Relationship of Resting Lung Mechanics and Exercise Pattern of Breathing in Patients With Chronic Obstructive Lung Disease*

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To investigate the influence of resting pulmonary mechanics on the pattern of breathing during exercise in chronic obstructive pulmonary disease (COPD), we studied 29 patients with moderate to severe COPD (FEV₁, 50±20 percent predicted), and 10 normal subjects. Lung mechanics were studied using esophageal balloon technique and body-box. Incremental exercise testing was performed to exhaustion. As minute ventilation (Ve) increases, COPD patients with the highest pulmonary resistance (Rl) or lowest elastic recoil pressure (Pl), used a greater tidal volume/vital capacity ratio (Vt/Vc) than the COPD patients with more normal Rl or lowest Pl. To describe the breathing pattern during exercise, an exponential constant (K) describes the rates of increase in Vt/Vc ratio with increasing Ve, calculated according to the equation Vt/Vc=K(Vt/Vc) (1-e⁻²⁰). The K values achieved by COPD patients were higher than in normal subjects. In addition, K value correlated negatively with the resting FEV₁ and FVC of COPD patients.

When COPD patients were grouped according to their K values, it was revealed that patients with high K values generated greater Vt/Vc ratio and also have the most abnormal resting lung mechanics. These results suggest that the exercise breathing pattern in COPD patients is significantly influenced by the degree of impairment of resting lung mechanics.

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\[ \text{Vt} = \text{breathing frequency; } K = \text{exponential constant; } \text{MVV} = \text{maximal voluntary ventilation; } \text{PETCO} = \text{expired end-tidal carbon dioxide tension; } \text{PETO} = \text{expired end-tidal oxygen tension; } \text{Pl} = \text{transpulmonary pressure; } \text{PaO} = \text{transpulmonary pressure at 90 percent of measured total lung capacity; } \text{Rl} = \text{pulmonary resistance; } \text{Vmax} = \text{maximal oxygen consumption; } \text{Vt/Vc} = \text{tidal volume/vital capacity ratio} \]

During incremental exercise in normal subjects, ventilation (Ve) increases linearly in relation with oxygen intake (VO₂) and carbon dioxide production (VCO₂) until the "anaerobic threshold" is reached. Most of the increase in ventilation is achieved by tidal volume (Vt) augmentation and only at heavier exercise, breathing frequency (f) increases markedly. At peak exercise, Vt usually reaches 50 to 60 percent of vital capacity.

Patients with moderate to severe chronic obstructive pulmonary disease (COPD) are primarily limited in their exercise performance by a decrease in ventilatory capacity due to abnormal pulmonary mechanics. The pattern of breathing in these patients during exercise has been described as rapid and shallow, or as slow and deep by others, and the reasons for these differences are not clear. Lung resistance and elastic recoil pressure at rest, the principal physiologic abnormalities in COPD, have not been related previously with the pattern of breathing during exercise in these patients.

The main goal of this study was to assess the pattern of breathing and its relationship to the mechanical properties of the lung at rest in patients with COPD. We analyzed the pattern of breathing using the constant exponential function, recently described by Jones et al., that treats the exponential behavior of tidal volume/vital capacity ratio (Vt/Vc) as a function of Ve during incremental exercise as a single number.

**METHODS**

**Patients**

Twenty-nine consecutive and unselected patients with COPD were studied. Diagnosis was made according to standard criteria. At the moment of the study, every patient was clinically stable and their forced expiratory volume in 1 s (FEV₁) ranged from 24 to 75 percent of predicted. Seven had hypoxemia (PaO₂ <60 mm Hg) and 5 had hypercapnia (PaCO₂ >45 mm Hg) at rest. We also studied ten nonsmoking control subjects without any cardiorespiratory or systemic disease.

**Pulmonary Function Test (PFT)**

Resting PFTs were done according to the National Institutes of Health-American Thoracic Society (NIH-ATS) standard protocol. All subjects underwent spirometric measurements performed with a calibrated spirometer (Eagle, W.E. Collins, Inc, Braintree, Mass). Patients with COPD also underwent single-breath carbon monoxide diffusion capacity (Medical Graphics 1070 System, Minneapolis), static lung volume determinations by body plethysmograph (P.K. Morgan, Lth, United Kingdom), and arterial blood gas analysis.
The predicted normal values for spirometric measurements were those of Morris et al.\textsuperscript{14} for lung volumes, those of Goldman and Becklake.\textsuperscript{15}

With the esophageal balloon technique as described by Milic-Emili et al.\textsuperscript{16} (1964), we measured pleural pressure. Transpulmonary pressure (Pt) was estimated with a differential pressure transducer at the difference between esophageal pressure and mouth pressure when airflow was zero. Flow was recorded by a pneumotachograph (Fleisch) and at least three reproducible static deflection pressure-volume curves were obtained for each patient. Transpulmonary pressure at 90 percent of measured total lung capacity (Pt.90) was expressed as percent predicted.\textsuperscript{19} Pulmonary resistance during expiration (Rl) was measured using the technique described by Mead and Wittenberger.\textsuperscript{19} Pulmonary function tests were performed without interruption of usual medication.

Exercise Testing

All subjects underwent incremental exercise (ie, 100 kpm/min) on an electrically braked cycle ergometer using a standard 1-min incremental protocol.\textsuperscript{4} Exercise studies were performed using an exercise system (2001, Medical Graphics). Subjects were seated on an electrically braked cycle ergometer (Mijnhardt, Holland). After 5 min of no pedaling, subjects cycled at a speed of 50 to 60 rpm/min, with the workload increasing 100 kpm/min to a symptom-limited maximum. Heart rate and rhythm were monitored by three-lead electrocardiogram, and blood pressure was measured by cuff technique. Subjects breathed through a low resistance, two-way valve (model 2700, Hans-Rudolph Co, Kansas City, Mo), connected on the expiratory limb to a heated linear pneumotachograph (Fleisch No. 3, Lausanne, Switzerland). Expired end-tidal carbon dioxide (PetrCO\textsubscript{2}) and oxygen tensions (Poro\textsubscript{2}) were monitored using an infrared absorption CO\textsubscript{2} analyzer (Normocap) and a zirconia fuel cell O\textsubscript{2} analyzer (Datex Co, Helsinki, Finland), with response times of less than 100 ms. Expired gas was sampled at rates of 150 ml/min for both CO\textsubscript{2} and O\textsubscript{2} analysis. After analog-to-digital conversion, these signals were then processed by the exercise system computer to yield carbon dioxide production (VCO\textsubscript{2}) and oxygen consumption (VO\textsubscript{2}). Arterial hemoglobin oxygen saturation (SaO\textsubscript{2}) was monitored noninvasively with a fiberoptic earpiece (Hewlett-Packard 47201A). The breath-by-breath signals were integrated by a computer to yield 30-s averages of minute ventilation (V\textsubscript{E}), tidal volume (V\textsubscript{T}), respiratory rate (f), VO\textsubscript{2}, VCO\textsubscript{2}, heart rate, SaO\textsubscript{2}, and PetrCO\textsubscript{2}. The pneumotachograph, O\textsubscript{2}, and CO\textsubscript{2} gas analyzers, ear oximeter, and cardiac monitor were all calibrated prior to each exercise study. All airflow and gas measurements were corrected for ambient temperature, barometric pressure and water vapor, and expressed in BTPS units. The subjects were strongly encouraged to cycle until discomfort or exhaustion was reported or abnormal ECG was recorded. Predicted maximal oxygen consumption (VO\textsubscript{2max}) was calculated according to Jones and Campbell.\textsuperscript{4} Predicted maximal voluntary ventilation (MV\textsubscript{V}) was expressed as MV\textsubscript{V} = FEV\textsubscript{1} × 35, in L/min.

At rest and at each workload, V\textsubscript{T}/VC ratio and V\textsubscript{T}/VC over V\textsubscript{E} were calculated. These points were formulated into a single exponential equation as described by Jones et al.\textsuperscript{12}

\[ V_T = V_C (1 - e^{-0.86}) \]

This method of analysis of the pattern of breathing proved satisfactory in all subjects and K mean value for tested regression analysis was as follows: r = 0.88 ± 0.1.

Statistical Analysis

Results are expressed as mean ± SEM. To compare the mean groups, we used the one-way analysis of variance (ANOVA). For multiple comparison, Fisher's least significant difference test was used. Pearson regression analysis was used to determine if there is a relationship between two sets of paired numbers. The significance level was set at p<0.05.

### Table 1 — Characteristics of Subjects and Pulmonary Function Test (PFT) Results at Maximal Exercise in Patients With COPD and Normal Subjects*\textsuperscript{a}

<table>
<thead>
<tr>
<th></th>
<th>Patients With COPD</th>
<th>Normal Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. (F/M)</td>
<td>29 (6/23)</td>
<td>10 (2/6)</td>
</tr>
<tr>
<td>Age, yr</td>
<td>60 ± 1.3</td>
<td>38 ± 1.5</td>
</tr>
<tr>
<td>Resting PFT and mechanics</td>
<td></td>
<td></td>
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<tr>
<td>FEV\textsubscript{1}, % predicted</td>
<td>49.9 ± 3.8</td>
<td>108 ± 3.1</td>
</tr>
<tr>
<td>FVC, % predicted</td>
<td>73.7 ± 3.3</td>
<td>112 ± 4.7</td>
</tr>
<tr>
<td>TLC, % predicted</td>
<td>113.8 ± 2.0</td>
<td>110 ± 3.1</td>
</tr>
<tr>
<td>FRC, % predicted</td>
<td>147.0 ± 5.5</td>
<td>108 ± 3.5</td>
</tr>
<tr>
<td>RV, % predicted</td>
<td>194.0 ± 9.7</td>
<td>111 ± 3.7</td>
</tr>
<tr>
<td>RV, % TCL (%) predicted</td>
<td>59.8 ± 3.7</td>
<td>107 ± 3.5</td>
</tr>
<tr>
<td>Rs, cm H\textsubscript{2}O/L/s</td>
<td>5.98 ± 0.54</td>
<td>1.66 ± 0.26</td>
</tr>
</tbody>
</table>

*Values are mean ± SEM.Abbreviations are expanded in text.

### RESULTS

### Resting PFT and Lung Mechanics

Results of the pulmonary function testing for normal and the COPD groups are given in Table 1. Patients with COPD had airflow limitation and hyperinflation. Lung elastic recoil at 90 percent of total lung capacity (Pt.90) ranged between 20 percent and 90 percent predicted. Total lung resistance (Rl) was in all cases greater than 2.5 cm H\textsubscript{2}O/L/s and ranged between 2.6 and 12.8 cm H\textsubscript{2}O/L/s.

### Exercise Test

All patients with COPD complained of dyspnea at the end of exercise. Maximum oxygen consumption (VO\textsubscript{2max}) achieved by these patients was about 40.2 percent of predicted (Table 1). At peak exercise, minute ventilation (V\textsubscript{E}max) in COPD patients averaged 76.1 percent of MV\textsubscript{V} (Table 1). Arterial O\textsubscript{2} saturation declined from a resting value of 94.5 ± 0.7 percent to 91.5 ± 1.1 percent at the end of exercise (means ± SEM). End-tidal CO\textsubscript{2} rose slightly from resting value of 34.5 ± 0.6 mm Hg to 36.9 ± 1.0 mm Hg at the end of exercise. The control subjects had normal PFT results and exercise responses (Table 1).

In normal subjects, K calculated from the equation of Jones et al\textsuperscript{12} ranged from 0.002 to 0.006 and in COPD patients from 0.005 to 0.032. To investigate whether K values were related to the severity of the disease processes, we related FEV\textsubscript{1} and FVC with K. K was negatively related to FVC (r = 0.65, p<0.05) and FEV\textsubscript{1} (r = 0.55, p<0.05), ie, patients with the highest FVC and FEV\textsubscript{1} developed the lowest K values during exercise. To further characterize the relationship between K and the severity of the disease processes, we divided the patients into three groups.
based on their K values: group 1 (n = 9): K < 0.01; group 2 (n = 13): K 0.01 to 0.02; and group 3 (n = 7): K > 0.02. Table 2 shows that group 3 patients have lower resting flow rates and more hyperinflation than group 1 and 2 patients. In addition, lung resistance was higher and Pt90 was lower in group 3 patients compared with group 1 and 2 patients (Table 2).

Figure 1 illustrates the changes in Vt (percent VC) and breathing frequency during exercise in normal subjects and in COPD patients divided according to their K values. At a given ventilation, group 1 COPD patients developed Vt/VC ratio similar to those achieved by normal subjects; however, f0 was significantly higher than those of normal subjects. Group 2 patients (K = 0.01 to 0.02) developed higher Vt/VC and f0 than in normal subjects. Finally, group 3 patients achieved the highest increase in Vt/VC ratio and f0, at a given VE during exercise in comparison with normal subjects and patients with low K values (Fig 2).

The Effects of Elastic Recoil and Resistance

In order to investigate whether resting lung elastic recoil or pulmonary resistance has a separate relationship to the breathing pattern during exercise, we divided the COPD patients into three groups according to their Pt90 percent and three groups according to their RtL. These groups are shown in Figure 2.

When divided according to their Pt90, group A patients (n = 9) have Pt90 > 75 percent predicted and average RtL of 5.4 cm H2O/L/s (Fig 2, top). Group B patients (n = 15) have Pt90 between 40 to 75 percent predicted with an average RtL of 6.0 cm H2O/L/s, whereas patients with the lowest Pt90 (40 percent predicted) were designated as group C (n = 5) with an average RtL of 6.5 cm H2O/L/s.

Figure 3 illustrates the changes in Vt (expressed as percent of VC) and f0 during exercise in normal subjects and in COPD patients divided according to their Pt90 percent. In group A patients, only at high ventilation did Vt/VC increase significantly higher than in normal subjects (p < 0.05 at VE of 25 and 30 L/min). In contrast, f0 was higher in this group than in normal subjects (p < 0.05). In group B patients, Vt/VC ratio at any given VE was higher than in normal subjects (p < 0.05) whereas f0 rose higher than that of normal subjects only at VE values of 25 and 30 L/min (p < 0.05). Finally, patients with the lowest Pt90 (group C) showed the greatest increase in Vt/VC ratio reach-

<p>| Table 2—Comparison by Analysis of Variance of COPD Patients Divided by Their K Values Achieved During Exercise* |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th></th>
<th>Group 3</th>
<th>Group 2</th>
<th>Group 1</th>
<th>F</th>
<th>p</th>
<th>Comparison</th>
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<tr>
<td>K &gt; 0.02</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
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<tr>
<td>Subjects, No.</td>
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<td>13</td>
<td>7</td>
<td></td>
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<tr>
<td>Age, yr</td>
<td>61 ± 1.2</td>
<td>62 ± 2.1</td>
<td>56 ± 2.5</td>
<td>1.91</td>
<td></td>
<td></td>
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<tr>
<td>FEV1, % predicted</td>
<td>38.5 ± 3.1</td>
<td>52.2 ± 5.6</td>
<td>64.3 ± 8.1</td>
<td>3.7</td>
<td>0.038</td>
<td>(1 &lt; 2 &lt; 3)</td>
</tr>
<tr>
<td>FEV1/FVC, % predicted</td>
<td>45.4 ± 4.2</td>
<td>48.1 ± 4.2</td>
<td>59.0 ± 6.3</td>
<td>1.58</td>
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<td>FEF25-75, % predicted</td>
<td>17.9 ± 3.1</td>
<td>26.5 ± 4.7</td>
<td>41.4 ± 6.5</td>
<td>5.37</td>
<td>0.011</td>
<td>(1 &lt; 2 &lt; 3)</td>
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<td>TLC, % predicted</td>
<td>116 ± 4</td>
<td>112 ± 3</td>
<td>111 ± 3</td>
<td>0.48</td>
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<td>FRC, % predicted</td>
<td>170 ± 10</td>
<td>141 ± 7</td>
<td>129 ± 8</td>
<td>5.72</td>
<td>0.007</td>
<td>(1 &lt; 2 &lt; 3)</td>
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<td>RV/TLC, % predicted</td>
<td>64 ± 3</td>
<td>54 ± 2</td>
<td>50 ± 4</td>
<td>5.56</td>
<td>0.009</td>
<td>(1 &lt; 2 &lt; 3)</td>
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<td>Don, % predicted</td>
<td>69.9 ± 5</td>
<td>55.5 ± 4.9</td>
<td>71 ± 8</td>
<td>1.63</td>
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<tr>
<td>Pt90, % predicted</td>
<td>47.4 ± 5.9</td>
<td>66.5 ± 5</td>
<td>64 ± 7</td>
<td>5.61</td>
<td>0.015</td>
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<td>RtL, cm H2O/L/s</td>
<td>8.1 ± 0.7</td>
<td>5.4 ± 0.8</td>
<td>4.3 ± 0.5</td>
<td>4.92</td>
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*Values are mean ± SEM.
ing a mean value of 42.6 percent (p<0.01 in comparison with normal subjects). In contrast, the changes in $f_e$ were similar to those of group B and A and were only significantly higher than normal subjects at $\dot{V}E$ values of 20 L/min (Fig 3, bottom).

When patients with COPD were grouped according to their resting transpulmonary resistance, group D (n = 8) patients had RL values of $<4$ cm H$_2$O/L/s with an average $Pt.90$ of 59 percent predicted (Fig 2, bottom). Group E patients (n = 13) had RL between 4 and $7$ cm H$_2$O/L/s and an average $Pt.90$ of 64 percent predicted, whereas group F patients (n = 8) had RL $>7$ cm H$_2$O/L/s and an average $Pt.90$ of 47 percent predicted (Fig 2, bottom).

Figure 4 illustrates the changes in $Vr$ and $f_e$ in normal subjects and in COPD patients grouped according to their resting transpulmonary resistance. At a given ventilation, group D patients developed $Vr/VC$ ratios similar to that of normal subjects except at $\dot{V}E$ of 30 L/min (Fig 4, top). In contrast, $f_e$ was significantly higher in group D patients in comparison with normal subjects (Fig 4, bottom). Group E patients showed higher $Vr/VC$ ratio and $f_e$ at a given $\dot{V}E$ than those of normal subjects (p<0.05). Finally, group F patients developed the highest increase in $Vr/VC$ ratio for a given $\dot{V}E$ in comparison with normal subjects and the other two groups. However, $f_e$ in this group was similar to that of group D and E patients except at $\dot{V}E$ of 30 L/min (Fig 4, bottom).

Figure 5 is an attempt to assess the separate and combined influences of loss of elastic recoil and increasing lung resistance on the exercise pattern of breathing as expressed by K. Because of the small number of patients in some compartments, the conclusion is only tentative. Patients are grouped by values of increasing resistance, x-axis, and decreasing elastic recoil, y-axis. For the same range of minimally increased resistance (x-axis), loss of elastic recoil (y-axis) results in an increase in K value (0.0083 to 0.0093 to 0.014) (vertical arrow), and for a mean normal elastic recoil range (75 to 100 percent predicted), increase in pulmonary resistance results in an increase in K value (0.0083 to 0.0112 to 0.0205,

**Figure 2.** The relationship between $Pt.90$ and lung resistance in patients with COPD. Top, The horizontal lines indicate the values of $Pt.90$ used to divide the patients into three groups according to their $Pt.90$. Bottom, The vertical lines indicate the values of lung resistance used to divide the patients into three subgroups according to their RL.

**Figure 3.** Tidal volume per vital capacity (top) and breathing frequency (bottom) to minute ventilation relationships during incremental exercise of normal subjects and COPD patients divided according to their $Pt.90$. 

**Minute Ventilation (l/min)**

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Pattern of Breathing During Exercise in Patients With COPD (Marin et al)
breathing frequency changes slightly, whereas tidal volume increases progressively, reaching a plateau value of about 50 percent of the vital capacity. Further increase in ventilation will, therefore, be achieved by increasing the breathing frequency. Jones et al. have recently challenged the above view of the changes in breathing pattern during exercise in normal subjects by describing a continuous increase in the tidal volume without reaching a single plateau value. In addition, these authors proposed that the curvilinear relationship between VT and VE during exercise could be described by fitting the data into an exponential formula.

It is widely believed that patients with COPD are ventilatory limited during exercise due to impaired pulmonary mechanics. Indeed, whereas VE reaches 60 to 80 percent of MVV during exercise in normal subjects, patients with COPD achieve a VE close to their MVV. Airflow limitation is the prime feature in patients with COPD and is a consequence of both a loss in elastic recoil pressure and a reduction in airway diameter with increases in resistance.

The breathing strategies of patients with COPD during exercise have been described considering COPD patients as a homogeneous group. In general, the prevailing concept is that exercise COPD patients breathe with smaller VT and greater f0 compared with normal subjects. For example, to achieve a VE of 30 L/min during exercise, patients with COPD breathe at a VT of 1 L and f0 of 30/min, whereas normal subjects breathe at a f0 of 20/min. Furthermore, patients with COPD appear to reach their maximum ventilation at workloads lower than in normal subjects. The abnormal breathing pattern of patients with COPD appears to be specific to the performance of exercise. Patients with COPD are known to breathe with higher VT and slower f0 to achieve a VE during CO2 rebreathing compared with exercise.
It is becoming more apparent that COPD is not a homogeneous disease and predominant recoil abnormalities or predominant resistance abnormalities might be found in these patients. It is conceivable that the pattern of breathing may be different depending on predominant alterations of either resistance or elastic recoil abnormalities. Attempts to describe the breathing pattern of COPD patients during exercise according to the severity of the disease has been scanty. Spiro et al. compared the breathing pattern during incremental exercise of patients with COPD to that of age-matched normal subjects. Patients with moderate (FEV\textsubscript{1}, 49 percent predicted) and severe (FEV\textsubscript{1}, 24 percent predicted) airway obstruction showed a greater ventilation at V\textsubscript{O2} of 0.75 and 1.0 L/min in comparison with normal subjects. However, there was no significant difference between the two groups of patients. Furthermore, absolute V\textsubscript{T} for a given V\textsubscript{E} was smaller in both groups of patients compared with normal subjects. In a more recent study, Gimenez et al. have demonstrated during incremental exercise that severely obstructed COPD patients (FEV\textsubscript{1}, 1.06 L) achieved greater increase in breathing frequencies and smaller tidal volumes (absolute value) for a given V\textsubscript{E} when compared with normal subjects (FEV\textsubscript{1}, 3.7 L). By comparison, only f\textsubscript{i} was higher in patients with moderate obstruction (FEV\textsubscript{1}, 2.1 L) compared with normal subjects. Our results suggest that the severity of the disease, expressed as alterations of lung mechanics and especially elastic recoil or resistance abnormalities, has an important influence on breathing pattern during exercise. The first abnormality in the breathing pattern of COPD patients appears to be the increase in breathing frequency. That was evident in patients with mild abnormalities in elastic recoil and lung resistance (group 1). As the severity of the disease process increases (groups 2 and 3), the second abnormality in the breathing pattern, namely, the progressive increase in V\textsubscript{T}/VC, became more apparent.

The mechanisms leading to the changes in breathing pattern in COPD patients are complex and may involve mechanical (changes in Pt\textsubscript{O2} and RL), chemical (arterial CO\textsubscript{2}, pH), neural (reflexes from the lung, chest wall, and limb muscles), or cardiovascular (changes in cardiac output or systemic blood pressure) factors. Discussion of these factors is beyond the scope of this article; however, we may speculate about the consequence of the breathing pattern adopted by patients with COPD, namely, higher f\textsubscript{i} and smaller V\textsubscript{T} compared with normal subjects. Traditionally, higher f\textsubscript{i} in patients with COPD has been viewed as a mechanism by which to reduce the elastic work done on the lung by the inspiratory muscles. Accordingly, this mechanism was considered as advantageous with respect to respiratory muscle energy require-

ment. However, this explanation does not take into account the problem of dynamic hyperinflation in these patients, especially during high frequencies of breathing.

Recently, Younes published a model simulation of the relationship among mean inspiratory pressure, V\textsubscript{E}, V\textsubscript{T}, and f\textsubscript{i} in normal subjects and in patients with COPD. In normal subjects, increasing V\textsubscript{E} at a given rate of respiratory muscle activation can be achieved by increasing V\textsubscript{T} and f\textsubscript{i}. However, there exists a critical f\textsubscript{i} above which the increase in V\textsubscript{E} becomes minimal because of dynamic hyperinflation leading to a progressive increase in expiratory reserve volume, and hence, reduction in V\textsubscript{T}. According to the model simulation, the magnitude of dynamic hyperinflation at a given f\textsubscript{i} in COPD patients is more severe than in normal subjects, leading to a larger increase in the expiratory reserve volume (smaller V\textsubscript{T}) as compared with normal subjects. In addition to the f\textsubscript{i} and the severity of lung damage, the magnitude of dynamic hyperinflation increases with an increasing degree of inspiratory muscle activation. It follows that with the progression of the disease, patients with COPD become progressively more dependent on peak inspiratory activity to increase V\textsubscript{E}. Accordingly, the breathing pattern adopted by our patients, namely, higher breathing frequency as compared with normal subjects, is detrimental to inspiratory muscle economy. On the other hand, while f\textsubscript{i} of COPD patients was higher than that of normal subjects, there was no difference in the f\textsubscript{i} achieved by patients with different severity of the disease. We speculate that patients with moderately severe COPD have achieved the critical f\textsubscript{i}, above which a greater recruitment of inspiratory muscle is required in order to increase V\textsubscript{E}. Consequently, patients with more severe COPD are forced to increase V\textsubscript{T} (as percent of VC) so as to achieve higher V\textsubscript{E}. Indeed, the ratio of V\textsubscript{T}/VC at a given V\textsubscript{E} increased with increasing severity of the disease. An alternative mechanism by which these patients may minimize the energy requirement of the inspiratory muscles is to reduce the duty cycle (the ratio of inspiratory time to total duration of breathing cycle). Lower duty cycles at a given f\textsubscript{i} may also result in the reduction of dynamic hyperinflation, thus leading to an increase in the V\textsubscript{T}. Unfortunately, duty cycle has not been measured in our study and, therefore, this mechanism remains speculative.

In summary, the earliest changes in the pattern of breathing during exercise in COPD patients appears to be an increase in breathing frequency. In addition, with lower FEV\textsubscript{1}, the other changes seen include the increase in the proportion of vital capacity used as tidal volume and the time course taken for tidal volume to increase (K values). Finally, resting transpulmonary resistance seems to have a larger influence on the
exercise breathing pattern than changes in pulmonary elastic recoil.

REFERENCES

2 Hey EM, Lloyd BB, Cunningham DCJ, Jukes MGM, Bolton DPG. Effects of various respiratory stimuli on the depth and frequency of breathing in man. Respir Physiol 1966; 1:193-205
3 Kay JDS, Petersen ES, Vejby-Christensen H. Mean and breath by breath pattern during steady state exercise. J Physiol 1975; 251:657-69
8 Jones NL, Campbell EJM. Clinical exercise testing. 2nd ed. Philadelphia: WB Saunders, 1982
20 Hey EM, Lloyd BB, Cunningham DJC, Jukes MGM, Bolton DPG. Effects of various respiratory stimuli on the depth and frequency of breathing in man. Respir Physiol 1966; 1:193-205