brief review

Criteria for maximal oxygen uptake: review and commentary

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ABSTRACT

HOWLEY, E. T., D. R. BASSETT, JR., and H. G. WELCH. Criteria for maximal oxygen uptake: review and commentary. *Med. Sci. Sports Exerc.*, Vol. 27, No. 9, pp. 1292–1301, 1995. Historically, the achievement of maximal oxygen uptake ($\dot{V}O_{2max}$) has been based on objective criteria such as a leveling off of oxygen uptake with an increase in work rate, high levels of lactic acid in the blood in the minutes following the exercise test, elevated respiratory exchange ratio, and achievement of some percentage of an age-adjusted estimate of maximal heart rate. These criteria are reviewed relative to their history, the degree to which they have been achieved in published research, and how investigators and reviewers follow them in current practice. The majority of the criteria were based on discontinuous protocols, often carried out over several days. Questions are raised about the applicability of these criteria to modern continuous graded exercise test protocols, and our lack of consistency in the terminology we use relative to the measurement of maximal oxygen uptake.

MAXIMAL AEROBIC POWER, PLATEAU, LACTATE, RESPIRATORY EXCHANGE RATIO, MAXIMAL HEART RATE, PEAK OXYGEN UPTAKE

Maximal aerobic power ($\dot{V}O_{2max}$) is one of the most common measurements made in exercise physiology laboratories. It is generally accepted as the best measure of the functional limit of the cardiovascular system (42) and is commonly interpreted as an index of cardiorespiratory fitness. Relative to this, $\dot{V}O_{2max}$ is a primary dependent variable in experimental studies designed to evaluate the effects of training (22,44) and detraining (11), exposure to altitude (39,59) and pollution (40), and the use of ergogenic aids such as blood doping (19,20). Finally, because $\dot{V}O_{2max}$ describes such a basic physiological characteristic, it has become a common descriptive variable much like height, weight, and age.

Figure 1 shows changes in oxygen uptake ($\dot{V}O_2$) with increasing intensities of exercise for a subject running at 7 mph (188 m·min^{-1}) on a treadmill. Oxygen uptake follows the increase in percent grade until 10% grade is reached. When the grade is increased to 12.5%, the $\dot{V}O_2$ levels off. This plateau in oxygen uptake with an increase in work rate is the primary criterion for having achieved $\dot{V}O_{2max}$. The term "maximal oxygen intake" and the concept of the plateau can be traced to an article by Hill and Lupton in 1923 (23). In their study the subject ran around an outdoor course at increasing speeds, and $\dot{V}O_2$ was measured during each run. Hill and Lupton found that "... the rate of oxygen consumption ... increases as speed increases ... reaching a maximum ... for speeds beyond 260 m/min. However much the speed be increased beyond that limit, no further increase in oxygen intake can occur .... " In spite of the clarity of the concept of the plateau, it is not uncommon for subjects to complete a maximal graded exercise test (GXT) on a treadmill or cycle ergometer, and fail to demonstrate a plateau in $\dot{V}O_2$.

For that reason a variety of secondary criteria have been used by scientists to characterize the oxygen uptake measured in the last minutes of a maximal GXT as the subject's $\dot{V}O_{2max}$. These secondary criteria include: (a) high levels of lactic acid in the blood in the minutes following the exercise test, (b) elevated respiratory exchange ratio (R), and (c) achievement of some percentage of an age-adjusted estimate of maximal heart rate. The purpose of this review is to reexamine these criteria, report on the consistency with which they are followed in published research articles, and raise some questions related to the measurement of $\dot{V}O_{2max}$ that need to be addressed by investigators and editorial review boards.

Plateau in Oxygen Uptake

The classic study by Taylor et al. in 1955 (56) described a careful and systematic approach to establish an operational definition of $\dot{V}O_{2max}$ for their testing procedures. Their subjects did a series of tests over approximately 3–5 d to establish that $\dot{V}O_{2max}$ had been achieved. On the first visit to the lab, the subject was familiarized with the equipment and procedures and completed a

0195-9131/95/2709-1292$3.00/0
MEDICINE AND SCIENCE IN SPORTS AND EXERCISE$_{\circledR}$

Submitted for publication November 1994.
Accepted for publication March 1995.

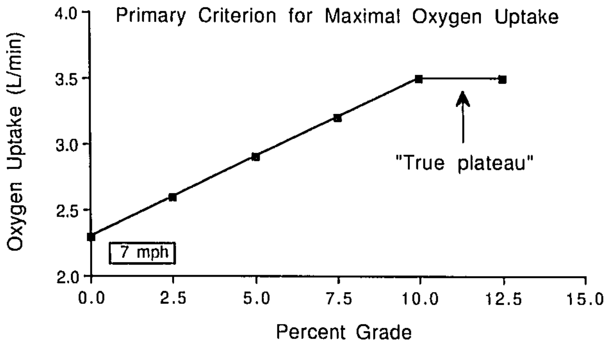

Figure 1—Plot of oxygen uptake versus percent grade showing a "true plateau" in oxygen uptake, signifying that maximal oxygen uptake ($\dot{V}O_{2max}$) has been achieved.

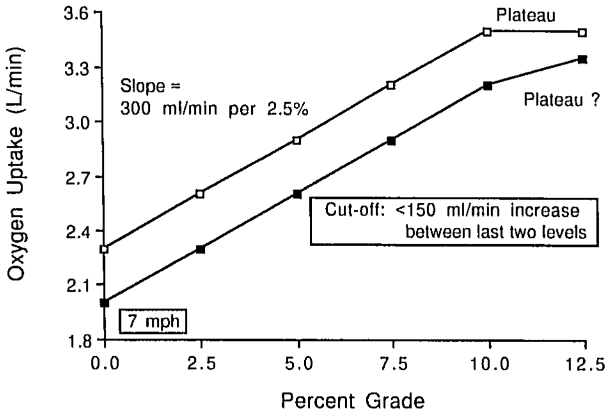

Figure 2—Plot of oxygen uptake showing the response of two subjects to a graded exercise test. One subject demonstrates a true plateau in $\dot{V}O_2$, while the other experiences an increase of less than one-half the expected change in $\dot{V}O_2$. Both achieve the plateau criterion. Adapted with permission from ref. 56: Taylor, H. L., E. Buskirk, and A. Henschel. Maximal oxygen uptake as an objective measure of cardio-respiratory performance. *J. Appl. Physiol.* 8:73–80, 1955.

treadmill version of the Harvard Fitness Test to estimate the treadmill grade that would yield $\dot{V}O_{2max}$. On the next visit, the subject warmed up by walking at 3.5 mph (94 $m \cdot min^{-1}$) on a 10% grade. Following a brief rest period (<5 min), the subject ran for 3 min at 7 mph (188 $m \cdot min^{-1}$) and at the previously selected grade. Expired gas was collected from 1:45 to 2:45. This procedure, from warm-up to gas collection, was repeated on the next visit at a 2.5% higher grade. Testing continued until the last two $\dot{V}O_2$ values measured on different days (representing two different grades) differed by less than 2.1 $ml \cdot kg^{-1} \cdot min^{-1}$ or 150 $ml \cdot min^{-1}$. Taylor et al. (56) found that the increase in oxygen uptake for a 2.5% grade change at 7 mph (188 m·min) was ($\bar{X} \pm$ SD) 4.2 ± 1.1 $ml \cdot kg^{-1} \cdot min^{-1}$. An increase in $\dot{V}O_2$ of less than 2-SD (<2.1 $ml \cdot kg^{-1} \cdot min^{-1}$) of the expected rise in oxygen uptake suggested that $\dot{V}O_2$ had leveled off and that there was a small chance of making an error in deciding that $\dot{V}O_{2max}$ had been achieved. The 150 $ml \cdot min^{-1}$ value is related to the mass of their subjects (approximately 72 kg).

Figure 2 shows how two subjects might respond to that test. Subject A demonstrates a "true plateau" while the value for subject B increases only 130 $ml \cdot min^{-1}$ over the last two work rates. Both subjects meet the criterion for having achieved $\dot{V}O_{2max}$. It is important to remember that in applying anyone else's value for having achieved a plateau, the test protocol and/or subject size have to be considered. It must be added that this was not the only definition of a plateau used by early researchers in exercise physiology. Table 1 summarizes values used by researchers as markers for having achieved a plateau in oxygen uptake. The actual cut-off value and the rationale for the value vary from study to study. A variety of concerns can be raised about the different standards used for a plateau in $\dot{V}O_2$. These include: measurement error for $\dot{V}O_2$, achieving higher values for $\dot{V}O_{2max}$ after plateau criteria have been met, and the applicability of these plateau standards to all populations.

Measurement error. At least two observations can be made with regard to the variability in the definition of a plateau in oxygen uptake: (a) some cut-off values may be too generous (e.g., <2.1 $ml \cdot kg^{-1} \cdot min^{-1}$) (56), and might result in an underestimation of a subject's true $\dot{V}O_{2max}$, and (b) other values may be so small (<50–60 $ml \cdot min^{-1}$) as to be beyond our ability to measure a real difference in $\dot{V}O_2$ (35). The value used by Taylor et al. (56) provided an objective standard for their testing procedures that allowed them to evaluate the effects of a wide variety of factors on $\dot{V}O_{2max}$. With their value, the vast majority of subjects (108 of 115) were able to achieve a plateau. However, some subjects who had met this criterion achieved higher $\dot{V}O_{2max}$ values when brought back to the lab for another test (18). This suggests that the cut-off value may be too liberal.

In contrast, cut-off values of approximately 50–60 $ml \cdot min^{-1}$ approach the limits of one's ability to measure $\dot{V}O_{2max}$, and may represent a cut-off for what would be considered a true plateau. For example, if an individual were to measure oxygen uptake during a submaximal run and found two consecutive 1-min gas collections to yield values of 2.30 and 2.36 l·min, an average of the two values would probably be used to characterize the "true" $\dot{V}O_2$ for that test. If that is the case, then a difference of 60 $ml \cdot min^{-1}$ between consecutive 1-min gas collections measured during two successive stages of a maximal test would suggest that the $\dot{V}O_2$ had not really changed; therefore, the values should be averaged, and expressed as $\dot{V}O_{2max}$. If gas collections for two successive stages of a maximal test gave values of 3.74 $l \cdot min^{-1}$ and 3.80 $l \cdot min^{-1}$, one might wonder if a plateau had been achieved. On the other hand, if the two successive values were 3.80 and 3.74 $l \cdot min^{-1}$, one might feel confident that a plateau had been achieved. The real question is whether there was any real difference between these two values. The following paragraphs address that question.

TABLE 1. Examples of plateau criteria used in studies published in the 1950s and 1960s.

Author	Test Protocol	Definition of Plateau	Rationale for Plateau
Åstrand (6)	Treadmill run test (between days) using increments of 1–2 $km \cdot h^{-1}$ until intensity caused exhaustion in 4–6 min	Leveling off of O_2 uptake	No change or a drop in $\dot{V}O_2$ for an increase in exercise intensity
Taylor et al. (56)	Intermittent test (between days) at 7 mph, with 2.5% grade change per 3-min stage	<2.1 $ml \cdot kg^{-1} \cdot min^{-1}$ or 150 $ml \cdot min^{-1}$	Less than 2 SD of expected rise in $\dot{V}O_2$
Mitchell et al. (35)	Intermittent test (within days) at 6 mph, with 2.5% grade change per 2.5-min stage	<54 $ml \cdot min^{-1}$	$\dot{V}O_2$ increment of 142 ± 44 $ml \cdot min^{-1}$ minus 88 $ml \cdot min^{-1}$ (2 SD)
Åstrand (4)	Intermittent test (between days) on a cycle ergometer with work rate change of 25 W per stage	80 $ml \cdot min^{-1}$	More than twice the error of measurement of $\dot{V}O_2$ during submaximal work
Issekutz et al. (25)	Intermittent cycle test (within days) with a stage of 25 W	<100 $ml \cdot min^{-1}$	One-third the oxygen requirement of the stage change
Cumming and Friesen (13)	Intermittent cycle test (between and within days) until load could not be maintained for 3 min	<50 $ml \cdot min^{-1}$	About one-third of their expected increase in $\dot{V}O_2$ for a 16-W increase in work rate over two stages

It is worth pointing out that in any discussion of "measurement" error in $\dot{V}O_2$ that, technically, it is not a measurement, but a calculation based upon the measurement of three distinct primary variables: the minute ventilation and the O_2 and CO_2 fractions. In addition, three other variables enter into this calculation: the barometric pressure, the gas temperature, and the water vapor pressure of the gas. Although all six can affect the accuracy of the $\dot{V}O_2$ calculation, the latter three have little effect on measurement error in $\dot{V}O_2$. For example, it would take an error in barometric or water vapor pressure of 7–8 mm Hg to cause an error in $\dot{V}O_2$ of 1% (7.6/760); it would also require an error of about 3°C to cause a 1% error (3/273) in $\dot{V}O_2$ or gas volume. So at least for the Douglas bag method, which was commonly used in the studies that set the plateau criteria for having achieved $\dot{V}O_{2max}$, estimates of $\dot{V}O_2$ are relatively insensitive to small errors in these variables. Thus, accurate determinations of $\dot{V}O_2$ in the classic approach depend especially upon reliable measurements of gas volume (or flow) and expired gas fractions. Traditional devices for the measurement of gas volumes include the Tissot gasometer and the dry gas meter, with the latter's calibration established using the former as the standard. These devices can measure volume to within ± 2% (10,14). In general, the early investigators collected expired gases into the Tissot gasometer directly, or into a Douglas bag whose volume was subsequently measured using the Tissot gasometer (4,35,56). This estimate of error of measuring volume does not carry over to all of the newer technologies (e.g., turbines, pneumotachographs, etc.) used for determination of gas volumes or flow rates. It is important for investigators using these newer methods to validate their instruments with flow rates ranging for what is observed for light through maximal exercise (32,38,60,61).

For gas fractions, the early studies used the Haldane chemical gas analyzer or electronic gas analyzers, which were calibrated with gases analyzed on a Haldane gas analyzer. Typically, the gas analysis of two syringes drawn from a single Douglas bag would have to agree within 0.10% before acceptance. By averaging the two values, one could assume that the error was not more than 0.05%. This should mean a maximal error in the gas fraction of <1.5%–2%. Following this argument, the combined effects of random error in volumes and gas fractions should result in maximal errors of no more than about 3% in $\dot{V}O_2$, or about 60 $ml \cdot min^{-1}$ at a $\dot{V}O_2$ of 2.0 $l \cdot min^{-1}$. This value would represent the largest errors resulting from the three principal variables; average errors should be less.

The use of electronic gas analyzers may actually be more precise than earlier chemical methods, that is, they may show a smaller variance for repeated estimates of the same gas sample. The accuracy of the latter analyzers, however, presents a potentially serious problem. Commercially available gas mixtures used to standardize electronic gas analyzers are often accepted without validation, which can lead to serious systematic errors in measuring $\dot{V}O_2$. Further, some laboratories use a two-point calibration (room air and one calibration gas). This is unacceptable practice in careful work; in fact, given the possible problems with commercial calibration gases, and the potential deviation from linearity in electronic analyzers, it is probably wise to insist on a three-point calibration (0%, span [6% CO_2 and 15% O_2], and midrange [3% CO_2 and 18% O_2]) for both gas analyzers.

The estimate for average errors given above includes only those inaccuracies that would arise from random errors in the measuring instruments. In practice, the error associated with the technical aspects of $\dot{V}O_2$ measurement is generally less than 10% of the total error of measurement (27,55). The errors are likely to be larger in actual experiments, where the inability of the subject to maintain a prescribed work rate, or an improperly set work rate, could contribute to larger variations. In our laboratory we have typically found that the coefficients of variation are <3% for repeated measurements on a subject performing submaximal steady state exercise (58). Even when comparing the steady-state $\dot{V}O_2$ for different subjects at specific work rates ranging from 60 to 225 W, the coefficient of variation ranged from 2% to 5%. Properly done, the estimate of $\dot{V}O_2$ during steady-state exercise is remarkably reproducible, and even at levels of $\dot{V}O_2$ as high as 3.0–4.0 l·min^{-1}, the variation from one minute to the next should rarely exceed 100 ml·min^{-1}. Consistent with this, I. Åstrand estimated her error in measuring submaximal $\dot{V}O_2$ to be about 30 ml·min^{-1} for a $\dot{V}O_2$ of about 1.7 l·min^{-1} (4). This estimate of error was taken into account in establishing her cut-off value of 80 ml·min^{-1} for a plateau in $\dot{V}O_2$.

The question of determining $\dot{V}O_2$ during maximal exercise is more problematic. In the first place, the Fick principle, on which the calculation is based, is technically valid only during the steady state. The condition under which $\dot{V}O_{2max}$ is determined is, by definition, not a steady state. Although, in theory, the use of the standard equation may be open to question, in practice, the problem seems not to be so serious as to invalidate the procedure.

Even if the failure to meet the steady-state assumption does not in itself invalidate the calculation of $\dot{V}O_2$, it must increase both the absolute error (ml·min^{-1}) and the variability (e.g., coefficient of variation). In one study from our lab, a series of 10 estimates on one subject at $\dot{V}O_{2max}$ (>4.2 l·min^{-1}) was reported—the SD was 170 ml·min^{-1} for collection periods of 45–60 s (58). These experiments were carried out with an attempt for the highest precision, and it was encouraging to find a coefficient of variation of about 4%, which is approximately in the middle of the range of values reported for repeated measurements of $\dot{V}O_{2max}$ (27). Within-subject variability of this magnitude must be considered in designing studies in which an expected change or difference in $\dot{V}O_{2max}$ is small (27). It should also influence our selection of a single value, among a series of values, as being $\dot{V}O_{2max}$.

If the highest value in a series of calculations of $\dot{V}O_2$ is taken as representing $\dot{V}O_{2max}$, a systematic error will be introduced with a bias toward the most extreme values. In other words, it will systematically overestimate $\dot{V}O_{2max}$. This error will occur even when collection periods are as long as 1 min, but it is even more serious when collection periods are shortened to 20–30 s, as is often done in evaluations of $\dot{V}O_{2max}$. With a shorter collection period, 30 s, for example, the random errors are effectively multiplied by 2. When this is combined with the larger inherent variability of the nonsteady-state condition, and the decision to use the largest calculated value in a series, the probability of systematically overestimating $\dot{V}O_{2max}$ becomes a matter of concern. It is preferable to use collection periods of 60 s, or if that is not feasible, to average at least two consecutive values. If this is not done, it is possible to introduce errors of 200 ml·min^{-1} or greater in maximal exercise, and most will overestimate the actual value.

One final note on this problem. The above comments were based mostly on experiments done with the Douglas bag method in which there is an exact matching of gas volumes and fractions. It did not address the increased variability and loss of accuracy that may accompany the use of automated systems that use mixing chambers for the expired gases and pneumotachographs or turbines for gas flows. In these systems special care must be taken to ensure the temporal matching of volume (flow) and expired gas fractions (9,24,38). For example, automated systems measuring inspired ventilation must hold that quantity in memory to match it with the correct expired O_2 and CO_2 values obtained after the gases pass through a mixing chamber and the gas analyzers. This time delay includes the time needed for the electronic gas analyzers to respond (a constant), and the time needed to washout the mixing chamber. The latter time is inversely related to the rate of ventilation, i.e., the lower the ventilation, the longer it takes to washout the mixing chamber (38). Such automated systems can increase the chance for errors, both systematic and random, in complicated arrangements that do not lend themselves to standard calibration techniques (32,36).

Higher $\dot{V}O_2$ values after the plateau. Error in measurement is not the only concern that has been raised about the plateau criteria. Glassford et al. (18) compared $\dot{V}O_{2max}$ using the protocols of Taylor et al. (56), Mitchell et al. (35), and Åstrand (4), applying the cut-off values of 150 ml·min^{-1}, 54 ml·min^{-1}, and 80 ml·min^{-1}, respectively. They found no difference in the measured $\dot{V}O_{2max}$ values between the two treadmill tests (35,56). However, they report that several subjects (number not given) experienced a significant increase in oxygen uptake on the two treadmill tests when they were tested at higher work rates after meeting the specified criteria for leveling off. This might be more likely in an intermittent protocol with stages of a fixed duration such as the Taylor et al. protocol in which gas collections were made between 1:45 and 2:45 of a 3-min stage (56). If the subjects had worked to volitional exhaustion at each stage of the test, the potential for a significantly higher $\dot{V}O_2$ to be achieved at the next higher stage would be reduced. Åstrand and Saltin (8) have shown that in heavy exercise the rate of increase in $\dot{V}O_2$ varies with the work rate. For work rates that can be tolerated for 5–6 min, $\dot{V}O_2$ increases over time, and equals the $\dot{V}O_{2max}$ values measured for work rates that can be tolerated for only 2–3 min.

Applicability of plateau cut-off values. Independent of the debate about what value should be used as the leveling off criterion, some attention needs to be given to the question, "Can everyone achieve a plateau in $\dot{V}O_2$?" Considerable variation in the achievement of a plateau has been reported in the literature. For example, the percent of subjects who achieved a plateau has been reported to be 90%–100% (4,18,35,56), 60%–80% (37,51), and ≤50% (6,13,17). It is clear that one must consider a variety of factors when making a judgment about the ease or difficulty in achieving a plateau in oxygen uptake. These include: (a) the population being

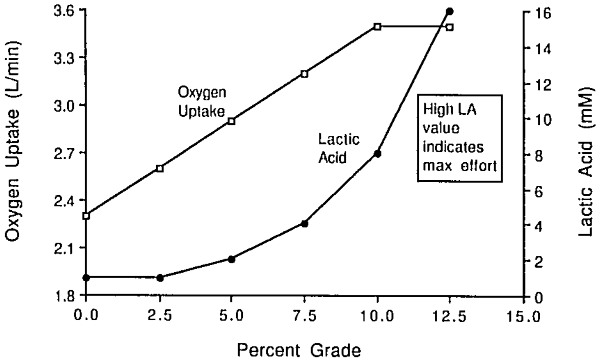

Figure 3—Theoretical plot of the change in blood lactic acid with increasing intensities of exercise, showing its relationship to a plateau in oxygen uptake.

studied: children, low-fit, and the elderly have a more difficult time achieving a plateau, and the cut-off value represents a large fraction of their $\dot{V}O_{2max}$ (6,13,46,51); (b) the protocol: an intermittent protocol allows one to have a subject return to the lab to meet a standard, and repeat testing increases the number of subjects achieving a plateau (51,56), and (c) motivation: more subjects making a good effort attain $\dot{V}O_{2max}$ than those making only a "poor effort" (48,51). The failure of some subjects to achieve a plateau in $\dot{V}O_2$ in a graded exercise test led researchers to evaluate the use of other physiological responses that would suggest that the subject had, in fact, been working maximally when the highest $\dot{V}O_2$ was measured. The use of these secondary criteria for $\dot{V}O_{2max}$ will now be considered.

High Levels of Blood Lactic Acid

Blood lactate is a good choice as an indicator of maximal effort. High levels of blood lactic acid are associated with the recruitment of fast-twitch muscle fibers (43), the rapid elevation of the plasma epinephrine concentration (28), and the reduction in liver blood flow (42) that occur during heavy exercise. Figure 3 shows the theoretical relationship between high levels of lactic acid and the plateau in oxygen uptake. It was this connection that Åstrand used to establish his lactic acid criterion for $\dot{V}O_{2max}$, when only 50% of the subjects achieved a plateau in $\dot{V}O_2$ (6). In his study the subjects completed a discontinuous test in which they ran at faster speeds on each successive test day. He found that for those who showed a plateau in $\dot{V}O_2$, the post-exercise blood lactate concentration ranged from 6.7 to 10.1 mM when the oxygen uptake curves leveled off, with the average values being 7.9–8.4 mM. When boys (14–18 yr) and girls (14–17 yr) who had experienced a leveling off in $\dot{V}O_2$ were compared with those who had achieved a high lactic acid value but not a leveling off in $\dot{V}O_2$, the average $\dot{V}O_{2max}$ was the same for both groups. Based on these observations, Åstrand used the lactic acid value and the subjective stress of the subject to select the highest $\dot{V}O_2$ value as the subject's $\dot{V}O_{2max}$, when a plateau in $\dot{V}O_2$ was not observed.

Just as there are several values to indicate that a plateau in $\dot{V}O_2$ has been achieved, a variety of lactic acid standards have been used to judge whether the highest $\dot{V}O_2$ value is the $\dot{V}O_{2max}$. For example, while Åstrand (6) used the plateau or LA values of 7.9–8.4 mM as criteria, other investigators used a plateau and LA values of 7.3 mM (5,26). Still others used a $\dot{V}O_2$ 10% below the requirement and/or LA values of 5.5 mM (16). As with the plateau criterion, the literature indicates some variation in the ability of subjects to achieve a LA criterion. Table 2 shows that in contrast to the young children in Åstrand's study (6), the children in Robinson's (41) and Cunningham et al.'s (15) studies had difficulty achieving the 7.9–8.4 mM standard. In Robinson's study (41) the lower value may be related to the use of a single supramaximal test to measure $\dot{V}O_{2max}$, in contrast to the intermittent tests used by Åstrand. In Cunningham et al.'s study (15), the lower LA values were measured on those who had demonstrated a plateau in $\dot{V}O_2$, but a continuous treadmill protocol was used. Similarly, in some elderly subjects, even those who gave a "good effort" and demonstrated a plateau in $\dot{V}O_2$, only 50% to 78% achieved post-exercise lactate concentrations of 8.8 mM (51). This suggests that the LA standard, based on children completing an intermittent run-test protocol, might not be applicable across all groups, ages, and protocols.

Respiratory Exchange Ratio

The respiratory exchange ratio (R) has been used as a secondary criterion for having attained $\dot{V}O_{2max}$. This is based, in part, on the following reaction between a rising plasma hydrogen ion (H^+) concentration and plasma bicarbonate (HCO_3^-):

$$H^+ + HCO_3^- \rightarrow H_2CO_3 \rightarrow H_2O + CO_2.$$

As the CO_2 is generated, ventilation increases and the respiratory exchange ratio is increased. Early work by Wasserman (57) confirmed the reciprocal change in lactate and plasma bicarbonate. Figure 4 shows how the rising respiratory exchange ratio might relate to a plateau in oxygen uptake during a graded exercise test, and be considered as a criterion for $\dot{V}O_{2max}$. The use of an R value $\geq$ 1.15 as a criterion for $\dot{V}O_{2max}$ can be traced to work by Issekutz et al. (25,26). In their 1961 study (26), subjects completed a series of intermittent exercise tests of 4–5 min duration until $\dot{V}O_{2max}$ was achieved. Lactate was measured post-exercise, and the investigators calculated "excess CO_2" (CO_2 production minus 0.75 times the $\dot{V}O_2$) based on gas collections made after 3.5–4 min of work. This calculation assumed a true "metabolic respiratory quotient (RQ)" of 0.75. They found a linear relationship between the change in LA (from pre- to

TABLE 2. Observations regarding lactic acid responses in tests of $\dot{V}O_{2max}$.

Study	Subjects	Lactate Responses
Robinson (41)	Males, X̄ age (yr):	X̄ LA (mM):
	10–17	5.7–7.4
	24–52	10.0–8.2
	63	6.5
P. O. Åstrand (6)	Boys, age (yr):	X̄ LA (mM):
	4–6	6.3
	7–9	9.2
	10–11	9.4
	12–13	8.9
	14–15	10.2
Cunningham et al. (15)	Boys, 10 yr, who demonstrated plateau	X̄ LA (mM): 4.9–6.5 mM
Shephard et al. (48)	Boys 11–13 yr	X̄ LA (mM): 8.8 mM
	Girls 11–13 yr	X̄ LA (mM): 8.7 mM
I. Åstrand et al. (5)	Men, 56–68 yr	89% achieved LA (mM) >7.9 mM
Cumming and Borysyk (12)	Men, 40–65 yr	78% achieved LA (mM) >8 mM
Sidney and Shephard (51)	Men and women 60–83 yr who gave a "good effort"	Men: 79% plateau; 78% ≥8.8 mM
		Women: 75% plateau; 50% ≥8.8 mM

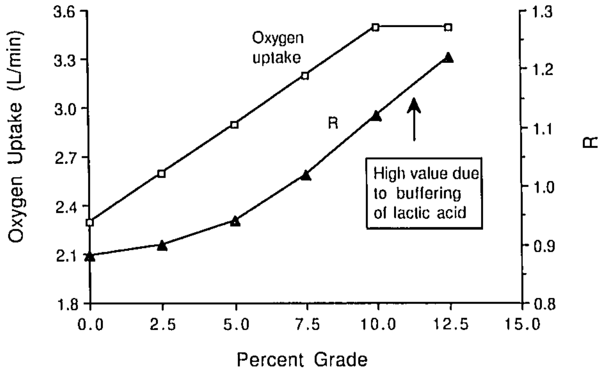

Figure 4—Theoretical plot of the change in the respiratory exchange ratio (R) with increasing intensities of exercise, showing its relationship to a plateau in oxygen uptake.

post-exercise) and the excess CO_2. This excess CO_2 was also expressed as the ΔRQ, (where ΔRQ = measured RQ − 0.75), and seemed to reflect the percent participation of anaerobic glycolysis in total energy expenditure. Their 1962 study (25) built on this work and demonstrated how the ΔRQ value could be used to predict $\dot{V}O_{2max}$. In this study, the subjects completed a series of 5-min intermittent exercise tests until $\dot{V}O_{2max}$ was achieved. They found that each subject, independent of sex or age (above 20 yr), reached $\dot{V}O_{2max}$ at the same ΔRQ value of 0.4 (or an RQ = 1.15 (0.75 + 0.4)).

As was true for the other criteria discussed above, Table 3 shows that not everyone can achieve the R ≥ 1.15 criterion, even when a plateau in $\dot{V}O_{2max}$ has been achieved. The average R reported by Robinson (41) for subjects over 20 and under 60 yr suggests that the R ≥ 1.15 standard may be reasonable; however, younger subjects in his study did not achieve it. Further, Cunningham et al. (15) found R values of less than 1.00, consistent with the low lactate values measured in their study. In contrast to Robinson's data on older men, Cumming and Borysyk (12) found only 54% of 40- to 65-yr-old men to achieve an R ≥ 1.12. Consistent with this, Sidney and Shephard (51) found that in 60- to 83-yr-old men and women who gave a "good effort," only 37% and 20%, respectively, achieved an R ≥ 1.15. Finally, while Aitken and Thompson (1) found the mean R to range from 1.01 to 1.11 when $\dot{V}O_2$ leveled off, it was systematically higher, mean R ranged from 1.11 to 1.16, at the end of exercise. Clearly, an R ≥ 1.15 is not a universal finding, even in those who demonstrate a plateau in $\dot{V}O_2$.

Age-Adjusted Estimates of Maximal Heart Rate

The achievement of some percentage of age-adjusted maximal heart rate is a problematic criterion. The standard deviation associated with the estimate is approximately ± 11 $b \cdot min^{-1}$, making it a very difficult "standard" to justify (30). Subjects in the lower half of the distribution would not be able to achieve the heart rate standard, even when working maximally; those at the other end of the distribution would achieve the estimate while working at submaximal work rates. For this reason, the American College of Sports Medicine states that predicted maximal heart rates should not be used as an absolute endpoint in test termination (3). Over 20 yr ago Cumming and Borysyk (12) concluded on the basis of their analysis of the criteria for $\dot{V}O_{2max}$, that the maximal heart rate range was too wide to use an average maximum value as a criterion for $\dot{V}O_{2max}$. Their conclusion appears to be as reasonable today as it was then.

Current Practice

What are today's investigators using as the criteria for having achieved $\dot{V}O_{2max}$? A summary of the criteria stated in 29 articles published in *Medicine and Science in Sports and Exercise* between October 1993 and May 1994 provides an answer to that question. Table 4 indicates that a great deal of variability exists in the standards used for each of the criteria previously discussed. On the basis of what is described in Table 4, one might conclude that there is no general agreement on the use of specific criteria for establishing that $\dot{V}O_{2max}$ has, in fact, been achieved. As Shephard noted more than 10 yr ago (47),

TABLE 3. Observations regarding the respiratory exchange ratio (R) in tests of $\dot{V}O_{2max}$.

Study	Subjects	R Responses	
Robinson (41)	Males, $\bar{X}$ age (yr):	$\bar{X}$ R:	
	10–17	1.12–1.11	
	24–52	1.21–1.17	
	63	1.09	
Cunningham et al. (15)	Boys, 10 yr, who demonstrated plateau	$\bar{X}$ R < 1.00	
Shephard et al. (48)	Boys 11–13 yr	$\bar{X}$ R: 1.08	
	Girls 11–13 yr	$\bar{X}$ R: 1.08	
Cumming and Borysyk (12)	Men, 40–65 yr	54% achieved R > 1.12	
Sidney and Shephard (51)	Men and women 60–83 yr who gave a "good effort"	Men: 79% plateau; 37% R ≥ 1.15	
		Women: 75% plateau; 20% R ≥ 1.15	
Aitken and Thompson (1)	Groups:	$\bar{X}$ R at $\dot{V}O_{2max}$	$\bar{X}$ R at end-exercise
	Young sedentary	1.08	1.16
	Over 60 yr, sedentary	1.06	1.11
	Endurance trained	1.11	1.16
	Team athletes	1.06	1.15
	Weight trained	1.01	1.14

TABLE 4. Criteria for $\dot{V}O_{2max}$: review of 29 studies in *Medicine and Science in Sports and Exercise* (Oct. 1993–May 1994).

Criterion	Value Used: No. Reporting
None stated	$N = 7$
Plateau in $\dot{V}O_2$	Absolute: $N = 1$
	Unspecified: $N = 3$
	≤ 2 ml·kg^{-1}·min^{-1}: $N = 4$
	≤ 150 ml·min^{-1}: $N = 3$
	$\dot{V}O_2$ less than predicted: $N = 1$
	≤ 0.28 l·min^{-1}: $N = 1$
Lactic acid	≥8 mM: $N = 1$
Respiratory exchange ratio	≥ 1.13: $N = 1$
	≥ 1.10: $N = 7$
	≥ 1.05: $N = 2$
	≥ 1.00: $N = 4$
Heart rate	± 10 b·min^{-1} of (220 − age): $N = 3$
	± 15 b·min^{-1} of (220 − age): $N = 1$
	≥ (220 − age): $N = 2$
	≥ 90% of (220 − age): $N = 3$
	Plateau: $N = 1$

Some authors used these in combination.

it is not clear how to use the additional pieces of information (secondary criteria) alone or in combination, to evaluate the quality of the test when a true plateau in $\dot{V}O_2$ does not occur. Part of the problem may relate to our attempt to generalize and use "standards" based on one type of protocol for all protocols.

The $\dot{V}O_2$ cut-off values (e.g., 150 ml·min^{-1}) for verifying the achievement of $\dot{V}O_{2max}$ were established using a discontinuous test, usually done between days (see Table 1). In many cases, the work rate change was equal to an increase of 300 ml·min^{-1} in $\dot{V}O_2$. In contrast, most of today's laboratories use continuous test protocols in which each stage of the test lasts more than 1 min. In this case, the application of a cut-off value to the $\dot{V}O_2$ measured in the second minute of a stage is inappropriate (relative to that measured in the first minute) since a work rate change did not precede the measurement. These latter tests are similar to GXT protocols used for cardiovascular assessment in which the investigator or clinician wishes to obtain a series of "steady state" responses at increasing exercise intensities, as well as a measurement of $\dot{V}O_{2max}$. It is possible that one purpose might interfere with the other. The focus in the original studies that set some of the standard criteria we use today was on measuring $\dot{V}O_{2max}$, and intermittent protocols were chosen accordingly. If a subject did not meet the criteria, another visit to the laboratory was scheduled.

The lactate standard established by Åstrand (6) over 40 yr ago was also based on an intermittent (between day) protocol designed to achieve an intensity that caused exhaustion in 4–6 min while running at a constant velocity. Blood samples were taken from a warmed hand during the first minute following work, and another sample was taken at 3–4 min. Other studies (4,5) obtained blood samples at these same times, and as well as at 6–8 min in an attempt to obtain the highest LA value. In all cases the lactate value reflected the energy demands of a single work rate, as opposed to a series of work rates as is experienced on a continuous graded exercise test. Contrasting traditional testing procedures with today's GXT procedures raises some questions about our ability to transfer standards from one protocol to another. However, another question could be raised about the consistency of current sampling methodology with those used in the early studies. The multiple-blood-sample procedure was designed to find the highest LA value, not simply report the value measured at some moment after maximal exercise. Finally, if the brief summary in Table 4 is reflective of what criteria are currently being used, it is surprising that only one of 29 studies used a post-exercise lactate measure as a criterion for $\dot{V}O_{2max}$. This may simply reflect concerns about handling blood samples, rather than represent a movement away from this criterion. However, it would appear reasonable to standardize the post-exercise collection times to allow comparisons of lactate values across studies.

The respiratory exchange ratio standard was also based on an intermittent protocol, with gas collections being made after 3.5–4 min (25,26). Using this protocol, the investigators found the ΔRQ values to follow the change in lactate (measured post-exercise), and in this way, the ΔRQ value was proposed as a noninvasive estimate of the lactate values. It must be remembered that this relationship of ΔRQ to $\dot{V}O_{2max}$ was based on their protocol and collection times. Shephard found that this relationship could not be generalized across ergometers, and to all populations (45), and raises some questions as to the applicability of that standard to other protocols.

Although one might wonder about the appropriateness of extrapolating $\dot{V}O_{2max}$ criteria across all protocols, there is ample evidence that $\dot{V}O_{2max}$ is the same when measured with a continuous or discontinuous protocol (31,33,49,52). This agreement exists even when lactate (49) and R (33) values differ between continuous and discontinuous protocols. Further, $\dot{V}O_{2max}$ was shown to be reproducible, even when preexercise lactate values were 16 mM, and a plateau in $\dot{V}O_2$ did not occur (53). These studies suggest that $\dot{V}O_{2max}$ can be measured accurately using a continuous protocol. However, the extent to which the classic criteria for $\dot{V}O_{2max}$ should be applied to these protocols is still unclear.

Concerns Regarding the Criteria for $\dot{V}O_{2max}$

A variety of concerns might be raised about the criteria for $\dot{V}O_{2max}$. They include the need for guidelines for measuring $\dot{V}O_{2max}$, agreeing on the differences in expectations for descriptive versus experimental studies, and finally, the need for consistent terminology.

Guidelines. In 1975 the American College of Sports Medicine published the first edition of the Guidelines for Graded Exercise Testing and Prescription (2). Its purpose was to help standardize the screening and testing of healthy and patient populations, and provide some direction in the interpretation of test results relative to disease risk and readiness for participation in an exercise program. Perhaps we need some "guidelines" to promote uniformity in testing subjects to measure $\dot{V}O_{2max}$. This would not require the detail of the 1975 publication, but it might clarify some of the steps one might follow to optimize conditions to measure $\dot{V}O_{2max}$ using a continuous protocol. The steps might include the following, many of which are taken from Shephard's and McConnell's reviews (34,49):

Orientation, practice session to estimate $\dot{V}O_{2max}$

Warm-up at 60–70% of $\dot{V}O_{2max}$ for 5 min, followed by a brief rest

Protocol: Initial load set at about 60–70% $\dot{V}O_{2max}$; rate of change of load set at about 5% $\dot{V}O_{2max}$ per minute to result in a test of about 8–10 min

Gas collection procedures: set a minimum collection time (e.g., 30 s), and require a minimum number of gas collections (e.g., last 3 min of the test.)

State the specific criteria used to verify the achievement of $\dot{V}O_{2max}$, and report the actual range of values measured.

One might also suggest that those of us using automated systems address the concerns raised earlier regarding the measurement of ventilation, the linearity of the gas analyzers, and the matching of gas fractions and ventilation when both are changing at a high rate in maximal work. However, we must also recognize that the same attention to detail may not be necessary for all situations in which an investigator needs data on $\dot{V}O_{2max}$.

Descriptive versus experimental studies. It would appear reasonable for scientists using an epidemiological approach to solve a problem that submaximal estimates of $\dot{V}O_{2max}$ are sufficient due to the field nature of some of their studies (50). Further, for those reporting $\dot{V}O_{2max}$ values as a simple descriptive characteristic of a population, it might be acceptable to use a minimum number of criteria in establishing a value as $\dot{V}O_{2max}$. On the other hand, for experimental studies in which $\dot{V}O_{2max}$ is a primary dependent variable, it would seem appropriate that a plateau and other criteria be used as a part of the standard methodology in defining a value as $\dot{V}O_{2max}$, both pre- and post-treatment.

Terminology. Finally, there is a need to standardize the terminology associated with measuring maximal oxygen uptake. In the work done in the 1950s and 1960s, scientists recognized that the highest value for oxygen uptake was lower when measured on a cycle ergometer, compared with a treadmill (18,35), but similar criteria were applied to both types of tests (see Table 1). In 1974, Rowell (42) described $\dot{V}O_{2max}$ as the highest oxygen uptake that can be achieved during treadmill exercise of sufficient intensity and duration, involving about 50% or more of the total muscle mass, and where objective criteria are met (specifically, a plateau and/or a high post-exercise lactate). He saw $\dot{V}O_{2max}$ as reflecting the limits of the cardiovascular system's ability to respond to exercise. In contrast, he used the term $\dot{V}O_{2peak}$ to describe the highest value reached under a specific set of circumstances or conditions, for example, cycle ergometry [typically, 89%–93% of treadmill value] (21,33) or arm ergometry (typically, 70% of cycle value in average subjects) (7). The problem in terminology is confounded by the fact that highly trained cyclists attain higher values for $\dot{V}O_{2max}$ on a cycle compared with that measured using a running test up a grade (54). The use, and misuse, of the terms $\dot{V}O_{2max}$ and $\dot{V}O_{2peak}$ has led to confusion in the research literature. For example, it is not uncommon for authors and reviewers to use of the term $\dot{V}O_{2peak}$ if "criteria" are not met, even though there is little agreement about what the criteria really are. In 1978 Knuttgen (29) published a brief two-page article to help standardize our terminology as it relates to the terms work, energy, power, and exercise. It seems that we are in need of another brief statement to help standardize the terminology for $\dot{V}O_{2max}$, which will allow scientists to make better comparisons across studies.

The authors wish to recognize the helpful comments and suggestions of Hiro Tanaka, Glen Duncan, and Dr. Dixie Thompson in the preparation of this manuscript.

Support was provided by UTK Exhibit, Performance and Publication Expense fund.

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