Maximal Oxygen Uptake as a Parametric Measure of Cardiorespiratory Capacity

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ABSTRACT

HAWKINS, M. N., P. B. RAVEN, P. G. SNELL, J. STRAY-GUNDERSEN, and B. D. LEVINE. Maximal Oxygen Uptake as A Parametric Measure of Cardiorespiratory Capacity. *Med. Sci. Sports Exerc.*, Vol. 39, No. 1, pp. 103–107, 2007. **Introduction:** Maximal oxygen uptake ($\dot{V}O_{2max}$) was defined by Hill and Lupton in 1923 as the oxygen uptake attained during maximal exercise intensity that could not be increased despite further increases in exercise workload, thereby defining the limits of the cardiorespiratory system. This concept has recently been disputed because of the lack of published data reporting an unequivocal plateau in $\dot{V}O_2$ during incremental exercise. **Purpose:** The purpose of this investigation was to test the hypothesis that there is no significant difference between the $\dot{V}O_{2max}$ obtained during incremental exercise and a subsequent supramaximal exercise test in competitive middle-distance runners. We sought to determine conclusively whether $\dot{V}O_2$ attains a maximal value that subsequently plateaus or decreases with further increases in exercise intensity. **Methods:** Fifty-two subjects (36 men, 16 women) performed three series of incremental exercise tests while measuring $\dot{V}O_2$ using the Douglas bag method. On the day after each incremental test, the subjects returned for a supramaximal test, during which they ran at 8% grade with the speed chosen individually to exhaust the subject between 2 and 4 min. $\dot{V}O_2$ at supramaximal exercise intensities (30% above incremental $\dot{V}O_{2max}$) was measured continuously. **Results:** $\dot{V}O_{2max}$ measured during the incremental test (63.3 ± 6.3 mL·kg^{-1}·min^{-1}; mean ± SD) was indistinguishable from the $\dot{V}O_{2max}$ during the supramaximal test (62.9 ± 6.2, N = 156; P = 0.77) despite a sufficient duration of exercise to demonstrate a plateau in $\dot{V}O_2$ during continuous supramaximal exercise. These data provide strong support for the hypothesis that there is indeed a peak and subsequent plateau in $\dot{V}O_2$ during maximal exercise intensity. **Conclusions:** $\dot{V}O_{2max}$ is a valid index measuring the limits of the cardiorespiratory systems' ability to transport oxygen from the air to the tissues at a given level of physical conditioning and oxygen availability. **Key Words:** TREADMILL TESTING, RUNNING, $\dot{V}O_{2max}$, DOUGLAS BAGS

Maximal oxygen uptake ($\dot{V}O_{2max}$) was first described by Hill and Lupton in 1923 as "the oxygen intake during an exercise intensity at which actual oxygen intake reaches a maximum beyond which no increase in effort can raise it" (6). They further postulated that the measurement of $\dot{V}O_{2max}$ defined the limits of the cardiovascular and respiratory systems' ability to transport oxygen.

Subsequently, the concept that the measurement of a plateau of $\dot{V}O_{2max}$ is a quantifiable and reproducible parameter of the cardiorespiratory system's ability to maximally deliver oxygen has been repeated sufficiently that it has achieved near universal acceptance. However, the concept of a truly maximal oxygen uptake and the resultant plateau with supramaximal exercise, as well as the experimental design of Hill's original investigation have been challenged (14,15). The principal argument in this challenge is that Hill and Lupton did not prove that $\dot{V}O_{2max}$ and the subsequent plateau were ever achieved because they did not attempt to validate the existence of a plateau by running at speeds higher than the maximal speed at which $\dot{V}O_{2max}$ was measured.

The logic involved in developing the challenge to the concept of $\dot{V}O_{2max}$ has been rebutted by Bassett and Howley (1,2). Howley (8) has correctly identified that the modern equipment and data-acquisition systems used today generally impose a measurement rigor in terms of breath-by-breath data collection and the identification of $\dot{V}O_{2max}$ that has, in many investigations, resulted in an inability to identify a clear plateau of $\dot{V}O_2$ in standard incremental tests. However, many of the contrary arguments have not used data from experiments that employed repeated measurements of $\dot{V}O_{2max}$ using the same methodologies applied by Taylor, Buskirk, and Henschel in which short-duration supramaximal exercise intensities were used (20). Moreover, it may be difficult for all but the most accomplished athletes to remain running long enough at supramaximal treadmill work rates to confirm that $\dot{V}O_2$ has truly plateaued.

Recently, Day et al. (3) demonstrated that although a plateau in $\dot{V}O_2$ may not be observed during every incremental exercise test, the $\dot{V}O_{2max}$ obtained is useful in

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determining cardiorespiratory capacity during exercise. This conclusion was based on the linear correlation between incremental $\dot{V}O_{2max}$ and a constant-load $\dot{V}O_{2max}$. However, only a small number (*N* = 6) of subjects in this experiment actually underwent a supramaximal test to confirm that $\dot{V}O_{2max}$ had been achieved, and even in these subjects, the increase in work rate above incremental max was small and within the measurement error of oxygen uptake; it is still necessary to provide conclusive evidence that the $\dot{V}O_{2max}$ obtained during incremental exercise is representative of the actual limitations of the cardiorespiratory system. Therefore, the purpose of this investigation was to test the hypothesis that there is no difference between the $\dot{V}O_{2max}$ obtained during incremental and supramaximal exercise bouts performed by a large number of highly competitive collegiate middle-distance runners and to verify that $\dot{V}O_2$ does attain a maximal value at which there is no further increase in the measurement of $\dot{V}O_2$, despite an increase in work intensity.

METHODS

Subjects

Fifty-two well-trained distance runners (35 male, 16 female) who were participating in an altitude training study completed three series of incremental $\dot{V}O_{2max}$ tests (156 tests) and subsequent supramaximal tests (156 tests): 1) at the end of a 2-wk lead-in training phase; 2) after 4 wk of sea-level training; and 3) after another 4 wk of training while living at high altitude or sea level and training at high altitude or sea level. Subject and experimental details have previously been reported (9,10). All subjects gave their voluntary written informed consent to a protocol approved by the institutional review board of the University of Texas Southwestern Medical Center at Dallas.

Treadmill evaluation. $\dot{V}O_{2max}$ was measured with a modified Astrand–Saltin protocol (10) involving incremental exercise on a treadmill. The test was preceded by a 10- to 15-min warm-up, during which the athletes performed their typical competitive warm-up either on an indoor track or an outdoor trail. For most athletes, this warm-up consisted of easy running at a level 1 (recovery) pace with a few strides consisting of short (20–40 m) higher-velocity sprints. After approximately 5 min of rest and stretching, the incremental test began on a calibrated treadmill, with the subjects running at 9.0 mph for men and 8.0 mph for women at 0% grade for 2 min. The grade was then increased 2% every 2 min until volitional exhaustion, which usually occurred 10–12 min after the initial increase in grade. Oxygen uptake ($\dot{V}O_2$) was measured using the Douglas bag method; gas fractions were analyzed by mass spectrometer (Marquette MGA 1100), and ventilatory volume was measured with either a Tissot spirometer or dry-gas meter (Collins). $\dot{V}O_{2max}$ was defined as the highest $\dot{V}O_2$ measured from at least a 40-s Douglas bag collection. To verify that $\dot{V}O_{2max}$ was achieved, a supramaximal treadmill run was performed on a separate day, with $\dot{V}O_{2max}$ and anaerobic capacity measured as described below. The typical error (expressed as the coefficient of variation (7)) for the incremental and supramaximal exercise treadmill tests performed on all subjects was 3.2 and 4.3%, respectively. In addition, heart rate was monitored continuously (Polar CIC, Port Washington, NY).

Supramaximal test. On the day after the incremental $\dot{V}O_{2max}$ test, each subject performed a test to confirm the $\dot{V}O_{2max}$ value obtained in the incremental test and to estimate anaerobic capacity from the accumulated oxygen deficit, according to the method of Medbo et al. (11). The subjects first performed the same warm-up as conducted before the incremental test. Supramaximal exercise then began with subjects running at 8% grade with the speed chosen individually to exhaust the subject between 2 and 4 min (generally 9–10 mph for women and 11–12 mph for men). This work rate required a $\dot{V}O_2$ that was at least 30% greater than that achieved on the incremental test. $\dot{V}O_{2max}$ was determined using the Douglas bag method, in which bags were collected continuously at 45-s intervals from the start of the test. Tests were included in the analysis only if a minimum of three complete bags had been collected; thus, at least three 45-s bags were collected in all 156 of the supramaximal tests performed. Immediately after the supramaximal run, fingertip capillary blood samples were

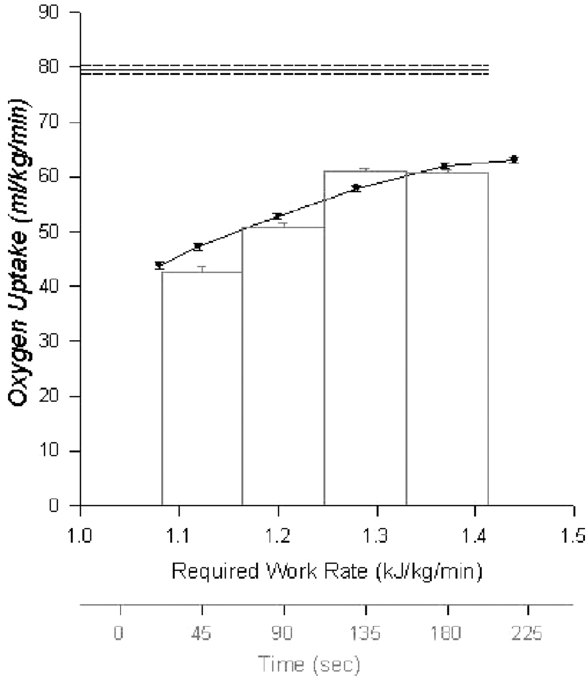

FIGURE 1—*Filled circles connected by lines* represent Douglas bags obtained during the second minute of each 2-min stage run at a fixed speed with an increase in grade by 2% every 2 min. The last bag at the highest work rate was occasionally obtained earlier in the stage to accommodate subject exhaustion. Required work rate (*dark abscissa*) was calculated directly from treadmill speed and grade. *Open bars* represent the last four 45-s Douglas bags collected continuously during the supramaximal test. The *light abscissa* reflects the time the bags were collected during the supramaximal test. On the basis of the running economy determined at this grade (8%), the oxygen uptake required to perform this amount of work aerobically was calculated and is shown as the *solid line*, with 95% confidence limits represented by the *dashed line*.

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collected every 2 min for 10 min during recovery to identify the peak lactate concentration (Yellow Springs Instruments 23L, Yellow Springs, OH).

Statistics

Numerical data are presented as means ± SD. Comparisons of incremental $\dot{V}O_{2max}$ to supramaximal $\dot{V}O_{2max}$ were determined using paired *t*-tests. All analyses were performed with a computer-based analysis system (SigmaStat 2.03).

RESULTS

During the incremental test, $\dot{V}O_2$ increased progressively with increasing work rate until the final bag, when the increment was less than half of what would be predicted from treadmill speed and grade (Fig. 1, solid symbols/lines). During the supramaximal test (Fig. 1, bars) these athletes were able to sustain this work intensity for more than 3 min. Oxygen uptake increased and then plateaued, or even decreased slightly despite an aerobic work requirement at least 30% greater than $\dot{V}O_{2max}$ (Fig. 1, solid straight line). Despite these very high and intense work rates typical of middle-distance runners, no subject reported any symptoms of myocardial ischemia or exhibited signs of circulatory collapse as would be predicted if a central governor were acting teleologically to prevent dangerous levels of work or cardiorespiratory effort beyond that observed in the incremental test.

There was no significant difference between the $\dot{V}O_{2max}$ obtained during the incremental test (63.3 ± 6.3 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$; mean ± SD) and that obtained during the supramaximal test (62.9 ± 6.2 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, $P = 0.77$) (Fig. 2). The individual data for each test (Fig. 2, line graphs) indicated that most individuals had almost identical $\dot{V}O_{2max}$ values for both tests, and some individuals had a supramaximal $\dot{V}O_{2max}$ value that was less then that obtained during the incremental $\dot{V}O_{2max}$ test. The peak lactate concentration measured after the supramaximal test was 12.5 ± 2.9 $mmol{\cdot}L^{-1}$; (mean ± SD), confirming high rates of glycolysis to support these supramaximal work rates. The maximal heart rate reached by the subjects during incremental (191 ± 7) and supramaximal (181 ± 8) exercise was not significantly different ($P = 0.094$).

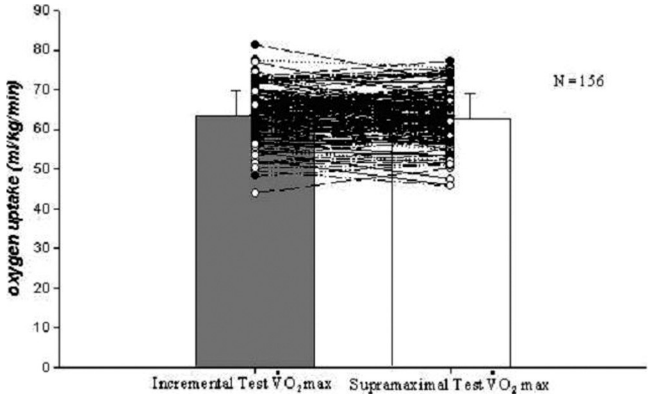

FIGURE 2—Comparison of mean incremental $\dot{V}O_{2max}$ (*gray solid bar*) and supramaximal $\dot{V}O_{2max}$ (*open bar*) for all 156 sets of tests. $\dot{V}O_{2max}$ data collected from each individual are represented by the *line graph*. Statistical analysis showed no significant difference between the incremental and supramaximal $\dot{V}O_{2max}$ results ($P = 0.77$).

DISCUSSION

The major finding of this study was that, in a large number of highly competitive middle-distance runners with sufficient motivation and anaerobic capacity to stay on a treadmill at supramaximal work rates long enough to achieve a stable oxygen uptake, this value rarely exceeded the $\dot{V}O_2$ achieved on an incremental treadmill test, and never by a substantial amount. These data strongly support the hypothesis that there is a level of oxygen uptake in humans beyond which increases in work rate will not elicit additional increments in $\dot{V}O_2$; this level is the maximal oxygen uptake.

The classic study of Taylor, Buskirk, and Henschel (19), reported in 1955, provided substantial evidence in support of $\dot{V}O_{2max}$ being a parametric measure of the cardiorespiratory system's capacity to deliver oxygen. In this investigation, 115 subjects were required to perform maximal exercise tests on a motor-driven treadmill to determine their maximal cardiorespiratory capacity to deliver oxygen. Subjects visited the laboratory on three to five separate days, at the first of which a Harvard fitness test (19) was given to determine the approximate maximal workload; the second day of testing consisted of a warm-up and 3 min of exercise at 7 mph on a grade (determined during the prior visit) with Douglas bag gas collections for 1 min during exercise. Each subsequent visit on successive days consisted of the grade being increased by 2.5% until $\dot{V}O_2$ differed by less then 2.1 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, which is one half to one third of the amount expected from this increase in grade (19). The major finding of this investigation was that $\dot{V}O_2$ increases linearly with increases in exercise workload, until a workload is reached at which the $\dot{V}O_2$ no longer increases and plateaus with further increases in work intensity (19).

The link between the achievement of $\dot{V}O_{2max}$ and the cardiorespiratory system's ability to deliver oxygen requires that both maximal cardiac output and a maximal extraction of oxygen relative to the circulatory transit time be achieved, thereby, fulfilling the quantifiable requirement of the Fick equation (5). Subsequently, Mitchell, Sproule, and Chapman (12) conducted a series of experiments requiring subjects to perform $\dot{V}O_{2max}$ tests with a protocol based on that used by Taylor et al. (19) to determine the hemodynamic effects of exercise at $\dot{V}O_{2max}$. Cardiac output (*Q*), systemic arterial oxygen tension (PaO_2), oxygen content (CaO_2), venous carbon dioxide content ($CvCO_2$), and hydrogen ion content (pH) were determined during maximal exercise. It was reported that at $\dot{V}O_{2max}$, *Q* had increased 4.3 times and arteriovenous oxygen difference (A-$\dot{V}O_{2diff}$) had increased 2.2 times to 14.3 mL per 100 mL of blood. $\dot{V}O_{2max}$ was considered to be the value at which

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the measurement immediately afterward had a $\dot{V}O_2$ no greater than 54 mL (the amount $\dot{V}O_2$ rose with each increase in workload minus twice the standard deviation) (12). Subsequently, after reaching this point in the $\dot{V}O_{2max}$ exercise test, with a continued increase in work intensity, Q began to decrease in all subjects, whereas the A-$\dot{V}O_{2diff}$ continued to increase (12). These findings confirmed that $\dot{V}O_2$ and Q had reached maximal values at a given workload intensity and that, when the workload was increased, both $\dot{V}O_2$ and Q plateaued or decreased. Furthermore, in these subjects, PaO_2 remained near resting values during the exercise, indicating that pulmonary gas exchange did not limit oxygen transport (12,13). However, it has been reported that in some athletes, evidence exists that desaturation may result from a mismatch between pulmonary transit time of the blood- and oxygen-diffusion capacity (4,17,18,20). Therefore, in healthy, nonelite, endurance-trained individuals, the measurement of $\dot{V}O_2$ provides a valid index of the cardiorespiratory capacity ($Q_{max} \times$ A-$\dot{V}O_{2diff}$) to deliver oxygen.

Noakes (14,15), however, has repeatedly disputed the concept of a plateau in $\dot{V}O_2$ being attained at maximal, and sustained at supramaximal, exercise workloads. This argument is centered on the exclusion of reported supramaximal exercise results for $\dot{V}O_{2max}$, confirming that a plateau has actually been reached, in the experiments performed by Hill and Lupton (6), Taylor et al. (19), and others who have previously studied the $\dot{V}O_{2max}$ plateau (12). A recent study (3) has demonstrated that incremental $\dot{V}O_{2max}$ is useful in exercise testing, whether or not a true plateau is reached, because of a correlation between the $\dot{V}O_{2max}$ obtained during constant-load exercise testing and that obtained during incremental exercise. In the present study, the data we collected provide strong support for the hypothesis that $\dot{V}O_{2max}$ is a quantifiable and reproducible parameter of the cardiorespiratory system's ability to deliver oxygen to the body at a given level of physical conditioning. After analyzing the results of 156 incremental tests, we brought each subject back to the laboratory for a supramaximal exercise test, collecting a total of 156 supramaximal $\dot{V}O_2$ tests. Each subject's supramaximal test resulted in a $\dot{V}O_{2max}$ virtually identical to that obtained during the subject's previous incremental maximal test, despite an aerobic work requirement that was 30% greater than that previously achieved, as well as a subsequent plateau in which the oxygen uptake did not increase above the subject's individual $\dot{V}O_{2max}$ despite the increased work intensity. Therefore, $\dot{V}O_2$ reached a maximum that was not increased with supramaximal work intensity, resulting in fatigue and, ultimately, termination of exercise.

The purpose of this study was not to identify the mechanisms of fatigue during maximal exertion that lead to the cessation of physical effort. However, we suggest that these data provide evidence against the concept of a central governor (16), which proposes that exercise is discontinued by the brain before truly maximal capacity, to avoid disturbance of homeostasis and to prevent complications of excessive effort, such as myocardial ischemia. Indeed, the athletes in this study were able to perform at extremely high work rates substantially above their maximal oxygen-transport capacity without negative consequences. Such supramaximal efforts are an intrinsic part of athletic events and are performed by competitive athletes for prolonged periods of time on a daily basis.

In conclusion, $\dot{V}O_{2max}$ is an invariable parameter defining the ability of the cardiorespiratory system to transport oxygen to various tissues of the body. These data confirm and extend the previous findings of Hill and Lupton (6), Taylor et al. (19), and Mitchell et al. (12), who used $\dot{V}O_{2max}$ as an index of maximal circulatory function despite arguments claiming it was not an accurate measurement representative of the maximal capacity of oxygen transport to the tissues. Therefore, $\dot{V}O_{2max}$ is a valid index measuring the limits of the cardiorespiratory system's ability to transport oxygen from the air to the tissues at a given level of physical conditioning and oxygen availability.

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