PHYSIOLOGICAL EFFECTS OF REPEATED EXERCISE

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SUMMARY

1. The physiological responses to repeated continuous (progressive) exercise together with the relationship between continuous and discontinuous work tests on an upright bicycle ergometer have been studied in healthy male subjects.

2. The results show a marked decline in mean cardiac frequency ($f_H$) from 145 beats/min to 124 beats/min during the first four experiments at a given submaximal oxygen intake of 1.5 l/min and thereafter a smaller decline to reach 118 beats/min on the final (sixteenth) day of the investigation. This latter decrease was associated with a small but significant rise in maximum oxygen intake ($\dot{V}O_2$ max) which occurred from Day 8 onwards. Pulmonary minute ventilation at an oxygen intake of 1.5 l/min ($V_{E1.5}$) decreased by about 5 l/min immediately following the first occasion of submaximal work but thereafter remained unchanged. There was however no decrease in $O_2$ cost of exercise, as $\dot{V}O_2$ at a fixed rate of external work remained unchanged throughout the investigation.

3. At maximal effort there was no significant decrease in either $V_{E}\text{max}$ or $f_H\text{max}$, but the $f_H$ at which the $\dot{V}O_2$ max was reached declined significantly from Day 8. Thus the asymptotic nature of the $f_H/\dot{V}O_2$ curve which was very pronounced on Day 1 virtually disappeared following the third visit to the laboratory. The accuracy of predicting $\dot{V}O_2$ max from $f_H$ and $\dot{V}O_2$ increased noticeably from $-15.4\pm8.9\%$ on Day 1 to $-6.5\pm10.5\%$ on Day 7 and $-0.9\pm3.4\%$ on Day 15. The possible physiological basis and implications of the results are discussed.

4. No significant differences were found between continuous and discontinuous work. Thus in large scale population studies of work capacity or in the evaluation of training programmes in rehabilitation studies, a continuous test may be used but attention must be paid to familiarization procedures. At least three preliminary test periods are necessary before the results become reproducible and reliable.

The maximum aerobic power ($\dot{V}O_2$ max) is now widely accepted by exercise physiologists as a

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reference standard of cardiorespiratory fitness (Shepherd, Allen, Benade, Davies, Hedman, Merriman, Myhre, di Prampero & Simmons, 1968). However, in many situations it is either impossible or inadvisable to measure \( VO_2 \) max directly and for this reason several standard procedures for the estimation of \( VO_2 \) max based on a person's response to submaximal exercise have been developed. The most commonly used are those based on measurements of cardiac frequency and oxygen intake (Astrand & Rhyming, 1954), ventilation (Sadoul, Durand & Aubertin, 1958), respiratory quotient (Issekutz, Birkhead & Rodahl, 1962), and finally levels of lactic acid in the blood (Williams, Bredell, Fleming, Morrison, Strydom, Ward & Wyndham, 1962). Unfortunately in many cases where only a single test is given the possible physiological contribution of habituation to, and learning of, the test exercise is ignored. Further, in practice, it is usual to give either a continuous exercise test in which the work load is progressively increased at set intervals of time (Wahlund, 1948; Balke, 1952), or a series of discontinuous work periods of increasing severity interspersed with suitable rest pauses to allow recovery from the previous exertion (Astrand, 1960; Maritz, Morrison, Peter, Strydom & Wyndham, 1961). Another problem therefore is whether these two forms of exercise yield similar and comparable results.

Exercise tests are also being increasingly used in the medical field for diagnostic purposes (Jones, 1967) and in the evaluation of rehabilitation programmes and drugs. In the majority of investigations the patient is used as his own control and his response to exercise is studied before and after some standard procedure (e.g. injection of a drug). It is tacitly assumed that any changes observed are due to the treatment.

We have investigated the effects of a repeated continuous (progressive) submaximal and maximal test and the relationship between continuous and discontinuous exercise on a bicycle ergometer.

**MATERIALS AND METHODS**

The investigation was in two parts. In part I, five healthy male subjects (aged 17–23 years) were each studied on 16 days during a period of 3 weeks and performed submaximal and maximal exercise on alternate days. The subjects were volunteers and a condition of enrolment was that they had never taken part in an experimental investigation or pedalled a bicycle ergometer before. All measurements were made with the subjects resting, but not basal, and no observations were obtained earlier than 1 h after a meal.

On the first visit to the laboratory the subject was instructed in the use of the mouthpiece and how to ride the Müller bicycle ergometer and how long he would be required to work. During the preliminary period the necessary electrodes were fitted and the subject rested in a chair for 15 min, during which period the cardiac frequency (\( f_H \)) was monitored. The lightweight recording electrodes (Devices Sales Ltd) were applied to each side of the chest in the mid-clavicular line about ½ in. below the lowermost insertion of the pectoralis major and a third (earthing) electrode over the xiphoid process. This electrode arrangement was found to reduce muscle noise to a minimum even during maximal exercise and thus a clear recording of \( f_H \) was always obtained. At zero time the subject was asked to mount the bicycle and to pedal for 30 min at a pedal frequency of 60 revolutions/min. The work load was increased in intensity at the end of each 6 min period, the aim of the test exercise being to span an \( f_H \) range of 110–170 beats/min. The first three work loads were identical for each subject (300 kpm/min,
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600 kpm/min and 900 kpm/min) but the final two work loads were adjusted in the light of the subject's probable VO₂ max as judged from his response to the first stages of the test. The fourth work load ranged from 960 to 1200 kpm/min and the last from 1020 to 1380 kpm/min. Once the individual pattern of increase in work load has been established on Day 1 it remained constant throughout the rest of the investigation.

For maximal work the resting procedure remained the same. Exercise commenced with a 4 min warm-up at a work load corresponding to approximately 60% of the subject's probable VO₂ max (fH approximately 150 beats/min), the work load was then increased to approximately 90% of his VO₂ max for 2 min and thereafter increased every minute until exhaustion was reached. The aim was to collect four sets of data at and beyond the subject's VO₂ max. The criterion of maximum performance was that VO₂ showed no further rise with increasing work load, i.e. at least two VO₂ values were required to agree within ±5%.

Throughout the resting submaximal and maximal work periods cardiac frequency was recorded continuously after the method of Davies & Neilson (1965). Expired air was collected during the fourth to sixth min at each submaximal work load and the final 45 s of each minute at maximal effort. The subject was connected via a low resistance Otis-McKerrow valve (dead space <100 ml) and a short length of smooth 1½ in. internal bore tubing, to a wide-necked vinyl plastic Douglas bag which was suspended to reduce its resistance to flow (Cotes, 1966). The total resistance to expired gas flow was <1·5 cm H₂O at 200 l/min. The bag was emptied through a dry gas meter (Parkinson-Cowan Ltd.) and a sample taken into small (1·5 l capacity) plastic bags for subsequent analysis of O₂ and CO₂ content using a paramagnetic O₂ analyser (Servomex Control Ltd) and infra-red CO₂ analyser (Beckmans Ltd). The analysers were calibrated before and after every reading with Standard gases which had to be previously analysed by the Lloyd-Haldane chemical method. The details of accuracy and reliability which might be expected from the method have already been given (Davies & Shirling, 1967).

In part II of the investigation, eleven subjects (aged 17–42 years) were studied on four separate occasions during continuous and discontinuous exercise. The protocol for the continuous work and methods for measuring cardiac frequency and expired air volume and content were identical to those described for part I of the study. The five work loads for the discontinuous tests were the same for the continuous work except that rest pauses (approximately commensurate with the severity of effort) of 10, 15, 20 & 30 min were allowed between each exercise period.

RESULTS

Submaximal exercise

Oxygen consumption

The regression lines of oxygen intake (VO₂) on work load (W) for each subject for the first and final submaximal experimental occasion are shown in Fig. 1. The mean VO₂ data at a W of 900 kpm/min (VO₂ 900) are summarized in Table I. They are substantially in agreement with the data of Astrand (1960) for pedalling the stationary ergometer. The calculated mechanical efficiencies of our subjects were very close to the normal 23% (range 20–25%). There is some slight evidence from our figures to suggest that there may have been a small improvement in mechanical efficiency in three of the subjects (Fig. 1). However, neither the individual
nor the group regression lines of $\dot{V}O_2$ on $W$ are significantly different from Day 1 to Day 16 ($P > 0.5$) and thus the $\dot{V}O_2$ at given $W$ remained unchanged throughout the experimental period.

![Graph](image)

**Fig. 1.** Oxygen intake ($\dot{V}O_2$) in relation to work load in the individual subjects. Day 1 ———; Day 15 ———.

**Table 1.** The effect of repetition on oxygen at 900 kpm/min ($\dot{V}O_2$, ventilation ($\dot{V}E_{1.5}$) and cardiac frequency ($fH_{1.5}$) at oxygen intake of 1.5 l/min. (mean data)

<table>
<thead>
<tr>
<th>Day</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>13</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{V}O_2$ 900 (ml/min) STPD</td>
<td>1978</td>
<td>2021</td>
<td>2040</td>
<td>1990</td>
<td>2052</td>
<td>2022</td>
<td>1995</td>
<td>1976</td>
</tr>
<tr>
<td>$\dot{V}E_{1.5}$ (l/min) BTPS</td>
<td>40.46</td>
<td>35.79*</td>
<td>35.72</td>
<td>37.85</td>
<td>34.83</td>
<td>34.45</td>
<td>34.97</td>
<td>35.42</td>
</tr>
<tr>
<td>$fH_{1.5}$ (beats/min)</td>
<td>145</td>
<td>134**</td>
<td>131**</td>
<td>124**</td>
<td>124</td>
<td>125</td>
<td>117*</td>
<td>118</td>
</tr>
</tbody>
</table>

**Ventilation**

$\dot{V}_E/\dot{V}_T$ relationship. In Fig. 2 the expired ventilation ($\dot{V}_E$) is plotted against the tidal volume ($\dot{V}_T$) for the first, seventh and final submaximal experiments for each subject. A linear relationship was found in each experiment which could be expressed as $\dot{V}_E = m(\dot{V}_T - k)$ where $m$ is the slope of the line and $k$ the intercept on the $\dot{V}_T$ axis (Hey, Cunningham, Bolton, Jukes & Lloyd, 1966). Subject D showed a decrease in $k$ over the experimental series, subject A showed an
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**Fig. 2.** Minute ventilation ($V_e$) in relation to tidal volume ($V_T$) in the individual subjects. Day 1 ——; Day 7 - - - -; Day 15 - - - -.

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**Fig. 3.** Ventilation ($V_e$) in relation to oxygen intake ($\dot{V}O_2$) in the individual subjects. Day 1 ——; Day 15 - - - -.
increase and subjects C and E showed very little change, the parameter \( m \) remaining nearly constant. Subject B showed variability in both parameters. The grouped data show no significant overall trend.

**Ventilatory equivalent.** The individual regression lines of \( V_E \) on \( V_O_2 \) for the first three work loads in the first and final experiments are shown in Fig. 3 for five of the subjects. Subjects A and C show little change but the pooled data for the five subjects shows a significant decrease in \( V_E \) at a \( V_O_2 \) of 1.5 l/min (\( V_E, 1.5 \)). This decrease occurred between the first and second sub-maximal exercise experiments (Day 1 and Day 3) and thereafter the ventilatory equivalent remained unchanged.

**Cardiac frequency**

The cardiac frequency (f\(_H\)) data are summarized in Fig. 4 and Table I. The cardiac frequency at an oxygen intake of 1.5 l/min (f\(_H, 1.5\)) decreased significantly (P<0.001) from a mean value of 145 beats/min on Day 1 to 124 beats/min on Day 7 and thereafter showed a smaller decline to reach 118 beats/min on Day 15 (Table I). From Day 1 to Day 7 the fall in f\(_H, 1.5\) was entirely due to the change in the intercept of the regression of the f\(_H\) on \( V_O_2 \), the slope of the line remaining constant (Fig. 4). From Day 7 onwards the individual changes in the slope and intercept of the f\(_H, V_O_2\) line were more variable (Fig. 4). In subjects A, C and E the small decrease in f\(_H\) was due to changes in slope and not intercept, whereas in subject B the reverse was true and subject D showed changes in both parameters.
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Maximal exercise

The data from the maximal exercise on Days 2–16 are summarized in Table 2. Maximum oxygen intake (\(\dot{V}O_2\) max) showed no significant change during the first three occasions of maximal work. However between Day 6 and Day 8 a small but significant rise in \(\dot{V}O_2\) max occurred but thereafter it remained unchanged throughout the rest of the experimental period. The increase was of the order of 200 ml (2·6 ml/kg) which represents a 5·5% change in the measured \(\dot{V}O_2\) max.

**Table 2. The effect of repetition on maximum oxygen intake (\(\dot{V}O_2\) max), cardiac frequency (\(f_H\) max), ventilation (\(V_E\) max), cardiac frequency at \(\dot{V}O_2\) max (\(f_H\) at \(\dot{V}O_2\) max) and ventilation at \(\dot{V}O_2\) max (\(V_E\) at \(\dot{V}O_2\) max)**

<table>
<thead>
<tr>
<th>Day</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\dot{V}O_2) max (l/min) STPD</td>
<td>3·18</td>
<td>3·17</td>
<td>3·23</td>
<td>3·33*</td>
<td>3·42*</td>
<td>3·31</td>
<td>3·41</td>
<td>3·45</td>
</tr>
<tr>
<td>(V_E) max (l/min) BTPS</td>
<td>142·82</td>
<td>143·14</td>
<td>152·20</td>
<td>146·94</td>
<td>149·24</td>
<td>148·28</td>
<td>149·94</td>
<td>152·84</td>
</tr>
<tr>
<td>(V_E) at (\dot{V}O_2) max (l/min) BTPS</td>
<td>123·04</td>
<td>129·81</td>
<td>120·47</td>
<td>121·15</td>
<td>121·30</td>
<td>113·64</td>
<td>112·85</td>
<td>111·45</td>
</tr>
<tr>
<td>(f_H) max (beats/min)</td>
<td>197</td>
<td>200</td>
<td>197</td>
<td>196</td>
<td>197</td>
<td>196</td>
<td>195</td>
<td>193</td>
</tr>
<tr>
<td>(f_H) at (\dot{V}O_2) max (beats/min)</td>
<td>196</td>
<td>198</td>
<td>196</td>
<td>193*</td>
<td>193</td>
<td>189*</td>
<td>190</td>
<td>189</td>
</tr>
</tbody>
</table>

* 0·05 > \(P\) > 0·01

![Graph](image)

**Fig. 5. Cardiac frequency (\(f_H\)) and oxygen intake (\(\dot{V}O_2\)) at submaximal and maximal effort. Days 1 and 2 ———; Days 4 and 5 ———.**

The mean maximum ventilation (\(V_E\) max) was 148·18 l/min (range 142·82 to 152·84 l/min) and showed no significant changes throughout the investigation (Table 2). However the \(V_E\) at which the \(\dot{V}O_2\) max was reached did show a decline of 12 l/min over the 16 day period.
(Table 2). This was also true of the corresponding cardiac frequency values; whereas the $f_{\text{Hmax}}$ remained unchanged (mean 196 beats/min; range 193–200 beats/min) the $f_{\text{H}}$ at the $\dot{V}O_2$ max decreased markedly from Day 8 onwards, reaching 189 beats/min on the final day of measurement. This significant decline in $f_{\text{H}}$($P<0.01$) was thus associated with the small rise in $\dot{V}O_2$ max previously noted. These changes in $f_{\text{H}}$ at $\dot{V}O_2$ max together with the decline in $f_{\text{H}}$ at given $\dot{V}O_2$ resulted in a dramatic change of the $f_{\text{H}}/\dot{V}O_2$ relationship over the 16 day period of repeated exercise. The asymptotic nature of $f_{\text{H}}/\dot{V}O_2$ curve which was only pronounced on Day 1 began to disappear and was completely absent by the end of the investigation (Fig. 5). The accuracy of predicting $\dot{V}O_2$ max from submaximal values of $f_{\text{H}}$ and $\dot{V}O_2$ increased from $-15 \pm 9\%$ on Day 1 to $-1\% \pm 3\%$ on Day 15 (Table 3).

**Table 3. Indirect estimation of maximum aerobic power ($\dot{V}O_2$ max) (see text)**

<table>
<thead>
<tr>
<th>Day</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) $\dot{V}O_2$ max l/min (observed)</td>
<td>3.18</td>
<td>3.17</td>
<td>3.23</td>
<td>3.33</td>
<td>3.42</td>
<td>3.31</td>
<td>3.41</td>
<td>3.45</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.17$</td>
<td>$\pm 0.27$</td>
<td>$\pm 0.20$</td>
<td>$\pm 0.26$</td>
<td>$\pm 0.17$</td>
<td>$\pm 0.15$</td>
<td>$\pm 0.15$</td>
<td>$\pm 0.19$</td>
</tr>
<tr>
<td>(iii) $\dot{V}O_2$ l/min (predicted)</td>
<td>2.68</td>
<td>3.01</td>
<td>3.16</td>
<td>3.07</td>
<td>3.32</td>
<td>3.27</td>
<td>3.52</td>
<td>3.43</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.23$</td>
<td>$\pm 0.16$</td>
<td>$\pm 0.05$</td>
<td>$\pm 0.13$</td>
<td>$\pm 0.28$</td>
<td>$\pm 0.31$</td>
<td>$\pm 0.42$</td>
<td>$\pm 0.19$</td>
</tr>
<tr>
<td>(ii)-(i) as % of (i)</td>
<td>$-15.4$</td>
<td>$-4.0$</td>
<td>$-2.4$</td>
<td>$-6.5$</td>
<td>$-2.7$</td>
<td>$-1.1$</td>
<td>$+2.4$</td>
<td>$-0.9$</td>
</tr>
<tr>
<td></td>
<td>$\pm 8.9$</td>
<td>$\pm 13.8$</td>
<td>$\pm 6.6$</td>
<td>$\pm 10.5$</td>
<td>$\pm 12.3$</td>
<td>$\pm 11.5$</td>
<td>$\pm 15.1$</td>
<td>$\pm 3.4$</td>
</tr>
</tbody>
</table>

![Fig. 6. Comparison between continuous (---) and discontinuous (----) work procedures. Oxygen intake ($\dot{V}O_2$) on work load; cardiac frequency ($f_{\text{H}}$) on $\dot{V}O_2$ ventilation ($V_T$) on $\dot{V}O_2$.](image)

The $V_{\text{E}}/V_T$ plots for all the subjects showed the expected linear relationship for values of $V_T$ below 2.5 l/min. At higher values of $V_T$ the relationship was curvilinear, tending to be more asymptotic at about $V_T$ 3.5 l/min.

At $\dot{V}O_2$ max there was a tendency for $V_T$ to decrease and respiratory frequency to increase.
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as exhaustion was approached. Mean $V_T$ for all experiments was 3.18 l on the penultimate work load and 3.09 l on the last work load (mean of 45 readings).

Comparison between continuous and discontinuous submaximal work

The comparison between discontinuous and continuous (progressive) exercise is shown in Fig. 6 and Tables 4 and 5.

It is clear that provided the subjects are familiarized with and habituated to the work, there is no significant difference between the two forms of exercise.

Table 4. Comparison of continuous and discontinuous work. Intercept (a) and slope (b) of the regression of (1) $\dot{V}O_2$ on W (11)$f_H$ on $\dot{V}O_2$ and (111) $V_E$ on $\dot{V}O_2$

<table>
<thead>
<tr>
<th></th>
<th>(I)</th>
<th>(II)</th>
<th>(III)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a)</td>
<td>(b)</td>
<td>(a)</td>
</tr>
<tr>
<td>Continuous</td>
<td>326.1</td>
<td>1.86</td>
<td>64.9</td>
</tr>
<tr>
<td>Discontinuous</td>
<td>334.9</td>
<td>1.81</td>
<td>73.8</td>
</tr>
<tr>
<td>$F_{100}$</td>
<td>1.39</td>
<td>0.33</td>
<td>1.44</td>
</tr>
<tr>
<td>Significance</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

Table 5. Comparison of continuous and discontinuous work

<table>
<thead>
<tr>
<th></th>
<th>$\dot{V}_{B.5}$ (l/min)</th>
<th>$f_{H.5}$ (beats/min)</th>
<th>$\dot{V}O_2_{00kpm/min}$ (ml/min)</th>
<th>$\dot{V}O_2_{max}$ (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>38.61 ± 5.25</td>
<td>126 ± 11</td>
<td>2010 ± 120</td>
<td>3091 ± 475</td>
</tr>
<tr>
<td>Discontinuous</td>
<td>39.25 ± 6.16</td>
<td>128 ± 8</td>
<td>1973 ± 113</td>
<td>3110 ± 494</td>
</tr>
<tr>
<td>$f_{10}$</td>
<td>0.48</td>
<td>0.94</td>
<td>1.38</td>
<td>0.27</td>
</tr>
<tr>
<td>Significance</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

DISCUSSION

The six subjects forming the basis of part I of the investigation can be regarded as normal healthy but sedentary subjects. None was in athletic training and four of the six subjects took no regular exercise at all. Their lack of fitness is shown in the relatively low $\dot{V}O_2_{max}$ values (Table 2) and the very high $f_H$ reached during exercise of low to moderate intensity. The selection of subjects with a low working capacity was deliberate because in our experience it is precisely these people one normally encounters in population studies and in hospitals and laboratories where exercise tolerance tests are given.

The response of our subjects to repeated submaximal exercise may be divided into two
stages: (i) Days 1–7 during which changes in the physiological responses to standardized submaximal work occurred without an observable change in the VO$_2$ max and (ii) Days 8–16 in which changes observed could be associated with an increased VO$_2$ max.

**Stage 1 (Days 1–7)**

During the first three occasions of submaximal work, though the VO$_2$ at a fixed work load and the VO$_2$ max remained constant, the circulatory system showed evidence of a profound change. The f$_H$ at given VO$_2$ of 1.5 l/min decreased from a mean value of 145 beats/min on Day 1 to 124 beats/min on Day 7. Ventilation at fixed oxygen consumption (V$_E$) on the other hand, though it declined from 40 l/min to 36 l/min following the first occasion of submaximal work, remained fairly constant thereafter.

The fall in f$_H$ cannot be attributed to a decrease in the external work performed by our subjects due to a rise in mechanical efficiency or increase in overall work capacity since neither the VO$_2$ at given work load nor the VO$_2$ max changed during the 7 day period. Nor is habituation as conventionally defined—the change of f$_H$ at a fixed VO$_2$ due to decreased anxiety—a plausible explanation of our results since one would have expected to see the more pronounced changes in f$_H$ at the lower work levels and for the effect to diminish with increasing severity of effort. The major changes in f$_H$ 1–5 were due to a parallel displacement of the f$_H$/VO$_2$ line (Fig. 2), intercept of the line being reduced but the slope remaining unchanged. One is therefore left with the conclusion that these changes in f$_H$ must reflect some internal readjustments of an hitherto ‘sedentary’ circulation to demands of repeated and unaccustomed exercise.

The transport of oxygen to the working muscles is governed by the equation:

\[ \text{VO}_2 = Q \times \text{AVD} = f_H \times \text{SV} (\text{Ca}_0,2 - \text{Cv}_O,2) \]

where \( \text{VO}_2 \) = oxygen intake; \( Q \) = cardiac output; \( \text{AVD} \) = arterio-venous difference; \( f_H \) = cardiac frequency; \( \text{SV} \) = stroke volume; \( \text{Ca}_0,2 \) = \( O_2 \) content of arterial blood and \( \text{Cv}_O,2 \) = \( O_2 \) content of mixed venous blood. During submaximal work it is known that \( f_H \) and \( Q \) vary as linear functions of exercise intensity (Donald, Bishop & Wade, 1954) whereas the relationship of AVD and SV to \( \text{VO}_2 \) is hyperbolic. Since our subjects showed a decrease in \( f_H \) on the first three occasions of sub maximal exercise (with unchanged work loads), this suggests that either they were incapable of maintaining an adequate SV during the exercise or had a lower than normal AVD, which in turn implies that a larger than normal volume of blood was used for a given oxygen intake. Both these factors could arise from the same cause.

An abnormally low AVD usually arises in conditions of venous pooling particularly in the skin and splanchnic regions (Bevegard & Shepherd, 1967). This will directly affect venous return. Since an adequate venous return and filling time of the ventricles in diastole are the main determinants of SV an impairment of either of these factors could result in a smaller than normal stroke output and a higher than normal cardiac frequency.

The literature on the dynamic responses to training in young men is confused (Åstrand, 1956; Bevegard & Shepherd, 1967), and from our results we have no way of deciding whether an increase in AVD or SV occurred. However we feel that the decrease of \( f_H \) together with the complete disappearance of the asymptotic nature of the \( f_H$/\text{VO}_2$ curve (Fig. 4) is at least consistent with an overall theory based on blood redistribution. It is probable that during the first few occasions of repeated work, particularly in sedentary subjects unused to exercise, a redistribution of blood flow in favour of the working muscles takes place, thus allowing maximum use of the available cardiac output. Such an effect is probably mediated via the
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autonomic system and represents an inherent readjustment of the body's circulation to the requirements of exercise.

Stage 2 (8–16 days)

During the second week of repeated exercise a more ‘normal’ training response was seen. The \( f_H \) showed a small but gradual decline of the order of 6 beats over the 8-day period. This was associated with an equally small but significant increase in \( \dot{V}O_2 \) max. It is also interesting to note that during this period, although the \( f_H \text{max} \), and \( \dot{V}E \text{max} \) remained constant, the \( f_H \) and \( \dot{V}E \) at which the \( \dot{V}O_2 \) max occurred decreased markedly. This suggests that during a sustained period of repeated work the actual limiting factor to maximal work may change. The presence of an asymptotic \( f_H/\dot{V}O_2 \) curve during the first two occasions of maximal exercise indicates that a small amount of oxygen was utilized by the muscles without a concomitant rise in heart output. This could have occurred by a further unsaturation of mixed venous blood and a widening of the AVD as already indicated or by a redistribution of the available Q occurring during the course of the exercise. Since it would seem that the muscles are able to accept additional oxygen for a brief period of time after the circulation has reached its maximum capacity, it would be fair to assume the limitation to further effort was central rather than peripheral. This view was supported by the subjects’ reactions to the first and second maximum test. During the final minute of the test they showed evidence of severe stress, were cyanosed and usually complained of overall and complete exhaustion.

In contrast during the second week of maximal testing when the \( f_H \) at the \( \dot{V}O_2 \) max had begun to decline and the asymptotic nature of the \( f_H/\dot{V}O_2 \) disappear, the overall picture of the limiting factor to maximal exercise began to change. Though the subjects found the work subjectively easier and were able to pedal at higher rates of work, this complaint was not of exhaustion but of localized pain in their legs, particularly in the quadriceps region.

Practical implications

The true nature of the physiological mechanism underlying the observed changes in healthy subjects performing repeated exercise await further investigation, but the practical implication of our results is clear. In situations such as large population studies of physical working capacity or in laboratory studies of training, where both the observers’ and subjects’ time are limited, a continuous exercise procedure may be used. However attention must be paid to familiarization procedures. The increase of predicted \( \dot{V}O_2 \) max without a concomitant change in observed \( \dot{V}O_2 \) max during the initial stages of the study suggest that at least three preliminary test periods should be given to ensure reliable and reproducible results.

REFERENCES


C. T. M. Davies, W. Tuxworth and J. M. Young


