Exercise responses in patients treated for pulmonary tuberculosis by thoracoplsty

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ABSTRACT Twenty eight subjects (mean age 64 years) who had been treated for tuberculosis by thoracoplsty in the past performed an increasing work rate exercise test, from which maximum oxygen consumption (Vo2max), ventilation and heart rate were measured. Vo2max was significantly lower than predicted, being 0·75 l/min in 17 subjects, 1·0 l/min in 10, and 1·5 l/min in one. Only one subject achieved a heart rate of 85% of the predicted maximum. The ratio of heart rate to oxygen consumption (HR/Vo2) and heart rate at standard interpolated submaximal levels of oxygen uptake at 0·75 l/min (heart rate 0·75) and 1·0 l/min (heart rate 1·0) were normal. Vo2max correlated with ventilation at maximal exercise (VE max) (r = 0·87) and FEV1 (r = 0·47). It did not correlate with resting arterial oxygen or carbon dioxide tensions, FEV1, maximum inspiratory pressure, angle of scoliosis, or number of ribs resected. The relation between ventilation and oxygen consumption (VE/Vo2) and VE at the submaximal levels of oxygen consumption of 0·75 l/min (VE 0·75) and 1·0 l/min (VE 1·0) were normal. In 10 subjects a plateau of breathing frequency (fmax) was reached, after which the increase in ventilation was achieved by a further increase in tidal volume (VT). These subjects showed significantly lower values for the forced expiratory ratio, Vo2max, and VEmax than those with a normal relationship between tidal volume and breathing frequency. VEmax was correlated with FEV1 (r = 0·61), FVC (r = 0·46), maximum VT (r = 0·55), change in VT (r = 0·52), fmax (r = 0·56), and change in breathing frequency (r = 0·72). These results indicate that exercise in patients treated for tuberculosis by thoracoplsty is limited by ventilatory capacity and that this is due to a reduction in both dynamic lung volumes and respiratory frequency.

Introduction

Many patients who were treated for pulmonary tuberculosis by thoracoplsty now report reduced exercise tolerance. The reasons for this have not been established but several factors may be important. Patients with a thoracoplsty have a restrictive ventilatory defect as a result of the operation. This worsens with time because of the thoracic scoliosis that is an almost inevitable long term complication. Airflow obstruction was a common finding in patients with chronic pulmonary tuberculosis during the thoracoplsty era. Cor pulmonale is a late complication in some patients with a thoracoplsty, while in others pulmonary hypertension and right ventricular dysfunction limit exercise before peripheral oedema appears.

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The respiratory and cardiac responses to exercise may be measured during an increasing work load exercise test with calculation of ventilation and heart rate at standard levels of submaximal oxygen uptake. This test has been used in normal subjects and in patients with restrictive lung disease, airflow obstruction, and scoliosis. In normal subjects and those with cardiac disease exercise is limited by circulatory factors whereas ventilation usually limits exercise in patients with lung disease and scoliosis. We have used an increasing work rate test to ascertain whether abnormalities of ventilation or cardiac function, or both, limit the exercise tolerance of patients treated by thoracoplsty.

Subjects and methods

We studied 28 subjects (18 men, 10 women), whose ages ranged from 51 to 76 (mean 64) years. All had
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previously been treated for pulmonary tuberculosis by thoracoplasty. Three patients had had bilateral operations. All the patients gave informed consent.

The number of ribs resected was determined from a chest radiograph and the angle of scoliosis from a radiograph of the thoracic spine, the method described by Cobb being used. The partial pressures of oxygen and carbon dioxide were measured in arterial blood (Pao2 and Paco2) drawn with the patient breathing room air at rest (Radiometer, Copenhagen, ABL 3). FEV1 and forced vital capacity (FVC) were measured with a dry bellows spirometer (Vitalograph). Maximal inspiratory pressure (Pimax) was measured at residual volume in 18 subjects.

Exercise was performed on a treadmill (PK Morgan). The subject breathed through a two way valve (Otis-McKerrow), which delivered expired gas through a mixing chamber to a pneumotachograph (Fleisch No 2) connected to a pressure transducer (Validyne MP 45) and amplifier. The flow signal was integrated (PK Morgan respiratory integrator) and, together with the oxygen and carbon dioxide concentrations of the expired gas, derived by mass spectrometry (Centronics 200 MGA), was recorded continuously on a three channel recorder (Gould 2000S).

Minute volume, gas concentrations, and a 12 lead electrocardiogram were recorded at rest and at a single point during a steady state at or after the end of each level of exercise according to the response times of the monitors. Heart rate was recorded continuously throughout. From the results oxygen uptake and carbon dioxide excretion were derived by manual transcription of chart recorder data into an Apple II plus computer by the formula

\[
\dot{V}O_2 = \left( \frac{1 - F_{I}O_2 - F_{ECO2}}{1 - F_{I}O_2} \times F_{EO2} \right) - F_{EO2} \times \dot{V}E \times (STPD) \times 10^3, ml
\]

where \(F_{EO2}\) and \(F_{ECO2}\) are the fractional concentrations of oxygen and carbon dioxide respectively in expired air and \(F_{EO2}\) the fractional concentration of oxygen in inspired air.

Before exercise baseline measurements were made over three minutes with the patient at rest. The treadmill was started at a speed of 15 m/min (0.9 km/h), which was increased by 15 m/min at one minute intervals. The subjects were encouraged to exercise until compelled to stop by dyspnoea or fatigue, or until a heart rate equal to 85% of the maximum predicted for their age was reached.

Over the range of exercise achieved, the relation between ventilation and oxygen uptake (\(\dot{V}E/\dot{V}O_2\)) and between heart rate and oxygen uptake (HR/\(\dot{V}O_2\)) was linear. The ventilation and heart rate responses to exercise were expressed as the slope of the relation to \(\dot{V}O_2\) (\(\dot{V}E/\dot{V}O_2\), HR/\(\dot{V}O_2\)), maximum values (\(\dot{V}E_{max}, HR_{max}\)), and interpolated values at an oxygen uptake of 0.75 l/min (\(\dot{V}E 0.75, HR 0.75\)), 1.0 l/min (\(\dot{V}E 1.0, HR 1.0\)) and 1.5 l/min (\(\dot{V}E 1.5, HR 1.5\)). The pattern of breathing was assessed as change in tidal volume (VT) and breathing frequency (f) with increasing minute ventilation (\(\dot{V}E\)).

The results were compared with those obtained in normal subjects over the age of 40. Analysis was by comparison of means and Spearman's rank correlation test.

Results*

In the three subjects with bilateral thoracoplasties the upper five ribs had been removed from each side. In the other 25 the number of ribs resected ranged from four to nine (mean 6.6). The Cobb angle ranged from 0° (1 subject) to 61° (mean 25°). The FEV1 was less than the mean predicted value in all 28 subjects; FVC was less than the mean predicted value in 27. The mean (SD) FEV1 was 1.4 (0.6) l and mean (SD) FVC 2.0 (0.8) l. Pao2 ranged from 4.5 to 12.5 kPa, with a mean (SD) of 9.7 (1.8) kPa. Paco2 ranged from 4.9 to 8.8 kPa with a mean (SD) of 6.6 (0.9) kPa. Pao2 correlated with FEV1 (p < 0.05) but not FVC. Paco2 correlated inversely with FEV1 (p < 0.001) and FVC (p < 0.05).

During the increasing work rate test the 28 subjects exercised for one to nine (mean 4.7) minutes. One was limited by intermittent claudication and another by a fixed knee joint affected by old tuberculosis. In the other 26 exercise ability appeared to be limited by cardio-respiratory function. Only one patient

*Tables of individual results may be obtained from the authors.
achieved a heart rate of 85% of the maximum predicted for her age. This was achieved after only two minutes of exercise and coincided with maximum exertion, limited by dyspnoea. Nineteen of the other 25 subjects stopped exercising because of dyspnoea, four were limited by fatigue and two by dizziness.

MAXIMUM OXYGEN UPTAKE

\[ \bar{V}_E \text{max} = 10.99 \text{FEV}_1 + 9.6 \]
\[ n = 26; r = 0.61; p < 0.001 \]

Fig 2  Relation between maximum minute ventilation (\( \bar{V}_E \text{max} \)) and FEV

\[ \bar{V}_E \text{max} \] ranged from 6.8 to 23.1 ml/min/kg body weight (mean (SD) 14.3 (4.3)), and was less than expected from the predicted values of Bruce\(^1\) in all except one subject. Seventeen subjects exercised to an oxygen consumption of 7.75 l/min, 10 reached 1.0 l/min, but only one achieved 1.5 l/min. \( \bar{V}_O_2 \) correlated with \( \bar{V}_E \text{max} \) (r = 0.73, p < 0.001), FEV\(_1\) (r = 0.53, p < 0.01), and to a lesser extent FVC (r = 0.43, p < 0.05). The relation between \( \bar{V}_O_2 \text{max} \) and \( \bar{V}_E \text{max} \) is illustrated in figure 1.

MAXIMUM VENTILATION

\( \bar{V}_E \text{max} \) ranged from 9.0 to 63.5 l/min (mean (SD) 24.7 (411)). It correlated with \( \bar{V}_E \) (r = 0.61, p < 0.01) to a lesser extent with FVC (r = 0.55, p < 0.01), but not with \( P_m \) (r = 0.44, NS). The relation between \( \bar{V}_E \text{max} \) and FEV\(_1\) is illustrated in figure 2.

MINUTE VENTILATION DURING EXERCISE

The response of \( \bar{V}_E \) during exercise is shown in table 1. There were no differences in \( \bar{V}_E/\bar{V}_O_2 \), \( \bar{V}_E \) 0.75, or \( \bar{V}_E \) 1.0.

Table 1  Response of ventilation to exercise (mean (SD) values)

<table>
<thead>
<tr>
<th>Index</th>
<th>Sex</th>
<th>n</th>
<th>Patients (breaths/min)</th>
<th>Normal subjects*</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{V}_E ) rest (l/min)</td>
<td>M</td>
<td>18</td>
<td>10 (0.6)</td>
<td>8 (0.6)</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>10</td>
<td>7.8 (0.6)</td>
<td></td>
</tr>
<tr>
<td>Slope ( \bar{V}_E/\bar{V}_O_2 )</td>
<td>M</td>
<td>18</td>
<td>26.4 (8.5)</td>
<td>23.2 (10.3)</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>10</td>
<td>24.6 (4.7)</td>
<td>27.1 (7.8)</td>
</tr>
<tr>
<td>( \bar{V}_E \text{max} ) (l/min)</td>
<td>M</td>
<td>11</td>
<td>19.5 (3.6)</td>
<td>18.7 (4.5)</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>6</td>
<td>16.8 (2.9)</td>
<td>21.2 (2.4)**</td>
</tr>
<tr>
<td>( \bar{V}_E \text{max} ) (I/min)</td>
<td>M</td>
<td>6</td>
<td>27.5 (7.8)</td>
<td>25.0 (4.5)</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>4</td>
<td>21.4 (3.6)</td>
<td>27.0 (2.7)**</td>
</tr>
</tbody>
</table>

**p < 0.01.

\( \bar{V}_E \) — minute ventilation; \( \bar{V}_O_2 \) — oxygen uptake.

Fig 3  Relation between minute ventilation (\( \bar{V}_E \)) and tidal volume (\( \bar{VT} \)) (Hey plot) in eight patients with a normal breathing pattern.
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**Fig 4** Relation between minute ventilation (VE) and tidal volume (VT) (Hey plot) in 10 patients showing a plateau of breathing frequency.

between the sexes. For the men all values were within 1 SD of the mean value obtained by Spiro et al in normal men over the age of 40. For the women VE/VO₂ was similar to the value obtained in normal women but VE 0.75 and VE 1.0 were lower than expected.

**RELATION OF OXYGEN UPTAKE AND VENTILATION TO OTHER FACTORS**

There were no significant correlations, either for the group as a whole or for either sex, between VO₂max, VEmax, VE/VO₂, VE 0.75, or VE 1.0 and the number of ribs resected, the angle of scoliosis, Pao₂, or Paco₂. VO₂max was correlated with Pimax (Spearman's rho (p) = 0.43, p < 0.05) and VEmax (p = 0.47, p < 0.05).

**PATTERN OF BREATHING**

At rest the typical breathing pattern was a low tidal volume (VT) and high breathing frequency (f). The mean (SD) values for VT and f at rest were 0.46 (0.14) l and 20.9 (4.8) breaths/min. There were significant correlations (table 2) between both maximum tidal volume (VTmax) and the change in tidal volume from

<table>
<thead>
<tr>
<th>Index</th>
<th>Normal breathing pattern (n = 8)</th>
<th>Plateau of breathing frequency (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δf (breaths/min)</td>
<td>18.75 (15.3)</td>
<td>6.5 (4.2)*</td>
</tr>
<tr>
<td>V0₂max (l/min)</td>
<td>1.13 (0.27)</td>
<td>0.76 (0.24)**</td>
</tr>
<tr>
<td>VEmax (l/min)</td>
<td>35.6 (14)</td>
<td>20.1 (6.2)*</td>
</tr>
<tr>
<td>FEV₁ (l)</td>
<td>1.8 (0.6)</td>
<td>1.4 (0.7) NS</td>
</tr>
<tr>
<td>FVC (l)</td>
<td>2.4 (0.9)</td>
<td>2.2 (0.9) NS</td>
</tr>
<tr>
<td>FER %</td>
<td>74.1 (8.8)</td>
<td>62.9 (11.8)*</td>
</tr>
<tr>
<td>ΔVT (l)</td>
<td>0.50 (0.22)</td>
<td>0.35 (0.22) NS</td>
</tr>
<tr>
<td>VTmax (l)</td>
<td>0.97 (0.30)</td>
<td>0.79 (0.33) NS</td>
</tr>
<tr>
<td>fmax (breaths/min)</td>
<td>37.6 (18.1)</td>
<td>27.4 (5.3) NS</td>
</tr>
</tbody>
</table>

* p < 0.05; **p < 0.01.

Δf—change in breathing frequency; ΔVT—change in tidal volume; fmax—maximum breathing frequency; VTmax—maximum tidal volume. Other abbreviations as in tables 1 and 2.
rest to maximum exercise ($\Delta V_r$) and $FEV_{1}$, $FVC$, forced expiratory ratio (FER), $Pao_2$, and $Paco_2$. There were no significant correlations between either maximum breathing frequency ($f_{max}$) or change in breathing frequency from rest to maximum exercise ($\Delta f$) and any of these indices or $P_{imax}$, $V_{Emax}$. $V_{Emax}$ showed a significant correlation with $V_{max}$, $V_r$, $f_{max}$, and $f$.

Analysis of the response in individual subjects showed no change in $V_r$ in two, the small increase in ventilation observed being due to an increase in breathing frequency. These two subjects reached maximum exercise after only one and two minutes respectively. In the other 24 subjects whose exercise was limited by cardiorespiratory function $V_r$ increased linearly, at least during the early stages of exercise. In eight subjects a maximum tidal volume that was lower than normal was reached before the limit of exercise; a further rise in minute ventilation then occurred through an increase in breathing frequency. This is the normal pattern of breathing response to exercise described by Hey et al. and Kelman and Watson. The Hey plot (minute ventilation against $V_r$) for these eight subjects is shown in figure 3. In a further six subjects $V_r$ and $f$ were both increasing when $V_{Emax}$ was reached. This pattern may also be seen in normal people, but is less common.

The other 10 subjects showed an unusual pattern of breathing in response to exercise. They reached their maximum breathing frequency ($f_{max}$) before the last work load, and a further increase in minute ventilation was then achieved by a further rise in $V_t$, with no inflexion point on the Hey plot (fig 4). The influence of a maximum limit in breathing frequency on ventilation in these 10 patients is shown in figures 5 and 6. When these 10 subjects were compared with the eight with the normal breathing pattern (table 3), they showed significantly lower values of $f$, $V_{Omax}$, $V_{Emax}$, $P_{imax}$, and FER. Their values for $FEV_{1}$, $FVC$, $V_r$, $V_{Emax}$, and $f_{max}$ were lower but the differences were not significant. There were no differences in age, resting $Pao_2$, $Paco_2$, tidal volume, or breathing frequency at rest between the two groups.

### Heart Rate
At maximum exercise the heart rate for men ranged from 67 to 140 beats/min (mean (SD) 110.3 (18.5)) and for women from 92 to 150 beats/min (123.6 (19.9)). The heart rate responses to exercise are shown in table 4. HR/$V_{O2}$, HR 0-75, and HR 1-0 are, as expected, greater in women than in men. The values for each index do not differ significantly from the values obtained by Spiro et al. in normal subjects.

### Discussion
These results confirm that patients treated for pulmonary tuberculosis by thoracoplasty have a reduced exercise tolerance. They show that the exercise tolerance of individual patients cannot be predicted from resting arterial blood gas analysis, number of ribs resected, or the angle of scoliosis. Our subjects showed a more limited exercise tolerance than the patients with fibrosing alveolitis, chronic bronchitis, and scoliosis who have been studied in this way.

In normal subjects the limit to exercise is imposed by the circulation. A heart rate of 85% of the predicted maximum was observed in only one of our subjects and maximum exercise and interpolated submaximal indices for heart rate and HR/$V_{O2}$ were normal. This contrasts with patients with restrictive lung disease and obstructive bronchitis, in whom these submaximal indices are increased to compensate for the abnormally low stroke volume, which may result from either a reduction in right heart filling pressure or from left ventricular disease. In our subjects the normal values of HR/$V_{O2}$, HR 0-75, and HR 1-0 suggest that the stroke volume response is not abnormal and that the circulation does not limit exercise.

The correlations between $V_{Omax}$ and the three indices of ventilatory capacity, $V_{Emax}$, $FEV_{1}$, and $FVC$, indicate that it was the reduction in ventilatory capacity that limited exercise. Such correlations are not found in normal subjects but they have been noted in patients with lung disease and scoliosis, in whom exercise is usually limited by ventilation. In patients with interstitial lung disease Burdon et al. found that maximum exercise correlated with $V_{Emax}$. In chronic airflow obstruction most investigators have found that maximum exercise correlates with $FEV_{1}$ when bicycle ergometry but not 12 minute walking distance is used as the index of exercise.

In our subjects the measurements of ventilatory response to submaximal exercise did not show the importance of decreased ventilatory capacity in limiting exercise. Minute ventilation was reported at interpolated values of $V_{O2}$ such as 1-0.1. These values reflect both the intercept of ventilation on the $V_{O2}$ axis and the slope of the ventilatory response. The relation of ventilation to oxygen uptake ($VE/V_{O2}$) was normal.
A normal $\dot{V}E/\dot{V}O_2$ relationship may, however, conceal a high $V_d/V_t$ in conjunction with a rising $P_{CO_2}$ during exercise. Such a relationship has been found in patients with scoliosis and in patients with obstructive bronchitis with an $FEV_1$ of less than 1.0 litre, in both of whom exercise is limited by ventilation. In our series the values of minute ventilation at submaximal levels of exercise were normal in the 11 men who were able to exercise to an oxygen consumption of 0.75 l/min. This differs from results obtained from the patients with scoliosis and severe obstructive bronchitis, where minute volumes at submaximal levels of exercise were greater than normal. The lower than normal values of $\dot{V}E$ 0.75 and $\dot{V}E$ 1.0 seen in our female subjects is unexplained but the numbers of subjects (six and four respectively) were small.

In normal subjects breathing frequency remains constant at the start of exercise while tidal volume increases. Later both tidal volume and breathing frequency increase. In most a plateau of tidal volume is reached and the final increase in ventilation is through a further rise in breathing frequency. Patients with restrictive lung diseases typically respond to exercise by breathing with a lower tidal volume and a rapidly increasing breathing frequency. This pattern of breathing minimises the work of breathing in the presence of decreased lung compliance. Patients with airflow obstruction might be expected to respond to exercise with a large tidal volume and decreased breathing frequency, but they also increase breathing frequency during exercise. Garrard and Lane suggested that in patients with airflow obstruction subjected to carbon dioxide induced hyperpnoea this pattern of response may be explained by the "restrictive defect" imposed by the decrease in chest wall compliance associated with hyperinflation. Patients with airflow obstruction are unable to increase breathing frequency to the same degree as those with restrictive lung disease, however, because of the characteristic reduction in expiratory flow rates. Though there was no correlation between FER and maximum breathing frequency for the group as a whole our 10 subjects with a low maximum breathing frequency had significantly lower values of FER than those with a normal breathing pattern, and they achieved significantly lower levels of $V_{O_2}\text{max}$ and $V\text{emax}$ than did FVC, unlike in restrictive lung disease and scoliosis, where the strongest correlation is with FVC. The pattern is similar to that seen in obstructive bronchitis, emphasizing the importance of airflow obstruction. An unusually low maximum breathing frequency during exercise was associated with greater airflow obstruction and with lower values of $V_{O_2}\text{max}$ and $V\text{emax}$.

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