**Can Maximal Cardiopulmonary Capacity be Recognized by a Plateau in Oxygen Uptake?**

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The failure of oxygen uptake to increase with increasing work has been considered a marker of the limits of the cardiopulmonary system for many years. However, the concept has suffered from inconsistencies in definition, criteria, and data sampling, all of which affect the interpretation of the relation between changes in work and oxygen uptake. To evaluate the response and reproducibility of the slope in oxygen uptake at peak exercise, six subjects (mean age, 33 ± 6 years) performed two individualized ramp treadmill tests on separate days. During exercise, oxygen uptake (for a given sample of 30 eight-breath running averages) was regressed with time and the slope was calculated. Maximal oxygen uptake, maximal heart rate and maximal perceived exertion were reproducible from day 1 to day 2 (mean difference, 0.4 ml/kg/min, 1.0 beats per minute, and 0.2 for maximal oxygen uptake, heart rate, and maximal perceived exertion, respectively [not significant]). Considerable variability in the slopes was observed during each test and from day to day. This occurred despite the use of large gas exchange samples, averaging techniques, and constant, consistent changes in external work. A plateau, defined as the slope of an oxygen uptake sample at peak exercise that did not differ significantly from a slope of zero, was not a consistent finding within subjects between days. We conclude that marked variability in the slope of the change in oxygen uptake occurs throughout progressive exercise, despite the use of large samples and a linear change in external work. These findings appear to preclude the determination of a plateau by common definitions.

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Technologic advances have greatly improved the precision with which gas exchange measurements are used to evaluate the physiologic response to exercise testing. These advances, however, have raised a number of uncertainties concerning the interpretation of data. For example, disagreement exists regarding the recognition of maximal cardiorespiratory limits.1,2 It is often assumed that this limit has been attained when oxygen uptake no longer increases concomitantly with increasing work (oxygen uptake plateau). However, automated systems that have become common allow variations in data sampling that can greatly affect the interpretation of maximal exercise.2

The plateau concept presented by Taylor and coworkers3 has been widely applied for more than 30 years. These investigators suggested that a 2.5 percent increase in treadmill grade not accompanied by more than 150 ml O2/min increase in oxygen uptake reflected an individual's cardiopulmonary limit. However, a discontinuous protocol was employed to study healthy individuals, circumstances greatly differing from those used for clinical testing today. In addition, the plateau concept has been subjected to many different interpretations,3-13 and some question or dismiss the concept entirely.1,2,14

We recently observed a remarkable degree of variability in the slope of the change in oxygen uptake relative to the change in work load among healthy subjects during ramp treadmill testing.2 By individualizing ramp work rates and varying the gas exchange sampling interval, we were able to observe the effect of these variables on the plateau phenomenon. We defined a plateau as a slope in oxygen uptake vs time at peak exercise that did not differ significantly from zero (ie, a slope that was flat). The present report addresses these observations further and evaluates the extent to which a given slope, variability in slope, or plateau could be reproduced on different days within the same individual.

**METHODS**

Five healthy male subjects and one healthy female subject (mean ± SD age, 33 ± 6 years) participated in the study. None was taking any medication or had any remarkable medical history. All had at least average fitness; the mean (± SD) maximal oxygen uptake was 50.0 ± 12 ml O2/kg/min.

**Exercise Testing**

Maximal exercise tests were performed using a ramp treadmill protocol, ie, using a constant, continuous change in external work. Initially, an exercise test was performed to familiarize subjects with the procedure and to determine maximal oxygen uptake. Using this information, treadmill ramp rates were individualized to attain a test duration of approximately ten minutes.15 The same ramp rate,
time of day, and laboratory conditions were employed for a given subject on day 2, and tests were performed a mean of 15.8 days apart. Ramp rates ranged between 1.2 and 7.0 ml \( O_2 \)/kg/min, with a mean of 4.0±2 ml \( O_2 \)/kg/min, expressed as change in external work. The software and hardware used to perform these tests were developed by the Burdick Corporation (Milton, Wis). Exercise was continued to volitional fatigue and subjects were encouraged to give a maximal effort. The Borga 6 to 20 scale was used to quantify effort.

**Gas Exchange**

Pulmonary gas exchange variables were determined continuously throughout the exercise tests using the Medical Graphics Corporation 2001 System. Quality control documentation was performed using techniques outlined by Jones and Campbell. Data were sampled using 30 consecutive eight-breath average recursive sums. A single eight-breath average sample represented an average of the current breath and the seven preceding it. Thus, sampling was analogous to the average of 30 breaths, each breath representing an average of eight. The estimations of slope were made from each of these samples. The use of these averaging techniques has the effect of filtering variation. Figure 1 illustrates the averaging techniques used from which the estimations of slope were generated.

**Statistics**

The Student's \( t \) test for paired observations was used to assess differences in perceptual, heart rate, and gas exchange responses between day 1 and day 2. To evaluate the slope of the regression lines for each individual ramp test, a BASIC computer program was developed to calculate the following: the slope of the change in oxygen uptake over time, the confidence interval and standard deviation of the slope, the calculated and critical \( T \) statistic, the \( Y \) intercept, and regression and residual sum of the squares.

**Table 1—Heart Rate, Perceived Exertion, and Gas Exchange Responses on Days 1 and 2**

<table>
<thead>
<tr>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal Heart Rate, beats/min</td>
<td>Maximal Perceived Exertion</td>
</tr>
<tr>
<td>Subject</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
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<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>180 ± 12</td>
</tr>
</tbody>
</table>

*Average oxygen uptake slope indicates average measured rate of change in oxygen uptake during ramp testing.
†Ramp rate indicates rate of change in external work during ramp testing. Ramp rate was the same for each subject on days 1 and 2.
**FIGURE 2.** Individual slopes in oxygen uptake regressed with time for subject 1 on day 1. Each darkened square represents a 30 eight-breath average sample in which the slope was not significantly greater than zero. Each open square denotes those that were greater than zero. Dashed line represents the mean of the observed change in oxygen uptake (3.73 ml/kg/min).

**FIGURE 3.** Individual slopes in oxygen uptake regressed with time for subject 1 on day 2. Each darkened square represents a 30 eight-breath average sample in which the slope was not significantly greater than zero. Each open square denotes those that were greater than zero. Dashed line represents the mean of the observed change in oxygen uptake (3.26 ml/kg/min).
RESULTS

Differences between measurements made on day 1 and day 2 of heart rate, gas exchange, and perceptual responses are presented in Table 1. The slope of the change in oxygen uptake for subject 1 on day 1 and day 2 are illustrated in Figures 2 and 3, respectively.

The mean maximal oxygen uptake of the subjects was 50.0 ± 11.7 ml/kg/min on day 1 and 49.6 ± 11 ml/kg/min on day 2. This difference was not significant (NS). Accordingly, treadmill time was not different between day 1 (9.0 ± 1.4 minutes) and day 2 (9.3 ± 1.2 minutes). The mean maximal perceived exertion was 19.8 ± 0.4 and 20 ± 0 on days 1 and 2, respectively (NS), and the mean maximal respiratory exchange ratios were 1.30 ± 0.10 and 1.24 ± 0.12 on days 1 and 2, respectively (NS). These values are consistent with maximal effort on both days.

Each of the data points in Figures 2 and 3 represents the slope of a 30-breath running recursive sample, where each breath is a running recursive eight-breath average, for subject 1. Since a single eight-breath average sample is an average of the current breath and the seven preceding it, each data point in Figures 2 and 3 represents the slope of the line derived from 30 such samples at that point in time (Fig 1). Open squares denote samples in which the slope in oxygen uptake was significantly greater than zero, while closed squares denote samples that did not differ from zero. On day 1, the slope did not differ significantly from zero at peak exercise, i.e., a plateau appeared to occur. This was contrasted by day 2, in which the slope at peak exercise was significantly greater than zero. Irrespective of the response at peak exercise, considerable variability in the slope of the change in oxygen uptake was observed throughout submaximal exercise, including samples that both differed and did not differ from zero. From Figure 3, the subject may have been judged to “plateau” and thus reached physiologic maximum, at three points submaximally.

Variability in the slope of the change in oxygen uptake during progressive exercise was similar in the other subjects. Although all six subjects demonstrated a plateau (slope not different from zero at peak exercise) on day 1, this observation was not made in three of the subjects on repeat testing (subjects 1, 2, and 5). Further, variability in the slope of the change in oxygen uptake differed greatly for some subjects between tests (Table 1), as illustrated for subject 1 in Figures 2 and 3. It should be noted further that the distribution of the slopes was non-Gaussian in all but one of the 12 tests. This suggests that the frequency of obtaining a given oxygen uptake value over the course of the exercise test did not fit a normal distribution curve.

DISCUSSION

An important observation made from the present data was the variability in the slope of the change in oxygen uptake throughout progressive exercise, despite a constant, consistent change in external work and the use of large, averaged samples. A slope, in the present context, is defined as the change in oxygen uptake for a given sample associated with a unit change in external work. Thus, a slope not different from zero at peak exercise suggests that oxygen uptake was not increasing concomitantly with external work. The degree of variability observed would appear to preclude the determination of a plateau by common definitions. It should also be noted that a plateau was not a consistent finding with repeated testing, even though maximal heart rate, perceived exertion, and maximal gas exchange parameters did not differ between days. The variability demonstrated during each test and the lack of consistency of the slopes on different days suggests that the occurrence of a plateau may be random.

The plateau concept has been defined in many different ways, and its criteria has depended on population, protocol, and by the method in which the data are sampled. For example, the work increment near peak exercise would presumably have a marked effect on gas exchange kinetics. In addition, we have previously observed that the method of sampling data significantly affects the slope, plateau, and variability in oxygen uptake. Thus, an optimal method with which to study this phenomenon would require the ability to consistently increase work, an automated system allowing continuous gas exchange acquisition, variations in the method of sampling data, and the ability to average breaths or intervals. Although the ramp bicycle protocol has recently been studied, we believed that the ramp treadmill would be advantageous, as maximal oxygen uptake is approximately 10 percent higher on the treadmill in comparison to the bicycle ergometer. Naturally, this difference could be critical when evaluating the limits of the cardiopulmonary system. The large sampling intervals were chosen to reduce variability as much as possible and to give the subjects the best chance to plateau, if this phenomenon were to occur.

The ramp treadmill protocol employed in the present study may offer several advantages for cardiopulmonary assessment. It has been suggested that an optimal test duration, determined by individualized work increments that yield the highest oxygen uptake, is approximately ten minutes in duration. Redwood and coworkers demonstrated that tests which use large work increments in patients with angina resulted in reductions in exercise capacity and poor reliability for studying the effects of therapy. Standardized pro-
ocols that are commonly used clinically employ large
and/or unequal work increments resulting in a nonlin-
ear relation between oxygen uptake and work rate.\textsuperscript{15,26}
A number of investigators have therefore described
the importance of adapting the exercise test to the
subject and purpose of the test.\textsuperscript{13,24,27,28} Thus, the
ability to individualize ramp rates to reproduce exer-
rise capacity, a given myocardial oxygen demand, the
onset of angina, or other symptoms when evaluating
interventions is provocative. A simple computer pro-
gram was developed for the present study, from which
ramp rates were individualized resulting in good
reproducibility and a test duration of approximately
9.1 ± 1 minute.

**CONCLUSION**

Intuitively, the body's cardiorespiratory and meta-
bolic systems must reach some finite limit beyond
which oxygen uptake can no longer be increased. The
factors that limit exercise capacity are not entirely
clear, however, exercise capacity depends on disease,
fitness, and the type and duration of exercise. The
traditional interpretation of the plateau concept as-
sumes oxygen delivery always limits exercise capacity.
However, this may not be the case under all condi-
tions.\textsuperscript{1} This may explain the fact that, subsequent to the studies of Taylor et al,\textsuperscript{3} researchers have reported
between 7 and 80 percent of subjects demonstrate a
plateau.\textsuperscript{2,6-12,18} It should be noted also that these studies
derived greatly in population, protocol, and criteria.
The considerable variability in the slope of the change
in oxygen uptake during progressive exercise in the
present study suggests that the plateau concept has
limitations for general application during standard
exercise testing.

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1316

Maximal Cardiopulmonary Capacity Recognition (Myers et al)