Behavior of Cardiac Output during Progressive Exercise Tests: A Preliminary Report

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The behavior of cardiac output (Q) during progressive incremental exercise tests was studied in young healthy men. Q approached a plateau and leveled off at almost the same work rate at which oxygen uptake (VO₂) attained its maxima, while heart rate (HR) still continued to rise. This suggests that the limiting factor for maximal aerobic capacity in healthy subjects is Q. The rate of increase in Q and HR accelerated from a work rate which is close to the ventilatory anaerobic threshold (AT). The prime cause of the progressive augmentation in cardiac activity is probably an accelerated release of plasma catecholamine and/or potassium. There is a possibility that these substances might also affect the AT.


Key words: Exercise test, Anaerobic threshold, Cardiac output, Gas exchange

The anaerobic threshold (AT), determined by changes in ventilatory and gas exchange variables in response to incremental exercise tests, is a widely-used and useful measure for assessing physical fitness in patients with cardiorespiratory diseases, as well as in healthy subjects including athletes (Davis et al., 1979, Kumagai et al., 1982, Matsumura et al., 1983, Wasserman and McIlroy, 1964 and Wasserman et al., 1973).

Little is known, however, about the behavior of cardiac output (Q) during incremental exercise, although Miyamoto et al. (1985) reported that subjects with a greater stroke volume (SV) have a higher AT and maximum capacity of O₂ uptake (VO₂ max). The present report is concerned with the behavior of heart rate (HR) and Q during progressive exercise tests in healthy subjects. Special attention has been given to changes in cardiac variables at the AT and VO₂ max.

METHODS
Experiments were carried out on two different subject groups at separate occasions. The first group consisted of fourteen high school boys (15-16 yrs.), eight of whom took part in daily training in judo. The outcome of a study in this group has been published elsewhere (Miyamoto et al., 1985). The second subject group consisted of six male university students (22-26 yrs.).

After a few min of unloaded exercise (0W), each subject performed an incremental exercise test (15 W/min) to the limit of tolerance on a cycle ergometer. Ventilatory, gas exchange and cardiac variables were measured simultaneously. Q was determined by automated impedance cardiography developed by Miyamoto et al. (1982), which was calibrated using a rebreathing method immediately before and after each exercise test (Niizeki et al., 1989 and Niizeki and Miyamoto, 1991).

The AT was detected by visual inspection of graphical plots of ventilatory equivalents and endtidal gas concentrations. The following criteria were adopted as per Wasserman (1984): 1) The ventilation equivalent for O₂ (VE/VO₂) curve, hav-
Fig. 1 Graphic plots of stroke volume (SV), heart rate (HR), cardiac output (Q), minute ventilation (VE), O2 uptake (VO2), CO2 output (VCO2), end-tidal pressure of CO2 (PETCO2) and gas exchange ratio (R) obtained from a high school boy. Note that the HR and Q curves turn upwardly from the ventilatory anaerobic threshold (AT).
ing been flat or decreasing, begins to rise as the ventilation equivalent for CO₂ (\(\dot{V}E/\dot{V}CO₂\)) curve remains constant or is decreasing; 2) The end-tidal tension of O₂ (PETO₂) curve, having been declining or flat, begins to rise while the end-tidal tension of CO₂ (PETCO₂) curve is slowly rising or constant (isocapnic buffering). An alternative method proposed by Beaver et al. (1986) using a regression analysis of the slopes of the CO₂ output (\(\dot{V}CO₂\)) vs. O₂ uptake (\(\dot{VO}_2\)) plot (V-slope method) was also adopted for determining the AT of the university subject group.

RESULTS

The AT values determined by the graphical method coincided well with those obtained from the V-slope method as shown in Table 1.

Table 1 Ventilatory anaerobic threshold (AT) determined by the visual inspection of graphical plots (G-method) and the regression analysis of \(\dot{VO}_2\)-\(\dot{V}CO₂\) plots (V-method) obtained from six male university students.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>G-method</th>
<th>V-method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.28</td>
<td>1.65</td>
</tr>
<tr>
<td>2</td>
<td>1.24</td>
<td>1.28</td>
</tr>
<tr>
<td>3</td>
<td>0.87</td>
<td>0.81</td>
</tr>
<tr>
<td>4</td>
<td>2.10</td>
<td>1.81</td>
</tr>
<tr>
<td>5</td>
<td>1.40</td>
<td>1.41</td>
</tr>
<tr>
<td>6</td>
<td>0.97</td>
<td>0.78</td>
</tr>
</tbody>
</table>

| Mean     | 1.31     | 1.29     |
| SD       | 0.40     | 0.33     |
| SE       | 0.16     | 0.16     |

The AT (expressed in \(\dot{O}_2\) uptake, l/min) values are an average of three runs for each subject. The difference between the two mean values is statistically insignificant while the correlation between these AT's is significant (\(r = 0.840, p < 0.05\)).

Fig. 1 shows changes in the ventilatory, gas exchange and circulatory variables during an incremental exercise test carried out by a high school subject. SV, HR and \(\dot{Q}\) augmented with increasing work rate, but SV leveled off when the work rate exceeded the AT. On the contrary, the slope of the HR curve became more positive beyond the AT, which resulted in a concomitant augmentation in the \(\dot{Q}\) curve. When the work rate approached the limit of tolerance of the subject, the \(\dot{VO}_2\) curve attained a maximum and then leveled off. The \(\dot{Q}\) curve also leveled off at almost the same work rate while the HR curve was still increasing.

The relationship between the maximum values of

\[ \dot{Q} \] vs. \(\dot{VO}_2\) max

\[ r = 0.749 \quad (P < 0.01) \]

Fig. 2 Upper panel: The relationship between the maximum \(\dot{O}_2\) uptake (\(\dot{VO}_2\) max) and maximum \(\dot{Q}\) (\(\dot{Q}\) max) obtained from fourteen high school boys. The dotted line indicates the \(\dot{VO}_2\)-\(\dot{Q}\) relationship reported by Astrand et al. (1964) during the steady-state of exercise.

Lower panel: The relationship between both the work rates at which \(\dot{VO}_2\) and \(\dot{Q}\) level off.
\( \dot{V}O_2 (\dot{V}O_2 \text{ max}) \) and \( \dot{Q} (\dot{Q} \text{ max}) \) is shown in Fig.2 (upper panel). The slope of the \( \dot{Q} \) vs. \( \dot{V}O_2 \) max plot is not much different from that of the \( \dot{V}O_2-\dot{Q} \) relationship reported by Åstrand et al. (1964) who determined \( \dot{Q} \) using a dye dilution technique during steady-state exercise. The relationship between the work rates at which \( \dot{V}O_2 \) and \( \dot{Q} \) reach a plateau is shown in Fig. 2 (lower panel). The significant correlation coefficient \( r = 0.794 \) and the slope of the regression line which is close to unity suggest that \( \dot{Q} \) and \( \dot{V}O_2 \) attain their respective maxima at almost the same work rate.

The work rates from which the slope of the augmentation of a variable becomes steeper were

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Fig. 3 Upper panels: The relationship between the upward turning points of \( \dot{V}E \) (\( \dot{V}E \) (TP)) and HR (HR (TP)) (left) and that between \( \dot{V}E \)(TP) and the turning points of \( \dot{V}CO_2 \) (\( \dot{V}CO_2 \) (TP)) (right) obtained from six male university students.

Lower panels: The relationship between the ventilatory anaerobic threshold (AT) and HR(TP) (left) and that between the AT and VE(TP) (right).
discriminated for minute ventilation (VE), HR and \( \dot{V} \text{CO}_2 \). The upward turning points for HR (HR(TP)) and \( \dot{V} \text{CO}_2 \) (\( \dot{V} \text{CO}_2 \) (TP)) were plotted against those for \( \dot{V} \text{E}(\dot{V} \text{E} \) (TP) (Fig. 3, upper panel). There was a close correlation between \( \dot{V} \text{CO}_2 \) (TP) and \( \dot{V} \text{E} \) (TP), and between HR (TP) and \( \dot{V} \text{E} \) (TP). HR (TP) and \( \dot{V} \text{E} \) (TP) were also highly correlated with the AT when expressed in terms of \( \dot{V} \text{O}_2 \) (Fig. 3, lower panel).

**DISCUSSION**

We found that \( \dot{Q} \) leveled off when \( \dot{V} \text{O}_2 \) approached the maxima. This observation suggests that cardiac output is the limiting factor for the maximal aerobic capacity (\( \dot{V} \text{O}_2 \) max) in healthy subjects whose voluntary minute ventilation is far greater than the maximal \( \dot{V} \text{E} \) attainable at the highest work rate, and whose diffusion barrier between the alveolar-arterial interface does not impede gas transportation.

It is not surprising that the upward turning points of the \( \dot{V} \text{CO}_2 \) vs. work rate relationship (\( \dot{V} \text{CO}_2 \) (TP)) correlate well with those of \( \dot{V} \text{E} \) (\( \dot{V} \text{E} \) (TP)), since the excessive increase in \( \dot{V} \text{CO}_2 \) above the AT is thought to be a result of the respiratory compensation for lactic acidosis (Wasserman et al., 1973). However, we also observed similar upward turning points in the HR and/or \( \dot{Q} \) vs. work rate curves and these points correlate closely to the turning points of \( \dot{V} \text{E} \).

The primary origin of the progressive increase in HR or \( \dot{Q} \) during heavy work load can be ascribed to the augmented sympathetic activity triggered by central and peripheral neurogenic drive, and an excessive release of plasma catecholamine (Dejours, 1964). Also, an increase in the plasma potassium level accompanying muscular activity might also play a role in the HR augmentation (Band and Linton, 1988).

An important observation is that the turning point of HR is very close to that of \( \dot{V} \text{E} \). This suggests that plasma norepinephrine and/or potassium can also affect the turning points of ventilatory and gas exchange variables, and thereby might alter the AT determined from the responses of these variables during incremental exercise. Hagberg et al. (1982) and more recently Paterson et al. (1990) have demonstrated that McArdle's subjects, who lack genetically the myophosphorylase B required for anaerobic metabolism of glycogen, have a paradoxical ventilatory AT. This suggests that the ventilatory response during heavy exercise should be attributed not only to lactic acidity but also to the functional role of plasma catecholamine and potassium. Though it should be noted, however, that an upward turning point on the HR or \( \dot{Q} \) vs. work rate curves is not observed in every subjects, despite that a ventilatory AT point is always detectable.

Further investigation is required to elucidate the nature of the "circulatory AT".

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**REFERENCES**


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