Ventilatory response to incremental and constant-workload exercise in the presence of a thoracic restriction

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O’Connor, Sinéad, Paul McLoughlin, Charles G. Gallagher, and Helen R. Harty. Ventilatory response to incremental and constant-workload exercise in the presence of a thoracic restriction. J Appl Physiol 89: 2179–2186, 2000.—In the presence of an externally applied thoracic restriction, conflicting ventilatory responses to exercise have been reported, which could be accounted for by differences in exercise protocol. Seven male subjects performed two incremental and two constant-workload ergometer tests either unrestricted or in the presence of an inelastic corset. Ventilatory variables and arterial estimates of Pco2 were obtained breath by breath. Subjects hyperventilated in the presence of restriction during the constant-workload test (38.4 ± 3.0 vs. 32.8 ± 3.0 l/min for the average of the last 3 min of exercise, P < 0.05), whereas, at an equivalent workload during the incremental test, ventilation was similar to unrestricted values (unrestricted = 26.3 ± 1.6 vs. restricted = 27.9 ± 2.3 l/min, P = 0.36). We used a first-order linear model to describe the effects of change in workload on minute ventilation (24). When the time constants and minute ventilation values measured during unrestricted and restricted constant-workload exercise were used to predict the ventilatory response to the respective incremental exercise tests, no significant difference was observed. This suggests that hyperventilation is not seen in the restricted incremental test because the temporal dynamics of the ventilatory response are altered.

exercise protocol; time constant; predicted minute ventilation

RESTRICTIVE LUNG DISEASE is a term used broadly to describe a number of restricted disease states, including diseases of the pleura, chest wall, or lung parenchyma (interstitial lung diseases). Methods of mimicking the effects of restrictive chest wall disease have been devised and include external thoracic restriction (1, 3, 5, 7–10, 14, 17, 21–23) and abdominal restriction (1, 3, 5, 10, 17, 22, 23).

In subjects who performed incremental exercise in the presence of an inelastic corset, maximum minute ventilation (Ve) decreased compared with the unrestricted condition (22). Unaltered or reduced maximum Ve was reported for patients with scoliosis performing incremental exercise (6, 12, 13, 18). In marked contrast, most studies of the ventilatory response to constant-workload exercise performed by normal subjects in the presence of restriction and by patients with interstitial lung disease demonstrated hyperventilation (9, 15, 19), although a single study reported no change in Ve from normal (10). Possible explanations for the discrepancy of results between incremental and constant-workload tests in different studies include differences in subject characteristics and the degree of restriction present, either as a consequence of the disease state or from the application of an external thoracic restriction. Alternatively, chest wall restriction may affect the ventilatory response to incremental and constant-workload exercise in different ways.

It has previously been shown that the ventilatory response to constant-workload exercise performed below the gas-exchange threshold (GET) is well described by a monoexponential function characterized by a time constant and a steady-state ventilation value (24). This implies that the ventilatory response to exercise depends not only on the workload at any time but also on the rate at which the workload changes. Thus it is possible that, if, as previously reported, the steady-state response of the system increases during thoracic restriction, an appropriate prolongation of the time constant would allow the ventilatory response to an incremental exercise test to remain unchanged.

The aim of this study was to investigate the ventilatory response to incremental and constant-workload exercise in the presence of an externally applied thoracic restriction in a single group of subjects and to determine whether the differing effects are a result of differing exercise protocols. We also used a previously described model (24) to determine whether altered ventilatory dynamics due to thoracic restriction, i.e., an increased steady-state value for Ve and an appropriately prolonged time constant, could account for the observed ventilatory responses to the two exercise protocols.

METHODS

Subjects. Seven male subjects who had never engaged in aerobic training were recruited. No subject had any history of
Ventricular response to restricted exercise

An estimate of arterial blood O2 saturation was obtained with syringe and precision O2 and CO2 gas mixes (Sensormedics). Calibrations were carried out before each test by using a calibration (infrared) analyzers (Sensormedics Vmax 229). Calibrations were repeated after every test.

The subjects attended the laboratory on three different occasions and completed four exercise tests on an electrically braked cycle ergometer (Excalibur, Lode, Groningen, The Netherlands). These included two ramped exercise tests to exhaustion, one performed in the presence and one in the absence of a thoracic restriction, and two constant-workload exercise tests, performed either in the presence or absence of a thoracic restriction. On days 1 and 2, subjects performed an incremental exercise test, and on day 3 subjects performed the two constant-workload exercise tests. The subjects' work rate was independent of pedaling frequency, and they were instructed to maintain the cadence between 50–80 rpm throughout all tests. Restriction of the movement of the rib cage was achieved by use of an inexpandable corset (T&S Surgical Appliances) that was fitted to the subject after he had expired to residual volume and that was tightened with the aid of Velcro straps to achieve a minimum reduction in forced vital capacity (FVC) of at least 35%.

Measurements. Subjects wore a nose clip and mouthpiece connected to a heated wire anemometer (Sensormedics) that allowed inspiratory and expiratory flows to be measured continuously. Signals were digitally integrated to obtain volume measurements. Respired gases were continuously analyzed by rapidly responding O2 (paramagnetic) and CO2 (infrared) analyzers (Sensormedics Vmax 229). Calibrations were carried out before each test by using a calibration syringe and precision O2 and CO2 gas mixes (Sensormedics). An estimate of arterial blood O2 saturation was obtained continuously by using pulse oximetry (Biox 3740, Ohmeda, Louisville, KY), with the probe positioned on the earlobe. Immediately before exercise, a topval vasodilator (Ralgex, SmithKline Beecham Health Care), the active ingredient of which is capsaicin, was applied to the earlobe to ensure adequate tissue perfusion. Heart rate was monitored continuously by means of a three-lead electrocardiogram. From this, a bipolar signal was obtained, and heart rate was determined. A visual analog scale was utilized for assessing the subjects' respiratory discomfort, which was rated by each subject by moving a dial that was linked to a needle on an analog display positioned on the handlebars of the ergometer. This dial moved the needle between two labeled extremes of respiratory discomfort, the far left indicating no urge to breathe and the far right representing maximum urge to breathe. Respiratory discomfort ratings were made every minute in response to a verbal command. After each rating was recorded, the needle was moved back to the zero position to reduce any effect a previous score might have on the next. All of these signals were digitized, and values were stored on a breath-by-breath basis for later analysis.

Spirometry was performed by using the spirometry module of the Vmax 229 system. Pulmonary function testing was performed in the seated position for a minimum of three efforts and gave values for FVC and forced expiratory volume in 1 s (FEV1). For unrestricted exercise tests, forced spirometry was undertaken before and immediately after exercise. For restricted exercise tests, the pulmonary function tests were undertaken without and with restriction before the onset of exercise and after exercise.

Incremental exercise tests. On the first and second visit to the laboratory, subjects performed an incremental exercise test in either the absence or presence of a thoracic restriction. The order of these tests was randomized. Subjects commenced exercise on the cycle ergometer at an initial load of 20 W for the first minute of the test. The work rate of the ergometer was subsequently increased in a continuous ramp at a rate of 20 W/min until the subject was unable to continue. Throughout the tests, subjects were verbally encouraged to exercise to exhaustion.

Constant-workload exercise tests. On the final visit to the laboratory, each subject initially performed a 12-min unrestricted, constant-workload exercise test at a predetermined workload. This work level was set to achieve a load equivalent to midway between 20 W and the GET. The GET was determined from the unrestricted incremental test. After a 1-h break, subjects then performed a second 12-min constant-workload exercise test, at the same workload, in the presence of a restriction. Each 12-min test was preceded by a 1-min rest period and a 4-min warm-up at a load of 20 W.

To avoid day-to-day variability in ventilatory and gas-exchange responses, the two constant-workload exercise tests were performed on the same day. Recovery after subthreshold exercise of short duration is rapid and in the absence of restriction, two such tests performed at an interval of 1 h should elicit identical V˙E and gas-exchange responses (25). Preliminary studies showed that thoracic restriction induced alterations in FEV1 and FVC that had not returned to prerestriction values 1 h after the removal of the restriction. For this reason, the unrestricted exercise test always preceded the restricted exercise test.

Calculations. Expired Ve and O2 uptake (VO2) were calculated by using standard formulas. Breath-by-breath endtidal CO2 readings were adjusted by using the Jones correction equation (11) to give an estimate of arterial CO2. The GET was identified by using the modified V-slope method of Sue et al. (20). European Community for Coal and Steel Working Party prediction equations were used when calculating predicted values of FVC and FEV1 (16).

Predicting incremental Ve from a constant-workload test. The phase 2 ventilatory component of constant-load exercise of moderate intensity has been described by a monoexponential function of the form

\[
\Delta V_e(t)_{cwl} = \Delta V_e(ss)(1 - e^{-\tau})
\]

where \(\Delta V_e(t)_{cwl}\) represents the difference between \(V_e\) at any time \(t\) after the onset of constant-workload exercise and the mean \(V_e\) during the last minute of cycling at 20 W, \(\Delta V_e(ss)\) is the difference between mean final steady-state \(V_e\) (average of final 3 min of constant-workload exercise) and mean \(V_e\) at 20 W (see above), and \(\tau\) is the phase 2 time constant (24). The value for \(\tau\) is obtained graphically by plotting \(\Delta V_e(ss) - \Delta V_e(t)_{cwl}\) against time (excluding the phase 1 component of the response) on a semilogarithmic scale. The \(\tau\) value is then derived from the slope of the resulting straight line. During a ramped exercise test, \(V_e\) at any workload will be less than \(V_e\) at that workload in a constant-workload steady-state test (24) because of the time delay in the ventilatory response. The change in \(V_e\) at any time \(t\) during a ramped incremental test \(\Delta V_e(t)_{incr}\) is given by

\[
\Delta V_e(t)_{incr} = \Delta V_e(ss)_{pred}[t - \tau(1 - e^{-\tau})]
\]

where \(\Delta V_e(ss)_{pred}\) is the change in \(V_e\) that would occur after the change in workload at time \(t\) if a steady state were achieved.
In the sub-lactate-threshold range, the relationship between \( \Delta V^E_{ss} \) and the corresponding increase in steady-state workload above 20 W [\( \Delta W_{ss} \)] is linear and is given by

\[
\Delta V^E_{ss} = s \Delta W_{ss}
\]

(3)

where \( s \) is a constant of proportionality. Furthermore, \( \Delta W \) at any time \( t \) during an incremental test [\( \Delta W(t)_{inc} \)] is represented by

\[
\Delta W(t)_{inc} = bt
\]

(4)

where \( b \) represents the work rate ramp. Combining Eqs. 2, 3, and 4 gives the following equation

\[
\Delta V^E(t)_{inc} = sb[t - \tau(1 - e^{-\lambda t})]
\]

(5)

Equation 5 was used to predict \( V^E \) for any time \( t \) in the ramped incremental tests with use of the time constant derived from the constant-workload exercise test (Eq. 1).

**Data analysis.** All restricted spirometry data were expressed as percentages of the unrestricted value.

In the unrestricted and restricted incremental exercise tests, cardiorespiratory variables were averaged over 20-W intervals. During the tests, the value of a variable for any 20-W period was expressed as the change (\( \Delta \)) from the value during warm-up cycling at 20 W (mean value over the minute before change in workload).

For the constant-workload exercise tests, a similar analysis was applied to measured variables to produce \( \Delta \) values with the last minute of the 4-min warm-up at 20 W being subtracted from the mean value obtained at each minute interval. Values for \( \Delta \) were then averaged for the last 3 min of exercise in a single individual, and this value was taken as the steady-state response of that individual.

To allow for a direct comparison between the two exercise protocols, values at the end of the submaximal constant-workload exercise tests would need to be compared with values at an equivalent workload in the incremental exercise tests. Therefore, the workload at which the subjects exercised in the constant-workload test was identified in the incremental test, and the variables were compared with the average value of the variables for the last 3 min of constant-workload exercise.

**Statistical analysis.** The mean spirometric values obtained for the restricted condition on the consecutive days of restriction and also before and after exercise were compared by using paired \( t \)-analysis. For the incremental tests, the \( \Delta \) values were compared between the two experimental conditions for workloads that all subjects completed by using an appropriately designed ANOVA. Paired \( t \)-tests were performed on maximum data (last minute of exercise). The average of the last 3 min of constant-workload exercise was compared between the two conditions by using paired \( t \)-analysis. For a direct comparison between the two exercise protocols, a paired \( t \)-test was performed between the two conditions in the incremental test and between the two conditions at an equivalent workload in the constant-workload test. A paired \( t \)-test was used to compare the calculated phase 2 time constants and predicted \( V^E \) for the unrestricted and restricted incremental tests. An ANOVA for repeated measures was performed between the unrestricted and restricted conditions for predicted ventilatory data at three different workloads (20, 40, and 60 W). In all comparisons, \( P < 0.05 \) was taken to indicate statistical significance. All data are shown as means \( \pm SE \).

**RESULTS**

All seven subjects completed the four exercise tests. Anthropometric and pulmonary function data in the unrestricted condition are shown in Table 1. Each subject was within the normal predicted range of FVC and FEV1.

**Pulmonary function tests.** Table 2 shows the mean \( \pm SE \) spirometric values during restriction before and after exercise expressed as percentages of the unrestricted value for the incremental and constant-workload exercise tests. There were no significant differences between the percentage decreases in FVC and FEV1 from before to after exercise, indicating that the degree of restriction was maintained throughout exercise in the incremental and constant-workload exercise tests. It can be seen that subjects were restricted by the same amount on both occasions.

**Incremental exercise tests.** Figure 1 illustrates \( \Delta \text{mean} \pm SE \) values for workloads that all subjects completed and also for maximum exercise in the presence and absence of restriction.

No difference in total \( V^E \) was observed between the unrestricted and restricted conditions at submaximal exercise workloads (Fig. 1A). There was no evidence of alveolar hyperventilation at these submaximal workloads because there were no differences in the PCO2 values between the two conditions (Fig. 1B). With restriction, there was a trend for respiratory frequency to be increased and tidal volume to be decreased at submaximal workloads (Fig. 1, C and D).

Table 3 shows absolute values recorded at peak workloads for the two conditions. At maximum exercise, peak \( V^E \) was significantly reduced in the presence of restriction (Table 3). Respiratory frequency was significantly increased and tidal volume signif-

### Table 1. Anthropometric and spirometric data

<table>
<thead>
<tr>
<th>Subject no.</th>
<th>Age, yr</th>
<th>Height, cm</th>
<th>Weight, kg</th>
<th>FVC, liters</th>
<th>FEV1, liters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28</td>
<td>170.0</td>
<td>70.0</td>
<td>5.9</td>
<td>5.1</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>176.0</td>
<td>68.0</td>
<td>5.7</td>
<td>4.7</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>180.0</td>
<td>75.0</td>
<td>5.6</td>
<td>4.9</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>185.0</td>
<td>63.0</td>
<td>5.1</td>
<td>4.1</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>190.0</td>
<td>81.0</td>
<td>6.2</td>
<td>5.7</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>184.0</td>
<td>80.0</td>
<td>5.4</td>
<td>4.9</td>
</tr>
<tr>
<td>7</td>
<td>23</td>
<td>183.0</td>
<td>81.0</td>
<td>6.3</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Mean \( \pm SE \) 24.1 \( \pm 0.9 \) 182.0 \( \pm 2.0 \) 75.0 \( \pm 2.6 \) 5.7 \( \pm 0.2 \) 4.9 \( \pm 0.2 \)

FVC, forced vital capacity; FEV1, forced expiratory volume in 1 s.

### Table 2. Spirometric values before and after exercise in the restricted condition during incremental and constant workload tests

<table>
<thead>
<tr>
<th>Workload</th>
<th>FVC, %</th>
<th>FEV1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
</tbody>
</table>

Incremental test 42.4 \( \pm 3.1 \) 39.9 \( \pm 3.3 \) 41.5 \( \pm 3.2 \) 39.6 \( \pm 3.6 \)

Constant-workload test 39.8 \( \pm 3.1 \) 38.0 \( \pm 2.8 \) 38.5 \( \pm 3.4 \) 37.6 \( \pm 4.3 \)

Values are means \( \pm SE \) expressed as a percentage of the unrestricted values. Pre, before exercise; Post, after exercise.
During constant-workload exercise, chest restriction resulted in a significant increase in total \( V_e \) (Fig. 2A). A concomitant significant drop in \( PCO_2 \) values (Fig. 2B) suggested alveolar hyperventilation. Although respiratory frequency increased at all time points throughout the test, the increase failed to reach significance for the average of the last 3 min of exercise (Fig. 2C). The \( VO_2 \) value at the end of exercise, expressed as the average of the last 3 min of the constant-workload test, did not differ between conditions.

Comparison between incremental and constant-workload exercise tests. Table 4 shows the absolute mean ± SE for the average of the final 3 min of constant-workload exercise and at an equivalent workload for incremental exercise. Total \( V_e \) was significantly increased in the constant-workload test in the presence of restriction compared with the unrestricted state. In the incremental exercise test at an equivalent workload, no difference in ventilation was revealed between the unrestricted and restricted conditions. A significant drop in \( PCO_2 \) during the restricted constant-workload test confirmed the presence of an alveolar hyperventilation, whereas no difference was observed for \( PCO_2 \) in the incremental tests. In both exercise protocols, respiratory frequency was significantly increased in the presence of restriction. Tidal volume was significantly decreased in the constant-workload test but not in the incremental test in the presence of restriction. Visual analog scale scores of respiratory discomfort were significantly increased in both the constant-workload test and the incremental test in the presence of restriction.

Predicting incremental \( V_e \) from a constant-workload test. After the onset of constant-workload exercise, \( V_e \) appeared to follow the pattern of a monoexponential function, as shown in Fig. 3A, which represents a typical response of one individual to unrestricted and restricted constant-workload exercise. A log plot of the same individual’s unrestricted and restricted ventilatory data resulted in a linear pattern, as shown in Fig. 3B. Also depicted in this figure are the equations of the lines of best fit from which the time constants were derived.

<table>
<thead>
<tr>
<th>Table 3. Absolute values shown for final minute of maximum exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>( V_e ), l/min</td>
</tr>
<tr>
<td>( PCO_2 ), Torr</td>
</tr>
<tr>
<td>( f ), breaths/min</td>
</tr>
<tr>
<td>( VT ), liters</td>
</tr>
<tr>
<td>( S_aO_2 ), %</td>
</tr>
<tr>
<td>( VAS ), %</td>
</tr>
<tr>
<td>( HR ), beats/min</td>
</tr>
<tr>
<td>( VO_2 ), ml·kg⁻¹·min⁻¹</td>
</tr>
</tbody>
</table>

Values are means ± SE. \( V_e \), minute ventilation; \( PCO_2 \), Jones-corrected \( CO_2 \); \( f \), respiratory frequency; \( VT \), tidal volume; \( S_aO_2 \), estimate of arterial blood \( O_2 \) saturation; \( VAS \), visual analog scale scores of respiratory discomfort; \( HR \), heart rate; \( VO_2 \), \( O_2 \) consumption.

* Significant difference between two conditions (\( P < 0.05 \), paired \( t \)-test).
Table 5 shows the individual and mean time constants and VE values for the unrestricted and restricted conditions. In the restricted condition, the mean steady-state VE value and the mean time constant were significantly increased compared with the unrestricted condition. We then asked the following question: do the altered steady-state VE and time constant values derived in the presence of restriction predict a ventilatory response to incremental exercise similar to that predicted in the unrestricted condition? To examine this, the ventilatory response of each individual to unrestricted and restricted incremental exercise at 20, 40, and 60 W was predicted by using each individual’s steady-state VE and time constant values. The mean predicted values at each of these workloads are shown in Table 6. There were no significant differences between the unrestricted and restricted conditions.

The 20-, 40-, and 60-W workload levels were arbitrarily chosen, but the model can also be used to predict VE at any given workload. Figure 4 is an illustration of the predicted VE for the unrestricted and restricted conditions in which the mean ΔVE(ss) and time constants in both conditions were used (Table 5) and substituted into Eq. 5. Despite the differences in time constants and steady-state values for ventilation between the unrestricted and restricted constant-workload exercise tests, similar ventilatory values were predicted for the unrestricted and restricted incremental tests. The VE data were not predicted for workloads >60 W because, at higher workloads, some subjects had reached their GET and their ventilatory responses had become nonlinear. Because this model assumes a linear relationship between steady-state ventilation and workload, model predictions above the GET would be invalid.

DISCUSSION

The findings of the present study indicate that, in the presence of an externally applied thoracic restriction, the ventilatory response to exercise is dependent on the protocol utilized. Subjects hyperventilated in the presence of restriction during the constant-workload test, whereas, at an equivalent workload during the incremental test, ventilation was similar to unrestricted values. VE was predicted for the unrestricted and restricted incremental tests by using the time constants and steady-state values for VE from the constant-workload tests, and no differences were found in the predicted ventilatory data for the two conditions. This would suggest that a hyperventilation does not occur in the restricted incremental test because of

Table 4. Absolute values shown for final 3 minutes of constant-workload exercise (average) and at an equivalent workload for incremental exercise

<table>
<thead>
<tr>
<th></th>
<th>Constant Workload</th>
<th>Incremental</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unrestricted</td>
<td>Restricted</td>
</tr>
<tr>
<td>VE, l/min</td>
<td>32.8±3.0</td>
<td>38.4±2.9*</td>
</tr>
<tr>
<td>PCO₂, Torr</td>
<td>40.9±0.8</td>
<td>38.7±1.2*</td>
</tr>
<tr>
<td>f, breaths/min</td>
<td>23.3±1.5</td>
<td>34.7±3.5*</td>
</tr>
<tr>
<td>Vt, liters</td>
<td>1.5±0.2</td>
<td>1.1±0.1*</td>
</tr>
<tr>
<td>SaO₂, %</td>
<td>96.3±0.2</td>
<td>95.9±0.2</td>
</tr>
<tr>
<td>VAS, %</td>
<td>29.4±8.0</td>
<td>51.2±5.8*</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>121.5±5.5</td>
<td>127.3±4.3*</td>
</tr>
<tr>
<td>VO₂, ml·kg⁻¹·min⁻¹</td>
<td>16.2±1.4</td>
<td>15.1±1.1</td>
</tr>
</tbody>
</table>

Values are means ± SE. *Significant difference between two conditions in the constant-workload test (P < 0.05, paired t-test); †significant difference between the two conditions in the incremental test (P < 0.05, paired t-test).
slower ventilatory dynamics, because it takes almost twice as long to reach a given ventilation in the presence of an externally applied thoracic restriction as in the unrestricted state. Whereas earlier studies have described the ventilatory response to either incremental or constant-workload exercise in the presence of a thoracic restriction (9, 10, 22), this was the first study to document the ventilatory response to both incremental and constant-workload exercise in the same subject group, and, for the first time, it has been shown that the differing ventilatory responses reported in the literature are a result of the varying exercise protocols.

During incremental exercise in the present study, a lower peak $V\dot{E}$ was reported in the presence of the restriction, reflecting a lower maximum $O_2$ consumption. At submaximal workloads during these tests, no differences were found in total ventilation between the unrestricted and restricted protocols. Also, no differences were observed for calculated alveolar $V\dot{E}$ between the two conditions at these lower workloads, because there were no differences in the $PCO_2$ values reported.

In a previous study (22), an incremental exercise test elicited a significantly lower $V\dot{E}$ at maximum exercise for similar levels of thoracic restriction. However, the authors failed to report any ventilatory data at submaximal workloads in the incremental tests, and, because the $PCO_2$ values were not documented, there is no indication of what was happening to alveolar $V\dot{E}$. In the present study, the constant-workload exercise tests were performed at a workload below the GET. This mild level of work was chosen to ensure that the ventilatory response observed was independent of the effects of increasing concentrations of circulating lactic acid. Because recovery after subthreshold exercise of short duration is rapid (25), an interval of 1 h between the unrestricted and restricted constant-workload exercise tests was of adequate duration to return $V\dot{E}$ and gas-exchange parameters to baseline values. Because the exercise load was set at a low level, it is highly unlikely to have induced an altered ventilatory re-

![Diagram A](image1)

**Fig. 3.** A: 10-s averages of minute ventilation ($V\dot{E}$) for 4-min warm-up and 12 min of exercise in 1 subject exhibiting monoexponential behavior to unrestricted and restricted constant-workload exercise. B: plot of $ln[\Delta V\dot{E}(ss) - \Delta V\dot{E}(t_{\text{cwl}})]$ (where ss signifies steady state, $t$ time, and cwl constant workload) against time for the same subject in the unrestricted and restricted states for the first 3 min of the test (10-s averages), excluding the warm-up and the first 30 s of exercise. Also included are the equations of the lines of best fit from which the time constants were derived.

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Unrestricted $\tau$, min</th>
<th>Unrestricted $\Delta V\dot{E}$, l/min</th>
<th>Restricted $\tau$, min</th>
<th>Restricted $\Delta V\dot{E}$, l/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td>16.3</td>
<td>1.8</td>
<td>29.6</td>
</tr>
<tr>
<td>2</td>
<td>2.1</td>
<td>6.9</td>
<td>2.8</td>
<td>9.0</td>
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<td>3</td>
<td>1.5</td>
<td>8.0</td>
<td>1.3</td>
<td>8.9</td>
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<td>4</td>
<td>1.7</td>
<td>8.1</td>
<td>2.8</td>
<td>14.8</td>
</tr>
<tr>
<td>5</td>
<td>2.1</td>
<td>13.2</td>
<td>4.2</td>
<td>19.5</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>17.6</td>
<td>1.7</td>
<td>29.6</td>
</tr>
<tr>
<td>7</td>
<td>0.9</td>
<td>13.1</td>
<td>3.3</td>
<td>16.9</td>
</tr>
<tr>
<td>Mean ± SE</td>
<td>1.5 ± 0.2*</td>
<td>11.9 ± 1.6*</td>
<td>2.6 ± 0.4</td>
<td>18.3 ± 3.3*</td>
</tr>
</tbody>
</table>

$\tau$, Time constants; $\Delta V\dot{E}$, change in $V\dot{E}$. *Significant difference between the unrestricted and restricted values ($P < 0.05$, paired $t$-test).

<table>
<thead>
<tr>
<th>$\Delta$Workload, W</th>
<th>Unrestricted $\Delta V\dot{E}_{\text{predicted}}$, l/min</th>
<th>Restricted $\Delta V\dot{E}_{\text{predicted}}$, l/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.4 ± 0.3</td>
<td>1.4 ± 0.4</td>
</tr>
<tr>
<td>40</td>
<td>4.0 ± 0.9</td>
<td>4.2 ± 1.0</td>
</tr>
<tr>
<td>60</td>
<td>7.3 ± 1.5</td>
<td>8.1 ± 1.9</td>
</tr>
</tbody>
</table>

Values are means ± SE. No significant differences between unrestricted and restricted conditions for predicted $\Delta V\dot{E}$ ($\Delta V\dot{E}_{\text{predicted}}$; $P > 0.05$, ANOVA).
response to the second exercise test completed in the presence of restriction. Therefore, the significantly increased VE observed in the presence of restriction is due to the effects of restriction alone.

In the study of Harty et al. (9), subjects exercised at 65% of maximum heart rate, and it is probable that a number of these subjects were exercising above their GET. Therefore, increasing circulating lactic acid levels may have augmented the magnitude of the hyperventilatory response to constant-workload exercise. In contrast to the findings of the above study, Hussain et al. (10) reported that an exercise test performed above the GET produced similar ventilation to that achieved in the unrestricted test. There was no difference in end-tidal PCO\(_2\) between thoracic restriction and control conditions and, therefore, no evidence of a change in alveolar ventilation. However, the authors suggested that because there was evidence of electromyographic diaphragmatic fatigue during exercise in the presence of restriction, subjects were unable to maintain ventilation at the required level to continue exercising.

There is evidence that exercise protocol also affects the ventilatory response to exercise in patient groups. A number of studies performed in scoliotic patients reported either a normal ventilation (6, 18) or a significantly reduced ventilation (12, 13) at maximum incremental exercise. Shneerson et al. (18) documented that there was a trend for a hyperventilation at submaximal workloads during the incremental test, but it failed to reach significance. Similarly, at submaximal workloads during an incremental test performed in patients with pulmonary fibrosis, Burdon et al. (2) found that there was a tendency for ventilation to be higher than normal at each power output during an incremental test, but, once again, it failed to reach significance. Constant-workload exercise tests performed in pulmonary fibrotic patients resulted in a relative hypventilation when the response was compared with normal healthy subjects (15, 19). The results of the present study demonstrate that the differences in the ventilatory response to incremental and constant-workload exercise do not arise because of differences in subject characteristics or degree of restriction. Rather, the differences arose because the effect of restriction on VE was dependent on the manner in which the workload changed.

We asked ourselves the question: how can restriction lead to a hyperventilation in the constant-workload exercise test and yet cause no change in ventilation at submaximal workloads during the incremental test? Whipp et al. (24) have shown that the ventilatory response to mild constant-workload exercise is well described by a first-order linear response system. It has been demonstrated that, by using the derived time constant and measured steady-state value for VE from the constant-workload test, the ventilatory response to incremental exercise is well predicted (24). The results of the present study indicate that the ventilatory response to unrestricted and restricted constant-workload exercise followed the pattern of a first-order linear response system. However, in the presence of the restriction, the mean time constant was significantly greater than the unrestricted value, and the mean change in the steady-state value for VE in the presence of restriction was significantly higher. On the basis of these results, the predicted response to VE below the GET in the incremental test was similar for both the unrestricted and restricted conditions (Fig. 4).

The aim of this study was to document the effects of an externally applied thoracic restriction on the ventilatory response to incremental and constant-workload exercise in the same subject group and to explore potential mechanisms that may explain the disparate responses observed. This study was not designed to address the mechanisms underlying the observed hyperventilation. However, it is the first to provide subjective measures of respiratory discomfort during both exercise conditions, and it is interesting to note that clear differences in the response to incremental and submaximal constant-workload exercise exist. Significant differences were observed in both tests, with the mean values obtained in the constant-workload tests being greater than those observed in the incremental tests in both the unrestricted and restricted conditions. These differences between the incremental and constant-workload tests may reflect temporal differences in the development of the sensory response to exercise in a fashion similar to that seen with ventilation. With regard to the incremental test, in the presence of restriction, the differences cannot be a reflection of an increased level of ventilation. However, in the constant-workload test, some of the increased level of respiratory discomfort could be attributed to the increase in ventilation (26) or the sensory consequences of an inappropriate hyperventilation (4). Direct measures of respiratory mechanics were not made in this study, but increased work of breathing presumably contributed to the increased respiratory discomfort scores observed.

The present study does not reveal the underlying mechanisms through which restriction alters the ventilatory response to exercise. However, the data show that the markedly different responses to the two exer-
exercise protocols can both be accounted for by the same underlying alteration in the response of the ventilatory control system.

In conclusion, the ventilatory response to thoracic restriction is dependent on the protocol utilized, with differing responses being produced in the incremental and constant-workload exercise tests. We can understand these differences by examining both the ventilatory dynamics of the response and the steady-state values for $V_e$ in the presence and absence of restriction.

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REFERENCES


