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ORIGINAL ARTICLE

Validity of criteria for establishing maximal O_2 uptake during ramp exercise tests

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Abstract The incremental or ramp exercise test to the limit of tolerance has become a popular test for determination of maximal O_2 uptake ($\dot{V}O_{2max}$). However, many subjects do not evidence a definitive plateau of the $\dot{V}O_2$ - work rate relationship on this test and secondary criteria based upon respiratory exchange ratio (RER), maximal heart rate (HR_{max}) or blood [lactate] have been adopted to provide confidence in the measured $\dot{V}O_{2max}$. We hypothesized that verification of $\dot{V}O_{2max}$ using these variables is fundamentally flawed in that their use could either allow underestimation of $\dot{V}O_{2max}$ (if, for any reason, a test were ended at a sub-maximal $\dot{V}O_2$), or alternatively preclude subjects from recording a valid $\dot{V}O_{2max}$. Eight healthy male subjects completed a ramp exercise test (at 20 W/min) to the limit of tolerance on an electrically braked cycle ergometer during which pulmonary gas exchange was measured breath-by-breath and blood [lactate] was determined every 90 s. Using the most widely used criterion values of RER (1.10 and 1.15), $\dot{V}O_{2max}$ as determined during the ramp test (4.03 ± 0.10 l/min) could be undermeasured by 27% (2.97 ± 0.24 l/min) and 16% (3.41 ± 0.15 l/min), respectively (both $P < 0.05$). The criteria of HR_{max} (age predicted HR_{max} ± 10 b/min) and blood [lactate] (≥8 mM) were untenable because they resulted in rejection of 3/8 and 6/8 of the subjects, most of whom (5/8) had demonstrated a plateau of $\dot{V}O_{2max}$ at $\dot{V}O_{2max}$. These findings provide a clear mandate for rejecting these secondary criteria as a means of validating $\dot{V}O_{2max}$ on ramp exercise tests.

Keywords Maximal oxygen uptake · Incremental and ramp exercise · Respiratory exchange ratio · Maximal heart rate · Blood lactate

Introduction

The maximal O_2 uptake ($\dot{V}O_{2max}$) represents the integrated capacity of the pulmonary, cardiovascular and muscle systems to uptake, transport and utilize O_2, respectively. The concept of $\dot{V}O_{2max}$, namely that there is a running speed or work-rate beyond which $\dot{V}O_2$ ceases to increase further, was developed by Hill and Lupton (1923). Today $\dot{V}O_{2max}$ forms a cornerstone of experimental and clinical exercise physiology and a criterion measurement for testing the efficacy of, for example training strategies and ergogenic aids. $\dot{V}O_{2max}$ is also commonly used to assess the impact of environmental conditions such as altitude and pollution as well as quantifying the functional predations of chronic diseases such as heart failure, COPD and diabetes (Howley et al. 1995; Wasserman et al. 1994).

The maximal incremental or ramp exercise test has replaced the discontinuous series of constant-work-rate tests to become a popular method of establishing key parameters of aerobic function in humans, for example work efficiency, the gas exchange threshold (GET) and $\dot{V}O_{2max}$ (Whipp et al. 1981). This test typically involves the work-rate (cycle ergometer) or speed/incline (treadmill) being increased systematically as a function of time until the participant is unable or unwilling to continue. Theoretically, at the limit of tolerance, the well-motivated subject or patient will have

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achieved their $\dot{V}O_{2max}$ as well as their maximal (exercise mode-specific) heart rate (HR) and cardiac output. To facilitate optimal detection of the GET and reduce the opportunity for premature fatigue, particularly in patient populations, the speed of work-rate imposition should ideally be selected to result in exhaustion in not more than 10–12 min (Buchfuhrer et al. 1983). In the classical literature the $\dot{V}O_2$ response is depicted as a linear increase in $\dot{V}O_2$ as a function of work-rate up to the achievement of $\dot{V}O_{2max}$, after which $\dot{V}O_2$ plateaus despite further increments in work-rate (e.g. Astrand 1960). Unfortunately, in reality, a substantial proportion of individuals will not exhibit a discernible plateau of $\dot{V}O_2$ prior to fatigue and the issue for the investigator or clinician then becomes whether or not a true $\dot{V}O_{2max}$ has been achieved (Day et al. 2003; Howley et al. 1995; Myers et al. 1990; Rossiter et al. 2006).

To circumvent this problem, several different criteria have been adopted to verify that $\dot{V}O_{2max}$ was reached in a particular test and that the measurements made reflect truly 'maximal' conditions. These include *in separatum* or in combination: respiratory exchange ratio (RER) > 1.00, 1.10 or 1.15; HR $\leq$ 10 b/min or $\leq$5% of the age-predicted maximum; and blood [lactate] of 8–10 mM (Astrand and Rodahl 1986; Horton et al. 2006; McArdle et al. 1996; Middlebrooke et al. 2006; Poole et al. 1992; Poole et al. 1991; Powers and Howley 1997; Robergs and Roberts 1997; Smith and Jones 2001). Given the substantial range of maximal values for each of these variables in the healthy population [RER, 1.0–1.44 (Sidney and Shephard 1977; Wasserman et al. 1994); HR_{max}, 95% confidence interval ± 35 b/min (Astrand and Rodahl 1986; Cooper et al. 1984); blood [lactate] 5–17 mM (Astrand and Rodahl 1986; Wasserman et al 1985), which is likely to be even greater in patient populations, it is possible that adoption of such fixed criteria may either provide false confidence in the successful attainment of $\dot{V}O_{2max}$ or exclude participants who may actually have achieved their $\dot{V}O_{2max}$.

To address this issue, we tested the hypothesis that use of such fixed criteria for achievement of $\dot{V}O_{2max}$ could either result in significant underestimation of 'maximal' exercising values, or alternatively, cause rejection of participants who had actually achieved $\dot{V}O_{2max}$.

Methods

Participants

Eight healthy males aged (mean ± SD) 27 ± 4 years and weighing 79.3 ± 8.9 kg participated in this investigation, after giving their written informed consent as approved by the Research Ethics Committee. Participants were familiar with performing maximal cycle ergometer exercise and with the laboratory procedures for measurement of pulmonary gas exchange. Whereas the participants could not be considered highly trained they participated to differing degrees in recreational sports and other physical activities such as cycling and running for health and fitness. The participants were instructed to avoid heavy exercise for 24 h prior to testing and to be at least 3 h post-absorptive. All procedures were performed at an ambient temperature of 20–22°C in a well-ventilated laboratory.

Ramp test and verification test

Following 3 min of baseline cycling at 20 W (the lowest work-rate available on the ergometer, Lode Excalibur Sport, Groningen, the Netherlands), work-rate was increased by 1 W every 3 s (i.e. 20 W/min) until the participant was unable to continue despite vigorous encouragement. The participants cycled at a self-selected pedal rate which remained constant throughout the test (70–90 rev/min). To validate that this protocol did indeed produce a valid measurement of $\dot{V}O_{2max}$, on a separate day, participants also completed a fatiguing, constant-work-rate test at 105% of the maximal work-rate achieved on the ramp test. This test began from a 3 min period of baseline cycling at 20 W followed by a step increase to the 105% level selected for each subject. As for the ramp test, the subjects were blinded as to the absolute work rate (WR), their $\dot{V}O_2$ and the time elapsed on the test. Subjects were verbally exhorted to cycle to the limit of their tolerance and the test was ended when the subject could no longer maintain the pedal frequency above 60 rev/min. Because the WR is independent of pedal frequency on the Lode Excalibur Sport ergometer this produces a crisp and unambiguous end point.

Measurements

Pulmonary gas exchange was measured breath-by-breath throughout the exercise tests. Participants breathed through a low-resistance volume transducer (Jaeger Triple V, Hoechberg, Germany), which had a dead space of 90 ml. Gas was continuously drawn down a capillary line into rapid-response gas analysers (Jaeger Oxycon Alpha, Würzburg, Germany) and gas exchange variables were calculated and displayed breath-by-breath after accounting for the delay between the volume and concentration signals. The volume transducer was calibrated before each test with a 3-l calibration syringe and the analysers were calibrated with precision-analysed gases that spanned the expected range of expired O_2 and CO_2 concentrations. HR was recorded every 5 s using short-range telemetry

(Polar PE 4000, Kempele, Finland). A fingertip blood sample was collected into a capillary tube immediately before, every 90 s throughout, and within 45 s of the termination of exercise. Blood samples were subsequently analysed for blood [lactate] using an automated analyser (YSI 1500 Sport lactate analyser, Yellow Springs Instruments, OH, USA). $\dot{V}O_{2\max}$ was calculated as the highest 20 s value achieved during the test. The identification of a plateau or reduction in slope of the $\dot{V}O_2$ –WR relationship close to fatigue was performed as follows: (1) the slope and 95% confidence interval (CI) of the $\dot{V}O_2$–WR relation (20 s average values) was determined by least-squares linear regression analysis of the 3 min immediately preceding any data points (notably the final few) that fell clearly away from the curve; and, (2) the presence of data points that fell below and outside the extrapolated 95% CI were taken as evidence of plateauing or levelling-off behaviour. In addition, an increase of <100 ml/min (i.e. ~50% of that expected for the 20 W/min protocol) was taken as supportive evidence for $\dot{V}O_2$ levelling-off.

The ramp test data for each individual participant were subsequently examined to assess the extent to which the secondary criteria (based on maximum values for RER, HR and blood [lactate]) could be used to confirm, or otherwise, the measured $\dot{V}O_{2\max}$. For RER, the $\dot{V}O_2$ values corresponding to RER values of 1.10 and 1.15 were calculated and compared to the $\dot{V}O_{2\max}$. For HR, the number and proportion of participants who satisfied the criterion of achieving a HR which was within ±10 b/min (or 5%) of the age-predicted maximum (220-age in years) was calculated. Finally, the number and proportion of participants who satisfied the criterion of achieving a peak blood [lactate] of ≥8 mM was established.

Statistics

Data are presented as mean ± SD or SE as appropriate. Standard least-squares regression techniques were performed using Sigmaplot 8.0 (San Jose, CA, USA). Within-subject comparisons were analysed using paired *t*-test analyses. Significance was accepted at $P < 0.05$.

Results

Profile of $\dot{V}O_2$ –WR response and validation of $\dot{V}O_{2\max}$ achievement on ramp protocol

The ramp tests were 1,149 ± 40 s in duration and elicited slopes ranging between 8.8 and 9.8 (mean ± SE, 9.3 ± 0.1) ml O_2/watt per min. Prior to the end of the test, when $\dot{V}O_2$ either plateaued or fatigue ensued, most subjects elicited a $\dot{V}O_2$–WR relationship with a slight upward curvature towards the higher WRs at the end of the test (e.g. Fig. 1, $n = 4$), in two subjects this curvature was more pronounced and in the remaining two it was absent (i.e., the response was close to linear.) $\dot{V}O_{2\max}$ (i.e. the highest $\dot{V}O_2$ attained) during the ramp test (4.03 ± 0.1 l/min) was not different from the highest $\dot{V}O_2$ achieved on the fatiguing, supra-maximal constant-work-rate test (3.95 ± 0.11 l/min). The coefficient of variation for the highest $\dot{V}O_2$ achieved between tests was 6%. Thus, when the $\dot{V}O_2$ –WR relationship is plotted for both tests (on the same plot) a distinct plateau becomes evident for each subject.

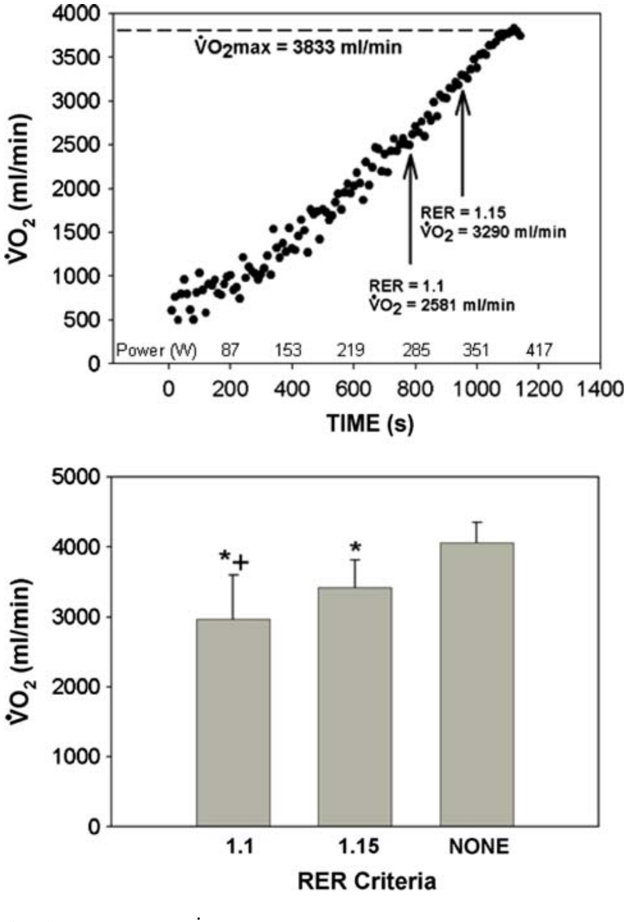

Fig. 1 *Upper panel* $\dot{V}O_2$ profile from unloaded (~20 W) cycling to the limit of tolerance on a 20 W/min ramp test for a representative participant (no. 2, Table 1). $\dot{V}O_2$ is averaged over 20 s intervals from unloaded cycling. There is a short but discernible plateau/decreased $\dot{V}O_2$ at maximum. *Arrows* indicate the $\dot{V}O_2$ corresponding to respiratory exchange ratios (RER) of 1.10 and 1.15. Note that they occur at very sub-maximal $\dot{V}O_2$ values. *Lower panel*: group mean responses ($n = 7$) for $\dot{V}O_2$ at criterion RERs of 1.10 and 1.15 and maximal exercise (none). One participant was rejected from the group because RER at fatigue was <1.10. *$P < 0.05$ vs. none, $^{+}P < 0.05$ vs. 1.15

Evidence for $\dot{V}O_2$ plateau at $\dot{V}O_{2max}$

Five participants evidenced a short but discernible plateau in $\dot{V}O_2$ prior to the termination of the ramp exercise protocol (e.g. Fig. 1). Of the remainder, two exhibited a linear $\dot{V}O_2$–WR relationship to their symptom-limited maximum and one an accelerated $\dot{V}O_2$-WR slope. Thus, by this criterion, five of the eight participants would have been judged to have achieved their $\dot{V}O_{2max}$ (Table 1).

Respiratory exchange ratio

Of the eight participants, one did not achieve an RER above 1.10 at fatigue despite demonstrating a clear plateau of $\dot{V}O_2$ (Table 1) and hence was not included in the following analysis. For the remaining seven participants, RER at maximum exercise was 1.24 ± 0.03 (range, 1.19–1.27) at a $\dot{V}O_{2max}$ of 4.03 ± 0.10 l/min (range, 3.59–4.45 l/min). At the criterion RER value of 1.10, $\dot{V}O_2$ averaged 2.97 ± 0.24 l/min, and at an RER of 1.15, $\dot{V}O_2$ averaged 3.41 ± 0.15 l/min both of which were significantly lower than the measured $\dot{V}O_{2max}$ ($P < 0.01$, Fig. 1, Table 1).

Heart rate

Three participants did not achieve a HR_{max} within ± 10 b/min (or 5%) of their age-predicted maximum and could have been excluded from acceptance of their having reached $\dot{V}O_{2max}$ on these grounds (Table 1). However, of these three participants, two elicited a $\dot{V}O_2$ plateau and two achieved RER values well above 1.15 (1.25 and 1.27). For these five subjects $HR_{max} - 10$ b/min occurred at a $\dot{V}O_2$ of 76.0 ± 4.4% of the measured $\dot{V}O_{2max}$ (i.e. $\dot{V}O_2$ at $HR_{max} - 10$ b/min, 3.02 ± 0.09 l/min; $\dot{V}O_{2max}$, 4.00 ± 0.17 l/min, $P < 0.05$).

Blood [lactate]

Post-exercise blood [lactate] (measured close to the end of exercise) averaged 7.1 ± 0.3 mM (range, 5.7–8.4). Based upon the criterion value of blood [lactate] ≥8 mM, six participants would not have fulfilled the standard criterion for the attainment of $\dot{V}O_{2max}$ (Table 1). Of these six participants, four demonstrated a plateau of $\dot{V}O_2$ at $\dot{V}O_{2max}$.

Discussion

The most important original finding of the present investigation is that generally accepted criteria for acceptance of a maximal exercise test can underestimate $\dot{V}O_{2max}$ by as much as 27%. This finding is particularly relevant to interpretation of investigations that have used repeated measurements of this parameter to establish a training response or evaluate other experimental perturbations. Specifically, the data presented herein demonstrate that, within the criterion of RER > 1.10, it would be possible to derive a substantial but fallacious increase in measured $\dot{V}O_{2max}$ without there being a real increase in the individuals' cardiovascular and muscle oxygen transport/utilization capacity (or vice versa). It is pertinent that training programs might be expected to increase $\dot{V}O_{2max}$ by 10–25%, i.e. less than the potential underestimation of $\dot{V}O_{2max}$ when secondary criteria are used to judge the acceptability of a test, as reported herein. Another pernicious quality of the generally accepted criteria for achievement of $\dot{V}O_{2max}$ is that, of the eight participants evaluated in the present investigation, three would have been rejected for not achieving an exercising HR within 10 b/min of their age-predicted maximum and five for their blood [lactate] response not achieving 8 mM. In the majority of instances the 'sub-maximal' HR and blood [lactate] responses were elicited concomitantly with a plateau of $\dot{V}O_2$.

Table 1 Individual participant data for $\dot{V}O_2$, respiratory exchange ratio, heart rate, and blood [lactate] at maximum exercise

Participant	1	2	3	4	5	6	7	8
$\dot{V}O_{2max}$ (ml/min)	3,588	3,833	4,294	3,944	3,879	4,453	4,177	4,104
$\dot{V}O_2$ plateau (Y/N)	Y	Y	Y	N	Y	N	Y	N
Maximum RER	1.19	1.27	1.27	1.23	1.01	1.27	1.21	1.25
$\dot{V}O_2$ at RER 1.10	2,697	2,572	3,919	2,581	N/A	2,185	3,652	3,150
$\dot{V}O_2$ at RER 1.15	3,303	3,290	3,945	3,071	N/A	2,939	3,972	3,376
HR_{max} within ± 10 b/min of 220-age (Y/N)	Y	Y	N	Y	N	Y	Y	N
Blood [lactate] ≥ 8 mM (Y/N)	N	Y	N	N	N	Y	N	N

Mean values ± SE; $\dot{V}O_{2max}$ = 4034 ± 98 ml/min, RER_{max} = 1.21 ± 0.03, $\dot{V}O_2$ at RER 1.10 = 2,965 ± 239 ml/min, $\dot{V}O_2$ at RER 1.15 = 3414 ± 151 ml/min. Note that participant no. 5 who did not meet any of the secondary criteria for achieving $\dot{V}O_{2max}$ exhibited a pronounced $\dot{V}O_2$ plateau

Comparison with previous investigations

Prior to the widespread popularity of the continuous incremental/ramp exercise test for determination of $\dot{V}O_{2max}$ and other characteristics of the exercise response, a plateau of $\dot{V}O_2$ at $\dot{V}O_{2max}$ was observed in the majority of participants (Astrand 1960; Glassford et al. 1965; Taylor et al. 1955). As demonstrated in the present investigation, this compares with a discernible plateau occurring in only ~60% or less of healthy adult subjects tested using an incremental/ramp protocol (Day et al. 2003; Doherty et al. 2003; Howley et al. 1995). This problem is further exacerbated in special populations such as extremely unfit subjects (Hansen et al. 1984; Howley et al. 1995), children (Cumming and Friesen 1967), the elderly (Sidney and Shephard, 1977) and patients (Wasserman et al. 1994).

The validity of the analyses performed and their applicability to the research literature depends, in part, on the values achieved in the present investigation being representative of those found in the literature. In this respect, RER values at maximal exercise (incremental/ramp protocol) are typically in the 1.15–1.4 range (Buchfuhrer et al. 1983; Wasserman et al. 1994) with the higher end of this range found in the shorter more rapidly incremented protocols (Buchfuhrer et al. 1983; Whipp 2007). This phenomenon is logical since the elevation of RER due to the HCO_3^- buffering of lactic acid-derived H^+ ions will be faster when work-rate is incremented more rapidly, i.e. the *rate* of CO_2 output will be greater because it tracks the *rate* of H^+ buffering (Whipp 2007). It is pertinent that the relatively modest rate of WR increase (20 W/min) and hence longer duration of the ramp tests in the present investigation (1,149 ± 40 s or 19–20 min) will, if anything, have acted to produce lower RER values at submaximal $\dot{V}O_2s$. Hence the underestimation of $\dot{V}O_{2max}$ at the criterion RERs assessed herein might be even greater for faster ramp protocols (i.e., those of 10–12 min duration). HR_{max} averaged 182 ± 4 b/min which was significantly lower than the age-predicted value but not from the averaged criterion value of 183 ± 4 b/min (i.e. age-predicted HR_{max} − 10 b/min). These values are in close agreement with those found previously (e.g. Poole and Gaesser 1985). Blood [lactate] can vary widely following maximal exercise (4–17 mM; Astrand and Rodahl 1986; Wasserman et al. 1985). The range reported herein (5.7–8.4 mM) is within that observed previously for similar protocols (e.g. Wasserman et al. 1985). On the basis of the above a strong case can be made for the broad applicability of the data set analysed herein and thus the conclusions developed from those data.

Selection of arbitrary 'cut-off' values for acceptance or rejection of exercise tests

Respiratory exchange ratio

In the absence of a $\dot{V}O_2$ plateau at $\dot{V}O_{2max}$, the RER has been, and continues to be, the most popular criterion for confirming that $\dot{V}O_{2max}$ was indeed reached. Whereas investigators have legitimately tried to establish objective criterion RER values, the validity of this approach is undermined by a substantial body of published experimental evidence. In addition to issues related to exercise test protocol (see earlier), there are individuals for whom RER does not increase above 1.0 (Sidney and Shephard 1977) whereas for others it exceeds 1.4 (Buchfuhrer et al. 1983; Wasserman et al. 1994)—yet these participants may be performing 'maximal' exercise that will yield $\dot{V}O_{2max}$. The present investigation has demonstrated the appreciable 'undermeasurement' of $\dot{V}O_{2max}$ in a subject population for whom RER cut-off values of 1.10 and 1.15 were applied. Clearly, in opposition to the early work of Issekutz and Rodahl (1961) who, based upon a series of 5-min intermittent exercise tests, found that each participant reached $\dot{V}O_{2max}$ at an RER of 1.15, one '$\dot{V}O_{2max}$ -RER equivalent' does not, and indeed cannot, fit all. Thus, adherence to supposedly rigorous RER criteria render it possible for the investigator to justify selection of very low criterion values for RER in order to incorporate the largest data set. One consequence of that choice will be to risk incorporating individuals who have actually not achieved their $\dot{V}O_{2max}$. This occurrence will weaken the legitimacy of the study design and increase the opportunity for erroneous results for the protocol or intervention being evaluated. By the same token, a more stringent approach (higher RER cut-off) would be likely to exclude a significant portion of the participants who may have legitimately achieved $\dot{V}O_{2max}$ but did not achieve some preset and arbitrary RER. This problem is likely to be especially acute in select groups such as older individuals (Cumming and Borysyk 1972; Howley et al. 1995; Sidney and Shephard 1977) and patient populations (Wasserman et al. 1994).

Heart rate

As the second most utilized criterion for establishing that $\dot{V}O_{2max}$ has been achieved, HR_{max} is famously difficult to define for any given population. Specifically, as noted by Howley et al. (1995), the standard deviation of the estimate of HR_{max} is ±11 b/min (Londeree and Moeschberger 1984). This means that, even using the generous allowance of HR_{max} − 10 b/min as the criterion for $\dot{V}O_{2max}$ (which in itself presents the possibility of error in those individuals with a higher HR_{max} than 220-age), there will be individuals excluded not because they could not reach $\dot{V}O_{2max}$ but because they exhibited a low HR_{max}, as was the case for three participants in the present investigation (Table 1). Moreover, of the five subjects who exceeded their age-predicted $HR_{max} - 10$ b/min criterion, $\dot{V}O_2$ at that criterion averaged only 76 ± 4% $\dot{V}O_{2max}$. In addition to the above problems, there is evidence that special populations such as extremely sedentary individuals (Hansen et al. 1984) and also children (Cooper et al. 1984) may have either 'reduced' or at least highly variable HR_{max} values. With respect to HR_{max} in children, Astrand and Rodahl (1986) reported that HR_{max} was 205 b/min in Scandinavian children whereas Cooper et al. (1984) found a mean HR_{max} of 187 b/min (with a lower 95% confidence interval of 160 b/min) in North American children ages 8–18 year. Considering the above, it is appropriate that the American College of Sports Medicine (1991) stipulated that HR should not be used as an absolute end-point criterion for test termination. However, it continues to be used in scientific investigations for exactly that purpose (Howley et al. 1995; Middlebrooke et al. 2006; Poole et al. 1991, 1992).

Blood [lactate]

In their comprehensive review on criteria used for establishing $\dot{V}O_{2max}$, Howley et al. (1995) stated that 'blood lactate is a good choice as an indicator of maximal effort'. However, for that statement to be valid, there should be little variability in blood [lactate] among individuals exercising at $\dot{V}O_{2max}$. As detailed above, this is clearly not the case, with there being twofold or greater differences among participants within a given study (present results; Wasserman et al. 1985) and between different populations [*cf*. N. American, 4–10 mM (Wasserman et al. 1985) and Scandinavian, >15 mM (Astrand and Rodahl 1986)]. As can be appreciated from this wide range, which is not explicable on the basis of measurement details, e.g. plasma vs. whole blood analysis, blood sampling site, or collecting the final blood lactate sample before the 2–4 min post-exercise window when values may peak (as herein), the commonly used criterion value of ≥8 mM, which would have excluded 6/8 of the participants in the present investigation and 8/10 in that of Wasserman et al. (1985), could still represent very sub-maximal exercise in individuals capable of accumulating blood lactate concentrations of 15 mM or more. It is pertinent that fewer studies today are using lactate-based criteria for verifying $\dot{V}O_{2max}$, possibly because of concerns regarding blood-borne infections.

A viable alternative strategy for validating $\dot{V}O_{2max}$ that is independent of arbitrary cut-offs

In keeping with the first descriptions of $\dot{V}O_{2max}$ presented by Hill and Lupton (1923), and the recognition that 'an obligatory plateau of $\dot{V}O_2$ provides unequivocal identification of $\dot{V}O_{2max}$' (Wasserman et al. 1994), Rossiter, Whipp and colleagues (Day et al. 2003; Rossiter et al. 2006) have demonstrated that a plateau of $\dot{V}O_2$ against work-rate can be constructed from as few as two exercise bouts. This is pertinent to the present study because it abrogates the necessity for relying upon secondary criteria to decide whether or not $\dot{V}O_{2max}$ has been achieved during a single ramp exercise test. The principle of this technique follows from the notion that, for exercise performed to fatigue in the severe intensity domain, $\dot{V}O_{2max}$ is achieved provided that the exercise duration is not too short to preclude the kinetic response of $\dot{V}O_2$ from driving $\dot{V}O_2$ to the maximum (Astrand and Rodahl 1986; Hill et al. 2002; Hughson et al. 2000; Wilkerson et al. 2004a, b). Thus an initial incremental or ramp test to the limit of tolerance is followed by a constant-load test, again to the limit of tolerance, at a WR above the highest achieved on the incremental test. If the $\dot{V}O_2$ does not increase (or does so less than some small pre-set amount) the plotting of the $\dot{V}O_2$–WR relationship for both tests on the same plot will yield the plateau identifying achievement of $\dot{V}O_{2max}$ (Day et al. 2003). This strategy has already been used by Poole, Wagner and colleagues (e.g., Knight et al. 1992) but is certainly not in mainstream practice as evidenced by the common use of secondary criteria to 'confirm' that $\dot{V}O_{2max}$ has been achieved. As defined by Gaesser and Poole (1996), the severe exercise intensity domain consists of a broad range of work-rates above critical power for which exercise to fatigue will yield $\dot{V}O_{2max}$. Despite the variable contribution of the $\dot{V}O_2$ slow component to the measured $\dot{V}O_{2max}$ in this domain, the absolute value for $\dot{V}O_2$ achieved is not affected by either the kinetics of $\dot{V}O_2$ or the tolerable duration of exercise (Hill et al. 2002; Özyener et al. 2001; Sloniger et al. 1996; Wilkerson et al. 2004b).

It is pertinent that, as demonstrated herein, in 'well-motivated' young, healthy, physically active participants, the 'validation' stage merely confirms the $\dot{V}O_{2max}$ value determined as the highest $\dot{V}O_2$ attained on the ramp/incremental test. This is true irrespective of whether or not a plateau of $\dot{V}O_2$ is evident on the ramp/incremental test (Day et al. 2003; Rossiter et al. 2006; Wilkerson et al. 2004b).

Conclusions

Utilization of ramp or incremental exercise tests precludes achievement of a $\dot{V}O_2$ plateau prior to exhaustion in a substantial proportion of individuals. Investigators have therefore resorted to a selection of secondary criteria to provide confidence that $\dot{V}O_{2max}$ has been achieved. The present investigation demonstrates that use of the so-called established secondary criteria of RER $\geq$ 1.10 or 1.15, $HR_{max} \pm 10$ b/min and/or blood [lactate] $\geq$8 mM can lead either to a significant undermeasurement of $\dot{V}O_{2max}$ or rejection of an untenably high proportion of participants who may actually have achieved their $\dot{V}O_{2max}$. On the basis of these findings for ramp exercise it is recommended that use of these secondary criteria, to establish $\dot{V}O_{2max}$, be abandoned.

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