AN INCREASING WORK RATE TEST FOR ASSESSING THE PHYSIOLOGICAL STRAIN OF SUBMAXIMAL EXERCISE

S. G. SPIRO, E. JUNIPER, P. BOWMAN AND R. H. T. EDWARDS

Department of Medicine, Royal Postgraduate Medical School, Hammersmith Hospital, London

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SUMMARY

1. A progressive exercise test was performed on forty-four male and twenty-nine female healthy Europeans, aged between 20 and 64 years. Values for cardiac frequency (fH) and ventilation (V) were interpolated to standard (submaximal) oxygen uptakes (Vo2) of 0.75 l/min and 1.0 l/min. The tidal volume (Vt) at a ventilation of 20 and 30 l BTPS/min was also determined (Vt 20 and Vt 30 respectively).

2. The slope of the linear relationship between cardiac frequency or ventilation and oxygen uptake (SfH and SV respectively) can be used as a measure of the fitness of an individual, as it indicates the increase in fH or V that is obligatory for an increase in energy expenditure equivalent to an additional oxygen uptake of 1.0 l/min (about the increase necessary for walking on the level at a normal speed). By analogy with the responses of an athlete, a 'fit' subject is one in whom responses are economically low, i.e. SfH and SV are lower than in sedentary individuals. Measures of SfH and SV can also be used to indicate the demands of everyday activities on fH and V.

3. When SfH and SV are related to the individual's capacity to adapt fH and V from resting to predicted maximum values ('adaptation capacity' ACfH and ACV respectively), the resulting index (SfH x 100/ACfH or SV x 100/ACV) expresses the percentage of the adaptation capacity used for an additional energy expenditure equivalent to a Vo2 of 1.0 l/min, and can be considered a measure of the 'physiological strain' of exercise. The effects on exercise responses of differences in body muscle can be allowed for by multiplying this index by lean body mass (LBM). The lower the (size-adjusted) physiological strain index, the fitter the individual subject.

Key words: exercise, ventilation, circulation, normal data.

The maximum oxygen uptake (Vo2 max) has been widely used as the defining index of cardiorespiratory fitness (Robinson, 1938; Astrand, 1952; Astrand, 1960; Shephard, Allen,

Correspondence: Dr R. H. T. Edwards, Department of Medicine, Royal Postgraduate Medical School, Hammersmith Hospital, Du Cane Road, London W12 0HS.

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Benade, Davies, Di Prampero, Hedman, Merriman, Myhre & Simmons, 1968). Direct measurement of $V_{O_2 \text{max}}$ is not generally satisfactory since repeated attempts are often necessary in order to establish the maximum value with certainty. The measurement is of extreme discomfort for the subject. Whilst the risks of exercise tests are small (Rochmis & Blackburn, 1971) they are not negligible, especially in maximal exercise (Jokl & McClellan, 1971).

Several attempts to predict $V_{O_2 \text{max}}$, from the responses to submaximal exercise have been made (Astrand & Rhyming, 1954; Margaria, Aghemo & Rovelli, 1965; Maritz, Morrison, Peter, Strydom & Wyndham, 1961; Von Doebeln, Astrand & Bergström, 1967) but all are open to criticism (Davies, 1968). The predicted $V_{O_2 \text{max}}$, has been used to assess effort tolerance and exercise responses in patients with mitral stenosis (Blackmon, Rowell, Kennedy, Twiss & Conn, 1967) in whom working capacity was limited by the circulation, but the prediction based on $fH_{\text{max}}$, is not useful in assessing patients with a ventilatory limitation to exercise capacity (Armstrong, Workman, Hurt & Roemich, 1969).

There have been several recent attempts to establish reliable indices of submaximal exercise performance which do not depend on the measurement of $V_{O_2 \text{max}}$. (Davies, 1972; Cotes, 1972). The responses of heart rate ($fH$) and ventilation ($V$) at an oxygen uptake of 1·5 l STPD/min have been included in recent population studies (Cotes, Davies, Edholm, Healy & Tanner, 1969; Davies, 1972; Edwards, Miller, Hearn & Cotes, 1972). We have also reported submaximal indices at 0·75 and 1·0 l STPD/min ($fH_{0.75}$, $fH_{1.0}$, $V_{0.75}$, $V_{1.0}$) so that the same concept of fitness and the method of its assessment is equally applicable in athletes, with 'supranormal' exercise performance, and in patients with reduced effort tolerance.

A ‘fit’ person may be considered to be one in whom the increase in $fH$ or $V$ is economically low for a given increase in $V_{O_2}$, i.e. the slopes of the relationships between $fH$ and $V$ with $V_{O_2}$ (SfH and SV respectively) are low. This concept may be taken further by relating the slope (SfH, SV) to an estimate of the individual’s capacity to increase $fH$ or $V$, i.e. the range (termed the ‘adaptation capacity’ $ACfH$, $ACV$) from resting to predicted maximum values. An index, which is a measure of the ‘physiological strain’, is thus obtained:

$$\text{Physiological strain (}% = \frac{\text{SfH} \times 100}{\text{ACfH}}, \frac{\text{SV} \times 100}{\text{ACV}}$$

An individual will then have a larger physiological strain and be less ‘fit’ if a given energy expenditure demands an adaptation of $fH$ or $V$ that is a large proportion of the relevant adaptation capacity. This ‘physiological strain’ concept of fitness is therefore an extension of Darling’s (1947) definition of fitness as ‘the ability... to maintain the various internal equilibria as closely as possible to the resting state during strenuous exertion...’.

**SUBJECTS AND METHODS**

The normal subjects studied (forty-four men and twenty-nine women, aged between 20 and 64 years) were allocated according to age and sex into a younger group aged 20–40 years, and an older group, aged above 40 years. The older subjects came from various walks of life, whereas the majority of persons below 40 years of age were medical or ancillary staff in the hospital. None was in regular athletic training.

A detailed medical history was taken on the day of the study. No subject gave a history of abnormal dyspnoea on exertion or of angina. Height, weight, and skinfold thickness over the biceps, triceps, subscapular and supra-iliac regions, were measured. Lean body mass (LBM) was calculated with the formula of Durnin & Rahaman (1967). Vital capacity and forced
expiratory volume in 1 s (FEV₁) were recorded with a bellows spirometer (McDermott, McDermott & Collins, 1968). Mean anthropometric and spirometric data for the groups studied are shown in Table 1.

Subjects exercised while sitting on an electrically braked cycle ergometer (Elema). They breathed through a low-resistance valve box (Lloyd type) with a dead space of 65 ml. Inspired ventilation was measured with a gas meter (Parkinson Cowan CD4) fitted with a potentiometer and output to a direct writing oscillograph (Mingograf 81). Expired gas was sampled on the distal side of a mixing chamber of 6.0 l capacity. The resistive pressure was less than 0.5 cmH₂O when gas flow through the valve box and mixing chamber was 120 l/min. The composition of mixed expired gas was determined with a paramagnetic O₂ analyser (Servomex OA137) and an infrared CO₂ analyser (URAS Capnograph). Both had electrical outputs to the oscillograph. They were calibrated at frequent intervals with standard gas mixtures analysed with a Lloyd–Haldane apparatus. The reading accuracy of each gas analyser was ±0.03% (absolute concentration). Allowance was made for the sampling delay time of the Capnograph (4 s) and the combined delay and response times of the Servomex (20 s). Oxygen uptake was calculated from inspired ventilation and expired gas composition measurements after applying a nitrogen correction (Cotes, 1968). Measurements of VO₂ by this technique, at rest and on exercise, agreed within 5% with simultaneous measurements based on chemical analysis of expired gas collected in Douglas bags.

Subjects rested on the cycle ergometer until recorded expired gas composition, inspired ventilation and cardiac frequency (obtained from the continuously recorded ECG) were steady. Subjects started to pedal at 60 rev./min, the work rate increasing from 16.7 W (100 kpm/min) by 16.7 W each minute. The younger subjects were encouraged to carry on exercising until they were unable to continue. The older subjects were stopped, as a safety precaution, when their cardiac frequency reached 85% of the maximum predicted from their age (Astrand, 1960, and Fig. 5). No test was terminated prematurely for clinical reasons and no ill effects followed the exercise testing procedure. Cardiac frequency, ventilation and oxygen uptake were measured over the last 15 s of each minute of exercise. Calculations were performed on an Elliott 4100 digital computer with a graph-plotting facility. A least-squares regression line for fH against VO₂ was automatically drawn for each subject, but as ventilation increased in a linear manner at high power outputs a line was fitted by eye to the points in the submaximal (linear) range. Examples of graphs relating V̇ and fH to VO₂ in a normal male and in two middle-aged male patients are shown in Fig. 1. Submaximal indices for V̇ and fH were obtained by interpolating to oxygen uptakes of 0.75, 1.0 and 1.5 l/min. The pattern of breathing was assessed from tidal volumes at ventilations of 20 and 30 l/min on Hey plots (Hey, Lloyd, Cunningham, Jukes & Bolton, 1966) drawn for half of the subjects from each group, chosen at random. The adaptation capacity for ventilation (ACV) and cardiac frequency (ACfH) was based on a resting measurement and an estimated maximal value. The maximal cardiac frequency (fHₘₐₓ) was calculated from the age (Astrand, 1960; see Fig. 5). The ventilatory capacity was taken to be the same as the sustained maximal voluntary ventilation (MVV) calculated from the FEV₁ (Freedman, 1970):

\[ 4 \text{ min MVV (l/min)} = 129 + 25 (\text{FEV}_1 - 4.01) \]

\[ (r = 0.74; P < 0.001; n = 20) \]

In all subjects the submaximal indices for fH and V̇ were obtained for at least two of the three

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**Submaximal exercise testing**
standard oxygen uptakes. From these the increments in $f_H$ and $V$ associated with the transport of an additional 1.01 STPD of oxygen/min, i.e. the slopes ($Sf_H$, $SV$) of the lines, were calculated for each subject and related to the relevant adaptation capacity as a physiological strain index (see Figs. 2 and 3).

**RESULTS**

The women were smaller and lighter than the men (Table 1). Lean body mass (LBM) was lower
Submaximal exercise testing

**FIG. 2.** Illustration of the concept of physiological strain as applied to the cardiac frequency response to submaximal exercise. Note that a given additional energy expenditure (4·9 kcal min\(^{-1}\) = 1·77 kJ min\(^{-1}\)) requires the use of almost the whole adaptation capacity in a cardiac patient but only a small proportion of that possessed by an athlete (e.g. a middle-distance runner). Hatched bars represent \(\Delta \dot{V}_O_2 = 1·01\) min\(^{-1}\) or \(\Delta\) energy expenditure = 4·9 kcal min\(^{-1}\).

**FIG. 3.** Illustration of the concept of physiological strain as applied to the ventilatory response to submaximal exercise. Note that a given additional energy expenditure (4·9 kcal min\(^{-1}\) = 1·77 kJ min\(^{-1}\)) requires the use of almost the whole adaptation capacity in the patients but only a small proportion in the athlete. The proportion used is greater in the older than in the young normal subjects largely because of the reduction in ventilatory capacity with age. Hatched bars represent \(\Delta \dot{V}_O_2 = 1·01\) min\(^{-1}\) or \(\Delta\) energy expenditure = 4·9 kcal min\(^{-1}\).
in the women than in the men. Mean values for the FEV₁ and vital capacity (VC) were lower in the older than in the younger subjects and less in the women than in the men.

There were no significant differences in the mean values for the submaximal indices within each sex (Table 2). However, the cardiac frequency was significantly higher in the women than in the men at all standard oxygen uptakes \((t = 6.36; P < 0.001; n = 44)\). None of the older women reached a \(\dot{V}O₂\) of 1.5 L STPD/min before being asked to stop. The ventilation indices tended to be higher in the women than in the men but the difference was significant only at a \(\dot{V}O₂\) of 1.5 L STPD/min \((t = 6.36; P < 0.001; n = 44)\). Changes in the pattern of breathing during exercise in all four groups are summarized in Table 3 and in Fig. 4. The tidal volume at 30 L/min was significantly larger in the older men than in the other groups \((t = 2.15; 0.05 > P > 0.025; n = 19)\). The tidal volume indices were smaller in the older than in the younger women. In both female groups tidal volume indices and maximum tidal volumes were smaller than the values in the males. Tidal volume indices were largest in the older men and smallest in the young men when allowance was made for differences in vital capacity \((t = 2.3; 0.05 > P > 0.025; n = 20)\). The maximum tidal volume represented a significantly larger percentage of the vital capacity in the older men compared with the two groups of women \((t = 2.2; 0.005 > P > 0.001; n = 20)\). The slope \(m\) of the increase in \(V\) with \(V_T\) tended to be higher in the women compared with the men at all ages, but the differences were not significant, even after allowing for variation in vital capacity.

The resting cardiac frequency \((fH_{rest})\) was measured whilst the subjects were sitting quietly on the cycle ergometer (Table 4). The younger women had a significantly higher resting rate than the two groups of men \((t = 2.2; 0.05 > P > 0.025; n = 40)\). As \(fH_{max}\) falls with age (Fig. 5) it was to be expected that \(ACfH\) would also decrease with age. This decrease was seen in the men \((t = 2.02; 0.05 > P > 0.025; n = 44)\), though the same trend did not reach statistical significance in the women. The slope \((SfH)\) was greater in the women than in the men \((t = 4.96; P < 0.001; n = 44)\), and the physiological strain indices for \(fH\) were also greater in the women \((t = 5.5; P < 0.001; n = 29)\).

Resting ventilation was highest in the older men, but was similar in the other three groups

### Table 1. Details of subjects (mean ± SEM shown)

<table>
<thead>
<tr>
<th></th>
<th>Men 20–40 years ((n = 24))</th>
<th>Men over 40 years ((n = 20))</th>
<th>Women 20–40 years ((n = 20))</th>
<th>Women over 40 years ((n = 9))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age (years)</strong></td>
<td>30.2 ± 0.9</td>
<td>54.3 ± 1.1</td>
<td>25.9 ± 1.3</td>
<td>47.1 ± 1.3</td>
</tr>
<tr>
<td><strong>Height (cm)</strong></td>
<td>178.7 ± 0.9</td>
<td>173.6 ± 1.5</td>
<td>163.9 ± 1.5</td>
<td>158.2 ± 1.8</td>
</tr>
<tr>
<td><strong>Weight (kg)</strong></td>
<td>75.0 ± 1.4</td>
<td>75.6 ± 2.2</td>
<td>59.7 ± 2.7</td>
<td>69.2 ± 5.2</td>
</tr>
<tr>
<td><strong>Fat (% body wt.)</strong></td>
<td>15.8 ± 0.7</td>
<td>18.1 ± 0.5</td>
<td>25.9 ± 1.0</td>
<td>33.1 ± 2.2</td>
</tr>
<tr>
<td><strong>Lean body mass (kg)</strong></td>
<td>62.9 ± 1.1</td>
<td>62.2 ± 1.6</td>
<td>43.6 ± 1.5</td>
<td>45.6 ± 2.3</td>
</tr>
<tr>
<td><strong>Forced expired volume in 1 s (FEV₁: 1 BTPS)</strong></td>
<td>4.69 ± 0.11</td>
<td>3.43 ± 0.11</td>
<td>3.30 ± 0.15</td>
<td>2.30 ± 0.11</td>
</tr>
<tr>
<td><strong>Vital capacity (VC: 1 BTPS)</strong></td>
<td>5.61 ± 0.12</td>
<td>4.52 ± 0.14</td>
<td>3.83 ± 0.15</td>
<td>3.07 ± 0.13</td>
</tr>
</tbody>
</table>
Table 2. Cardiac frequency (fH) and ventilation (V) indices of submaximal exercise responses (mean ± SEM shown)

<table>
<thead>
<tr>
<th></th>
<th>Men 20–40 years (n = 24)</th>
<th>Men over 40 years (n = 20)</th>
<th>Women 20–40 years (n = 20)</th>
<th>Women over 40 years (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac frequency indices (beats/min)</td>
<td>117.4 ± 5.6</td>
<td>105.6 ± 3.5</td>
<td>137.2 ± 8.8</td>
<td>136.9 ± 7.1</td>
</tr>
<tr>
<td>fH0.75</td>
<td>96.3 ± 2.4</td>
<td>95.0 ± 3.1</td>
<td>129.6 ± 3.5</td>
<td>129.7 ± 3.8</td>
</tr>
<tr>
<td>fH1.0</td>
<td>107.7 ± 2.3</td>
<td>106.6 ± 3.1</td>
<td>126.9 ± 4.6</td>
<td>126.9 ± 4.6</td>
</tr>
<tr>
<td>fH1.5</td>
<td>129.3 ± 2.3</td>
<td>129.3 ± 2.3</td>
<td>137.2 ± 5.6</td>
<td>137.2 ± 5.6</td>
</tr>
<tr>
<td>Ventilation indices (L STPD/min)</td>
<td>176.0 ± 0.7</td>
<td>18.7 ± 0.9</td>
<td>25.0 ± 1.0</td>
<td>27.0 ± 0.9</td>
</tr>
<tr>
<td>V0.75</td>
<td>23.9 ± 0.9</td>
<td>23.9 ± 0.9</td>
<td>36.6 ± 1.5</td>
<td>36.6 ± 1.5</td>
</tr>
<tr>
<td>V1.0</td>
<td>37.1 ± 1.1</td>
<td>37.1 ± 1.1</td>
<td>43.2 ± 1.9</td>
<td>43.2 ± 1.9</td>
</tr>
</tbody>
</table>

(Interpolated values at standard oxygen uptakes of 0.75, 1.0 and (where possible) 1.5 STPD/min.)
<table>
<thead>
<tr>
<th></th>
<th>Men 20–40 years</th>
<th>Men over 40 years</th>
<th>Women 20–40 years</th>
<th>Women over 40 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n = 10)</td>
<td>(n = 10)</td>
<td>(n = 9)</td>
<td>(n = 8)</td>
</tr>
<tr>
<td>(V_T) 20 (ml BTPS)</td>
<td>1356 ± 123</td>
<td>1521 ± 131</td>
<td>1066 ± 65</td>
<td>825 ± 69</td>
</tr>
<tr>
<td>(V_T) 30 (ml BTPS)</td>
<td>1691 ± 116</td>
<td>2017 ± 152</td>
<td>1348 ± 70</td>
<td>1104 ± 67</td>
</tr>
<tr>
<td>(V_T) max. (ml BTPS)</td>
<td>2969 ± 208</td>
<td>2696 ± 165</td>
<td>1754 ± 80</td>
<td>1333 ± 67</td>
</tr>
<tr>
<td>(V_T) 20 (as %</td>
<td>24 ± 2 ± 1</td>
<td>33 ± 3 ± 3</td>
<td>29 ± 2 ± 2</td>
<td>26 ± 2 ± 2</td>
</tr>
<tr>
<td>(V_T) max. (as %</td>
<td>53 ± 3 ± 5</td>
<td>57 ± 2 ± 5</td>
<td>48 ± 3 ± 2</td>
<td>42 ± 1 ± 4</td>
</tr>
<tr>
<td>(V_T) max. (as %</td>
<td>32 ± 3 ± 3</td>
<td>28 ± 3 ± 6</td>
<td>39 ± 3 ± 7</td>
<td>45 ± 2 ± 6</td>
</tr>
<tr>
<td>Slope ((m)^{(2)})</td>
<td>190 ± 24 ± 1</td>
<td>131 ± 12 ± 7</td>
<td>150 ± 19 ± 8</td>
<td>138 ± 20 ± 8</td>
</tr>
<tr>
<td>Intercept constant ((k)^{(2)})</td>
<td>0.62 ± 0.16</td>
<td>0.41 ± 0.25</td>
<td>0.90 ± 0.08</td>
<td>0.28 ± 0.10</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Interpolated values at standard ventilations of 20 and 30 lBTPS/min. \(V_T\) max. = maximum tidal volume observed during exercise.

\(^{(2)}\) \(m\) and \(k\) are parameters in the equation \(\dot{V} = m(V_T - k)\); Hey et al. (1966).
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![Graphs showing mean relationships of exercise tidal volume ($V_T$) and ventilation ($\dot{V}$) and mean relationships between the tidal volume as a percentage of the vital capacity, and $\dot{V}$.](image)

**Fig. 4.** (a) Mean relationships of exercise tidal volume ($V_T$) and ventilation ($\dot{V}$) illustrating the patterns in men and women of different age groups. The maximum tidal volumes reached are indicated by the inflexions. (b) Mean relationships between the tidal volume as a percentage of the vital capacity, and $\dot{V}$.

![Graph showing effect of age on maximum cardiac frequency ($f_{H_{max}}$).](image)

**Fig. 5.** Effect of age on maximum cardiac frequency ($f_{H_{max}}$). Values quoted for men (●) and women (○) in the literature (Astrand, 1952; Astrand, 1960; Astrand & Saltin, 1961; Cotes et al., 1969; Davies, 1968, 1972; Edwards et al., 1972; Robinson, 1938; Saltin et al., 1969; Strandell, 1964) and the regression line and equation of Astrand (1960) are shown.

$$f_{H_{max}} = 210 - (\text{age} \times 0.65)$$

$r = -0.96$

(Astrand, 1960)
TABLE 4. Estimations of adaptation capacity and 'physiological strain' of submaximal exercise for cardiac frequency (mean ± SEM shown). \( f_H \) = Cardiac frequency; LBM = lean body mass (kg).

<table>
<thead>
<tr>
<th></th>
<th>Men 20–40 years ((n = 24))</th>
<th>Men over 40 years ((n = 20))</th>
<th>Women 20–40 years ((n = 20))</th>
<th>Women over 40 years ((n = 9))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest cardiac frequency ((f_{H\text{rest}}): \text{beats/min}) (sitting on cycle ergometer)</td>
<td>85.4 ± 3.0 (81.4 ± 3.5)</td>
<td>86.0 ± 3.4</td>
<td>90.2 ± 2.9</td>
<td></td>
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<tr>
<td>Predicted max. cardiac frequency ((f_{H\text{max}}): \text{beats/min})</td>
<td>190.5 ± 0.6</td>
<td>175.1 ± 0.8</td>
<td>193.2 ± 0.8</td>
<td>179.3 ± 0.9</td>
</tr>
<tr>
<td>Adaptation capacity for (f_H) ((\Delta f_H = f_{H\text{max}} - f_{H\text{rest}}): \text{beats/min})</td>
<td>105.1 ± 3.0</td>
<td>93.6 ± 3.5</td>
<td>97.0 ± 3.5</td>
<td>89.2 ± 3.5</td>
</tr>
<tr>
<td>'Slope' for (f_H) ((S_{f_H}) [d(f_H)/d(\dot{V}_O_2): 1^{-1}])</td>
<td>42.2 ± 1.9</td>
<td>42.5 ± 1.9</td>
<td>62.9 ± 3.1</td>
<td>70.9 ± 8.7</td>
</tr>
<tr>
<td>'Physiological strain' for (f_H) ((% \times LBM \times 10^{-2}))</td>
<td>40.6 ± 1.9</td>
<td>46.3 ± 2.1</td>
<td>66.2 ± 3.7</td>
<td>79.8 ± 10.0</td>
</tr>
<tr>
<td>'Physiological strain' for (f_H) ((% \times LBM \times 10^{-2}))</td>
<td>25.5 ± 1.2</td>
<td>28.4 ± 0.93</td>
<td>28.3 ± 1.3</td>
<td>35.1 ± 2.9</td>
</tr>
<tr>
<td></td>
<td>Men 20–40 years (n = 24)</td>
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</tr>
<tr>
<td>Rest ventilation (V_{rest} l/min) (sitting on cycle ergometer)</td>
<td>11.6 ± 1.0</td>
<td>13.9 ± 1.3</td>
<td>10.1 ± 0.9</td>
<td>12.2 ± 1.4</td>
</tr>
<tr>
<td>Ventilatory capacity (MVV: l/min)</td>
<td>146.1 ± 2.8</td>
<td>117.0 ± 3.2</td>
<td>112.1 ± 3.6</td>
<td>86.2 ± 2.7</td>
</tr>
<tr>
<td>Adaptation capacity for V (ACV = MVV − V_{rest}: l/min)</td>
<td>135.6 ± 3.0</td>
<td>104.3 ± 3.3</td>
<td>101.8 ± 3.8</td>
<td>74.3 ± 3.4</td>
</tr>
<tr>
<td>Slope for V (SV) [d(V) dVo_{2}]</td>
<td>26.3 ± 1.2</td>
<td>23.2 ± 2.3</td>
<td>27.2 ± 2.1</td>
<td>27.1 ± 2.6</td>
</tr>
<tr>
<td>'Physiological strain' for V (%) = (\frac{SV \times 100}{ACV})</td>
<td>19.7 ± 1.1</td>
<td>23.3 ± 1.4</td>
<td>27.6 ± 2.1</td>
<td>37.5 ± 4.2</td>
</tr>
</tbody>
</table>
| 'Physiological strain' for V (%) \(\times LBM \times 10^{-2}\) | 12.2 ± 0.6               | 14.2 ± 0.8                | 11.7 ± 0.7                | 17.3 ± 2.6                

TABLE 5. Estimations of adaptation capacity and related 'physiological strain' of submaximal exercise for ventilation (mean ± SEM shown). LBM = Lean body mass (kg).
The ventilatory adaptation capacity (AC\(V\)) was smaller in the women than in the men but the ventilatory slope (SV) was similar in all groups. 'Physiological strain' for ventilation was higher in the older women than in the younger women (\(t = 2.4; 0.025>P>0.01; n = 29\)) and higher in the women than in the men (\(t = 4.12; P<0.001; n = 44\)).

Multiplying the physiological strain by LBM allows for the effects on exercise responses of variation in body size. The value for 'physiological strain x LBM' was similar in all groups except the older women, in whom it was significantly larger both for \(fH\) (\(t = 2.47; 0.025>P>0.01; n = 29\)) and for \(\dot{V}\) (\(t = 2.83; 0.01>P>0.005; n = 29\)).

**DISCUSSION**

This study provides data for interpreting the results of exercise tests in normal subjects and patients and a new concept of 'fitness' is suggested. Before this can be discussed it is necessary to consider some technical details.

The technique used for measuring \(\dot{V}O_2\) during exercise is convenient and accurate. It is, with the exception of a few minor modifications, the same as that used in field studies of normal populations (Edwards, Miller, Hearn & Cotes, 1972; Miller, Cotes, Hall, Salvosa & Ashworth, 1972). All clinical exercise tests necessitating measurements of gas exchange now carried out in our laboratory are made with the techniques described. Errors in estimating mixed expired gas composition are small in submaximal exercise, as proved by simultaneous measurement of \(\dot{V}O_2\) from collections of expired gas in Douglas bags.

Values for \(fH\ 1.5\) and \(\dot{V}\ 1.5\) in our young subjects agree closely with those reported for European men and women of the same age (Cotes et al., 1969; Davies, 1972). Our older women were unable to reach a \(\dot{V}O_2\) of 1.51 before their cardiac frequency had reached 85% of the predicted maximum value. For these subjects and for patients (such as those with chronic obstructive bronchitis; S. G. Spiro, H. L. Hahn, R. H. T. Edwards & N. B. Pride, unpublished work) it is clearly important to use the lower indices, \(fH\ 0.75\), \(fH\ 1.0\) and \(\dot{V}O_2\ 0.75\), \(\dot{V}O_2\ 1.0\).

Exercise responses are dependent on several items of body composition (Holmgren & Astrand, 1966; Cotes et al., 1969; Davies, 1972; Edwards et al., 1972; Miller et al., 1972). Two such 'structure–function' interrelationships will be considered here: (i) that between \(fH\) and an index of somatic muscle mass, and (ii) that between the patterns of breathing and an index of lung dimensions.

Exercise capacity, as measured by the \(\dot{V}O_2\) max, is highly correlated with indices of body muscle (Cotes et al., 1969; Cotes, Berry, Burkinshaw, Davies, Hall, Jones & Knibbs, 1973). We chose LBM as a convenient index of body muscle. Cotes et al. (1973) showed that \(fH\) and the reciprocal of LBM are highly correlated in men and women aged 18–38 years. However, in older women LBM, as calculated from skinfold thickness (Durnin & Rahaman, 1967), may be overestimated because of greater fat deposition between muscle fibres (Cotes et al., 1973). In agreement with Cotes et al. (1973) we observed significant correlations between \(fH\) 1.0 and the reciprocal of LBM in the younger men and women (correlation coefficients 0.67, 0.005>P>0.001, and 0.56, 0.01>P>0.005 respectively). There was a lower correlation for the older men (correlation coefficient 0.40, 0.05>P>0.025) and no relationship in the older women. The high physiological strain for \(fH\) and \(\dot{V}\) in the older women, which persisted after allowing for variation in LBM, may have been partly due to over-estimation of the true LBM.

A linear relationship was found between ventilation and tidal volume up to the maximum
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tidal volume (Fig. 4a); thereafter ventilation increased by increasing the breathing frequency (Hey et al., 1966; Cotes, Johnson & McDonald, 1970). We have quoted an interpolated tidal volume at a standard ventilation of 20 l/min (VT 20) as well as that for 30 l/min (VT 30, chosen by other authors) to provide a basis for interpreting the ventilatory response to exercise in patients with a very low working capacity. Further, the provision of two points defines the linear part of the response curve in a way that is impossible with the single index (VT 30).

According to Hey et al. (1966) this linear relationship can be expressed in the form \( \bar{V} = m(V_T - k) \) where \( m \) is related to the slope of the CO₂ response curve and \( k \) possibly to the respiratory dead space. There were, however, no significant differences between the calculated values for \( m \) or \( k \) between the groups.

The women had smaller values for VT 20 and VT 30 than the men (Table 3), though this difference was less when allowance was made for variation in vital capacity and remained significantly different only in the older men at VT 20 and VT 30, as shown in Fig. 4(b). A large tidal volume response was also found in another group of older men performing stepping exercise (Gupta, Fletcher & Edwards, 1973). The mean values for VT 30 in our young subjects agree well with those previously reported for young Europeans (Cotes et al., 1970; Edwards et al., 1972; Miller et al., 1972). The maximum tidal volume achieved was about 50% of the vital capacity as noted previously for hyperpnoea due to exercise (Astrand, 1952), voluntary hyperventilation (Freedman, 1970) and CO₂ breathing (Hey et al., 1966).

The reporting of exercise responses at two or more submaximal oxygen uptakes allows the slopes (SFH, SV) to be simply calculated. The expression of the response to progressive exercise by a single index (even the single point near the centre of gravity of the data, as suggested by Cotes, 1972) fails to convey the evolution of the response. Cardiac frequency increases linearly with \( \dot{V}O_2 \) until near the maximum, which is then approached asymptotically (Davies, 1968). Calculation of SFH from submaximal indices is thus an adequate guide to the cardiac response to exercise as it is linear in the ‘everyday’ range. The slope therefore indicates the increase in fH that is obligatory for a rise in energy expenditure equivalent to an increase of \( \dot{V}O_2 \) of 1-0 1 STPD/min (about the increase necessary for walking on the level at a normal pace). Though constant in submaximal exercise, SV increases markedly as the maximal work rate is approached (Cotes, 1968). In general, we have found that SV remains constant throughout the range of effort tolerance in most patients with a reduced working capacity (e.g. Fig. 1). The values for SV quoted here are minimal estimates for the ventilatory requirement of increasing \( \dot{V}O_2 \) by exercise with large muscle groups in normal subjects. The slope (SFH, SV) will be similar in other exercise activities involving large muscle groups (Asmussen, 1967), but in exercise with a smaller muscle bulk, e.g. work with the arms, both \( \dot{V} \) and fH at a given \( \dot{V}O_2 \) are higher than when the same \( \dot{V}O_2 \) is achieved in leg exercise (Cotes, Allsopp & Sardi, 1969).

The influences of age, sex and variations in some body dimensions are incorporated in the estimation of the adaptation capacity. The resting fH or \( \bar{V} \) values, which were measured with the subject seated on the cycle ergometer, although higher than expected basal values were taken as the base line of the adaptation capacity. From a comparison (Fig. 5) with the results for maximum heart rates reported by several authors (Robinson, 1938; Astrand, 1952; Cotes et al., 1969; Davies, 1972; Edwards et al., 1972) it appears that Astrand’s equation is an adequate estimator of fHmax. (coefficient of variation approximately 5%, Davies, 1968) in both men and women aged over 20 years (Fig. 5). There is some uncertainty in estimating fHmax. in cardiac patients. Gilbert & Auchincloss (1969) stated that fHmax. may be reduced, but in a
Swedish study of a group of cardiac patients $f_{H_{\text{max}}}$ was very close to the value expected for normal men of similar age (Sanne, Elmfeldt, Grimby, Rydin & Wilhelmsen, 1973). The $f_{H_{\text{max}}}$ cannot be predicted in patients with atrial fibrillation. In patients with a ventilatory limitation to exercise capacity, the calculated $f_{H_{\text{max}}}$ indicates the theoretical maximum cardiac frequency response to exercise, though this can never be achieved in practice as work is prematurely stopped by the development of dyspnoea.

The ventilatory capacity (MVV) was estimated from the FEV$_1$, which is influenced by age, sex and height (Cotes, 1968).

Exercise responses vary between different ethnic groups (Edwards et al., 1972) and the recognition of such influences will clearly become important as population migration increases. However, the effects of age, sex, body composition and ventilatory capacity can always be taken into account by relating the slope to the adaptation capacity. It is possible for a patient and a normal subject to have the same $S_fH$ or $S_d$ but the patient may have a smaller ACfH or ACV and consequently a high physiological strain index, even after allowing for differences in LBM. Abnormally low slopes do not necessarily indicate above average fitness. When $S_fH$ is low, as, for example, with heart block, the low cardiac output results in a lactic acidaemia (Edhag & Zetterquist, 1968), which may stimulate ventilation so that $S_V$ is higher than normal.

This unified approach to the interpretation of responses to submaximal exercise allows assessment of the strain imposed on an individual by a standard (and physiologically relevant) increase in energy expenditure. Since 'physiological strain' is estimated from $\dot{V}O_2$ measurements the results obtained in the laboratory may be used to interpret the symptoms of breathlessness and effort intolerance during everyday activities, the energy costs of which are now well known (Durnin & Passmore, 1967).

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REFERENCES


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