3](http://journal.publications.chestnet.org/pdaccess.ashx?url=/data/journals/chest/21606/ on 04/29/2017)

**Figure 3.** Percentage of recovery of \(\bar{\text{V}}_{\text{E}}\) (± SD) in patients with COPD.

RESULTS

Spirometric and \(\bar{\text{V}}_{\text{O}_2}\)max values were within normal limits in the control group (Table 1). In the patients with COPD, mean \(\text{FEV}_1\) was 43 percent of predicted (SD, 15 percent), and \(\bar{\text{V}}_{\text{O}_2}\)max was significantly reduced at 15.9 ml/kg/min (SD, 3.25 ml/kg/min; p<0.001 vs. controls).

Percentage of recovery for ventilation and \(\bar{\text{V}}_{\text{O}_2}\) are shown in Figures 1 and 2 for control subjects and Figures 3 and 4 for the patients with COPD; the pattern of return to baseline for all variables was biphasic, with a rapid initial recovery followed by a slower late decline. All gas exchange variables and HR recovered more slowly in the group with COPD (Table 2). For each variable the half-time of relative recovery was approximately twice as long in the patients with COPD as in the control subjects. Nevertheless, the extent of recovery was not significantly different between the groups for any of the gas exchange variables and HR (Table 3).

In the patients with COPD, correlation of the half-times of recovery with the \(\text{FEV}_1\) showed that all gas exchange variables were slowed in proportion to the severity of the airway disease (Table 4); the highest correlation was with excess \(\bar{\text{V}}_{\text{CO}_2}\). The recovery rate of the HR did not correlate with \(\text{FEV}_1\). Correlation...
with FVC was not significant (data not shown). Although the extent of recovery was similar in the two groups, the time required for 90 percent recovery of excess \( \dot{V}CO_2 \) was greater than ten minutes in ten of 12 patients with severe COPD (FEV\(_1\) 0.8 to 1.4 L/s) and in two of four patients with mild disease (FEV\(_1\) 1.9 to 2.1 L/s), whereas only one of ten control subjects had 90 percent recovery time for excess \( \dot{V}CO_2 \) which exceeded ten minutes.

In the control group, the respiratory rate was 15.5/min during warm-up and 19.5/min during eight to ten minutes of recovery, compared with values of 23.4/min and 25.7/min, respectively, in the group with COPD. The differences between groups are significant at both intervals (p<0.01), but the changes within each group after exercise are not significant.

**Discussion**

The mechanism of ventilatory impairment at maximal exercise in COPD cannot be stated with certainty, although the preponderance of evidence indicates that diaphragmatic fatigue is not the major limiting factor. In the present study the lack of a tachypneic response during recovery suggests that diaphragmatic fatigue was not present, which is consistent with the findings of Gallagher and Younes.\(^\text{11}\) In contrast, Bye et al.\(^\text{12}\) reported electromyographic evidence of diaphragmatic fatigue during exhaustive exercise in five of eight patients with COPD. It is possible that changes in frequency content of the diaphragmatic electromyogram with exercise in patients with COPD represent a response to loading, rather than the development of muscle fatigue.

In addition to marked reduction of work capacity, patients with COPD had prolonged relative hyperpnea, hypermetabolism, and tachycardia after exercise when compared to control subjects. It is important to note that although the absolute values for gas exchange variables were lower in the patients both at maximal exercise and during recovery, the relative recovery rates were significantly slower in the patients than in the control subjects. Nevertheless, the extent of recovery at eight to ten minutes after exercise was similar between the two groups.

After maximal exercise, carbon dioxide is eliminated rapidly from muscle, resulting in increased femoral venous P\( CO_2,\)\(^\text{13}\) and is transported to the lungs for excretion in respired air.\(^\text{14}\) The rate of elimination of increased body stores of carbon dioxide depends on carbon dioxide chemosensitivity\(^\text{15}\) and ventilatory capacity. It is unlikely that the delayed elimination of carbon dioxide in the group with COPD was due to impaired transport of carbon dioxide from muscle to blood, in view of the high solubility and rapid diffusion of carbon dioxide across biologic membranes. The bottleneck to carbon dioxide elimination in patients with airway disease most likely resides at the level of excretion in respired air, resulting from mechanical limitation to the attainment of adequate alveolar ventilation to rapidly restore body stores of carbon dioxide to resting levels.

The delayed elimination of excess carbon dioxide in COPD may contribute to impairment of exercise tolerance by both heightening and prolonging the perception of respiratory loads.\(^\text{16}\) The importance of

### Table 2—Half-Times of Recovery of Gas Exchange Variables and HR*

<table>
<thead>
<tr>
<th>Data</th>
<th>Control</th>
<th>COPD</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{V}E )</td>
<td>2.0 ± 0.5</td>
<td>3.3 ± 1.7</td>
<td>0.037</td>
</tr>
<tr>
<td>( \dot{V}CO_2 )</td>
<td>1.6 ± 0.3</td>
<td>3.1 ± 1.6</td>
<td>0.012</td>
</tr>
<tr>
<td>( \dot{V}O_2/Kg )</td>
<td>1.3 ± 0.2</td>
<td>2.3 ± 1.3</td>
<td>0.025</td>
</tr>
<tr>
<td>Excess ( \dot{V}CO_2 )</td>
<td>2.9 ± 0.6</td>
<td>5.7 ± 2.4</td>
<td>0.002</td>
</tr>
<tr>
<td>HR</td>
<td>2.3 ± 1.0</td>
<td>4.6 ± 2.8</td>
<td>0.032</td>
</tr>
</tbody>
</table>

*Values are means ± SD.

### Table 3—Extent of Recovery for Gas Exchange Variables and HR*

<table>
<thead>
<tr>
<th>Data</th>
<th>Control</th>
<th>COPD</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{V}E, ) percent†</td>
<td>133 ± 27</td>
<td>121 ± 18</td>
<td>NS</td>
</tr>
<tr>
<td>( \dot{V}CO_2, ) percent†</td>
<td>116 ± 23</td>
<td>115 ± 17</td>
<td>NS</td>
</tr>
<tr>
<td>( \dot{V}O_2/Kg, ) percent</td>
<td>111 ± 16</td>
<td>109 ± 12</td>
<td>NS</td>
</tr>
<tr>
<td>Excess ( \dot{V}CO_2, ) ml/kg/min‡</td>
<td>0.66 ± 0.28</td>
<td>0.89 ± 0.84</td>
<td>NS</td>
</tr>
<tr>
<td>HR, percent†</td>
<td>114 ± 8</td>
<td>116 ± 7</td>
<td>NS</td>
</tr>
</tbody>
</table>

†Recovery values of 8 to 10 minutes as percent of baseline (third minute of warm-up) values.

‡Mean absolute value for 8 to 10 minutes of recovery.

### Table 4—Correlation Coefficients for FEV, Half-Times of Recovery in Patients with COPD

<table>
<thead>
<tr>
<th>Data</th>
<th>r</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{V}E )</td>
<td>−0.65</td>
<td>0.009</td>
</tr>
<tr>
<td>( \dot{V}CO_2 )</td>
<td>−0.64</td>
<td>0.010</td>
</tr>
<tr>
<td>( \dot{V}O_2/Kg )</td>
<td>−0.61</td>
<td>0.017</td>
</tr>
<tr>
<td>Excess ( \dot{V}CO_2 )</td>
<td>−0.77</td>
<td>0.001</td>
</tr>
<tr>
<td>HR</td>
<td>−0.29</td>
<td>0.295</td>
</tr>
</tbody>
</table>

Gas Exchange Variables and Heart Rate after Exercise (Chick et al)
carbon dioxide elimination in limiting exercise performance in COPD has been confirmed by the observation that a large carbohydrate load resulted in increased resting V\textsubscript{CO\textsubscript{2}} and reduced 12-min walking distance.\textsuperscript{17} The central role of respiratory load perception in limitation of exercise in patients with COPD is supported by reports of enhanced exercise performance after administration of anxiolytic drugs and opiates; for example, administration of oral morphine (0.8 mg/kg) to a group of patients with COPD resulted in improvements in \( \text{VO}_{\text{max}} \) and maximal workload,\textsuperscript{18} probably on the basis of reduced ventilatory drive (reduced ventilation for the same \( \text{VCO}_{2} \)) or altered central perception of breathlessness (or both).

Delayed elimination of excess carbon dioxide in patients with obstructive airway disease has important implications for adaptations to changes in body stores of carbon dioxide. In normal subjects the rate of elimination of carbon dioxide after an acute increase in body stores of carbon dioxide induced by rebreathing was correlated with the slope of the ventilatory response to carbon dioxide, but not with the magnitude of hypercapnia;\textsuperscript{15} however, in patients with airflow limitation, delayed elimination of excess carbon dioxide is most likely attributable to reduced ventilatory capacity.

The prolonged requirement for increased ventilation and oxygen uptake must be considered in the total metabolic demand for the performance of work in these patients. In particular, work-rest intervals in COPD exercise rehabilitation programs must be adjusted to allow complete restoration of basal stores of carbon dioxide in order to avoid progressive hypercapnia. From our data, excess elimination of carbon dioxide may persist for more than ten minutes after maximal exercise.

Several considerations underscore the importance of measurement of recovery of gas exchange variables in patients with COPD. Such measurements may give further insight into the training response in these individuals; because patients with COPD have not shown significant cardiovascular or skeletal muscle adaptations to exercise training,\textsuperscript{19} and improved kinetics of recovery of gas exchange variables have been described in response to training,\textsuperscript{20} the period after exercise warrants further attention in this group of patients. In addition, exercise performed early during recovery from prior exercise has been shown to require higher oxygen uptake per workload than exercise performed under basal conditions;\textsuperscript{21} therefore, delayed recovery of ventilation and oxygen uptake confer an added metabolic cost to performance of repeated tasks and reduce maximal workload.\textsuperscript{21}

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