Emergence of the verification phase procedure for confirming "true" $\dot{V}O_{2max}$

A. W. Midgley[1], S. Carroll[2]

[1]Department of Sport, Health and Exercise Science, University of Hull, Hull, England
[2]Carnegie Research Institute, Leeds Metropolitan University, Leeds, England

Corresponding author:
Adrian W. Midgley, PhD
Department of Sport, Health and Exercise Science
University of Hull
Cottingham Road
Hull
HU6 7RX
ENGLAND
Phone: 44 (0)1482-466432
Fax: 44 (0)1482-465149
Email: A.W.Midgley@hull.ac.uk

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Abstract

Traditional $\dot{V}O_{2max}$ criteria are typically based on attainment of a $\dot{V}O_2$ plateau, and threshold values for the respiratory exchange ratio, heart rate and blood lactate concentration. Despite long-standing criticisms directed at these criteria, their use remains widespread. This article discusses an alternative procedure, termed the verification phase, for confirming the attainment of true $\dot{V}O_{2max}$. Following a continuous incremental exercise test to the limit of tolerance and appropriate recovery period, the verification phase is performed and is characterised by a supramaximal square wave exercise bout. Consistent peak $\dot{V}O_2$ values in the incremental and verification phases, confirms that a true $\dot{V}O_{2max}$ has been attained. Six recent studies investigated the utility of the verification phase for evaluating true $\dot{V}O_{2max}$. These studies consistently found small insignificant mean differences between the maximal $\dot{V}O_2$ attained in the incremental and verification phases. However, this group mean approach does not identify individual subjects who may not have attained a true $\dot{V}O_{2max}$. Notably, only one of the six studies reported a criterion threshold to verify the $\dot{V}O_{2max}$ of individual subjects. Further research is required to investigate the utility of different verification phase procedures and to establish a suitable verification criterion threshold for confirming true $\dot{V}O_{2max}$.

Key Words: CRITERIA, MAXIMAL OXYGEN UPTAKE, PLATEAU, TESTING

INTRODUCTION

The maximal oxygen uptake ($\dot{V}O_{2\,max}$) has long been regarded as the gold standard measure of cardiorespiratory fitness (ATS/ACCP, 2003; Shephard et al., 1968) and its determination has become one of the most widely used test procedures in exercise physiology laboratories (Howley et al., 1995). The seminal work of Hill, Lupton, and Long (1924; 1923) introduced the $\dot{V}O_{2\,max}$ concept; however, many issues relating to the most appropriate test procedures for its determination remain unresolved.

The attainment of $\dot{V}O_{2\,max}$ typically requires subjects to continue an incremental exercise test until they reach their limit of tolerance (Wagner, 2000). A problem arises in identifying those subjects who terminate the test prematurely and, therefore, may not have elicited a true $\dot{V}O_{2\,max}$. Taylor et al. (1955) stated that “the safest procedure is to insist on proof of the attainment of maximal oxygen intake in all cases." In pursuit of this ‘proof’ objective criteria have been proposed (see Howley et al., 1995, for review). Many investigators, however, have expressed concerns regarding the validity of these criteria (Cumming and Borysyk, 1972; Donnelly et al., 1990; Midgley et al., 2007; Niemela et al., 1980; Poole et al., 2007; Stachenfeld et al., 1992; Wyndham et al., 1959).

Despite the long-standing criticisms directed at the currently used $\dot{V}O_{2\,max}$ criteria, as far as we are aware, until recently, there had been no attempt to identify new criteria. A number of experimental studies published in the last two years have investigated the utility of a procedure termed the ‘verification phase’ for establishing a true $\dot{V}O_{2\,max}$ (Foster et al., 2007; Hawkins et al., 2007; Midgley et al., 2006; Poole et al., 2007; Rossiter et al., 2006). Following a continuous incremental exercise test to the limit of tolerance and an appropriate recovery period, the verification phase is performed and is characterised by a supramaximal square wave bout of exercise to exhaustion (Figure 1)(where ‘supramaximal’ is defined as a workload higher than the last completed stage of an incremental $\dot{V}O_{2max}$ test). Consistent peak $\dot{V}O_2$ values in the incremental and verification phases provide support for the view that a true $\dot{V}O_{2max}$ has been attained. A $\dot{V}O_{2max}$ test incorporating an incremental phase and appended verification phase, is conceptually similar to the discontinuous $\dot{V}O_{2max}$ tests most commonly used from the 1920’s to the 1960’s, but with the notable advantage of requiring only one visit to the laboratory. Furthermore, research published during the last five years investigating the physiological limitations to $\dot{V}O_{2max}$, derived using incremental and constant load exercise protocols, have supported the conceptual basis for the verification phase procedure. The main purpose of this article was to discuss current knowledge regarding the verification phase and provide directions for future research.

MECHANISTIC BASES FOR $\dot{V}O_{2max}$

Early researchers concluded that $\dot{V}O_2$ was limited by the rate of oxygen delivery and utilisation (defined by the maximal cardiac output and the maximal arteriovenous oxygen difference), despite an increased workload and oxygen demand. Using invasive measures, Mitchell et al. (1958) reported data on six male subjects whose oxygen uptake levelled off or actually declined at work rates beyond which elicited $\dot{V}O_{2max}$ and was coincident with a decline in cardiac output. The authors concluded that $\dot{V}O_{2max}$ is a measure of cardiac capacity and the ability to increase the arteriovenous oxygen difference, as opposed to the ability of the vascular bed to accommodate left ventricular output. The limitations to oxygen delivery and utilisation were, in turn, associated with an accumulation of the metabolites of anaerobic metabolism causing exercise to be terminated. This has been termed the cardiovascular/anaerobic/catastrophic model of the limitation to $\dot{V}O_{2\,max}$ (Noakes, 2008).

Unresolved debates continue on whether central cardiorespiratory or local muscle circulatory and metabolic factors (or both) limit $\dot{V}O_{2\,max}$ (Howley et al., 1995). A recent series of experimental studies from the Copenhagen Muscle Research Centre have measured cardiac output and other components of the Fick principle during both incremental and constant load cycling to the limit of tolerance. These studies have corroborated the ‘classical’ interpretation of $\dot{V}O_{2\,max}$ and refined some aspects of our current understanding of this topic (Gonzalez-Alonso and Calbet, 2003; Mortensen et al., 2008; Mortensen et al., 2005).

Gonzalez-Alonso and Calbet (2003) measured directly systemic haemodynamic and peripheral factors during constant load high-intensity cycling under conditions of heat stress and no heat stress. During both environmental conditions, cardiac output, mean arterial pressure, leg blood flow, and systemic oxygen delivery declined significantly at peak exercise, whereas arterial oxygen content and leg vascular resistance were maintained. The impaired systemic aerobic capacity that preceded the limit of exercise tolerance in both conditions was considered to be related to the diminished cardiac output and oxygen delivery to locomotive muscle.

A series of further investigations (Mortensen et al., 2008; Mortensen et al., 2005) evaluated the contribution of the oxygen transport system to $\dot{V}O_{2\,max}$ in trained subjects during both incremental and constant load cycling to the limit of tolerance. Mortensen et al. (2005) reported that during incremental cycling, whole body $\dot{V}O_2$ increased linearly with workload, with $\dot{V}O_{2\,max}$ attained during the last 30 s of the test protocol. Cardiac output and systemic oxygen delivery were shown to increase linearly up to 80% of peak power output and thereafter plateaued in conjunction with a decline in stroke volume and increased central venous and arterial pressures. In the constant load cycling at 85% of peak power output, $\dot{V}O_{2max}$ and peak cardiac output tended to be attained within 3 to 6 min, maintained for approximately 2 min, and declined before the termination of exercise. Systemic oxygen delivery reached peak values in 3-5 min but also declined before exercise termination. During both cycling conditions, systemic arteriovenous oxygen difference and oxygen extraction increased until the point of exercise termination. The similar $\dot{V}O_2$ and cardiac output responses during the maximal and supramaximal cycling suggest that blood perfusion to active muscles might be limited during high-intensity whole-body exercise.

Mortensen et al. (2008) subsequently examined the regulatory limits of systemic blood perfusion in exercising humans during constant load supramaximal cycling (110% of peak power output) compared with incremental cycling to the limit of tolerance. Incremental protocols involved increases in work rate every 1.5 min to elicit 25%, 50%, 75%, 90% and 100% of peak power output. Supramaximal workloads were imposed during the first 20 s of exercise to elicit 110% of peak power output. During supramaximal cycling, cardiac output, leg blood flow, and systemic and leg oxygen delivery reached peak values after 60–90 s and thereafter plateaued at values similar to or approximately 6% below that achieved at peak power output in the incremental test, while upper body blood flow remained unchanged. Cardiac output reached similar peak values in both cycling protocols, but was lower during supramaximal constant-load cycling at the point of exercise termination. Consequently, at exhaustion, systemic $\dot{V}O_2$ was lower despite systemic oxygen extraction reaching similar values. Leg blood flow and leg oxygen delivery reached similar values in the exercising limbs, however, leg $\dot{V}O_2$ was lower compared to incremental cycling because of a reduced arteriovenous oxygen difference in the legs.

These observations indicate that the limits of cardiac function and muscle vasoconstriction underlie the inability of the circulatory system to meet the increasing oxygen demand of skeletal muscles and other tissues during whole-body incremental exercise and constant load exercise in the severe exercise domain, when continued to the limit of tolerance.

ARE CURRENTLY USED $\dot{V}O_{2max}$ CRITERIA VALID?

Taylor et al. (1955) observed that in response to multiple discrete bouts of exercise, each with a higher workload than the previous bout, an upper limit of oxygen uptake per unit of time was reached, despite subjects typically being able to exercise at even higher workloads. Ordinarily, the point at which the oxygen uptake curve (plotted against workload) ceased to rise was taken as $\dot{V}O_{2max}$. In most cases, when the workload was increased beyond that eliciting maximal oxygen uptake, the $\dot{V}O_2$ either remained unchanged or declined. In some cases, however, a slight rise was observed, necessitating the formulation of a strict objective criterion for identifying a true $\dot{V}O_{2max}$. The rationale for the now ubiquitous '$\dot{V}O_2$ plateau' criterion (Midgley et al., 2007) proposed by Taylor et al. (1955), was that if $\dot{V}O_2$ increased by no more than half of the mean increase in $\dot{V}O_2$ (299.3 $mL \cdot min^{-1}$ for an average of 30 measurements taken from 13 subjects at two or more grades below the grades resulting in the $\dot{V}O_2$ plateau), then this was sufficient evidence that a maximal, or near maximal $\dot{V}O_2$ had been reached. Various $\dot{V}O_2$ plateau criteria methodologies have since been applied to a variety of exercise tests, including discontinuous, incremental step and ramp protocols (Astorino et al., 2005; Mitchell et al., 1958; Poole et al., 2007). The $\dot{V}O_2$ responses to these tests, however, have not consistently demonstrated plateau-like behaviour at the limit of tolerance despite apparent maximum effort**.** In fact, in contrast, Day et al. (2003) reported that 19 of 71 subjects in their study demonstrated an accelerated $\dot{V}O_2$ response as they approached fatigue during the end of an incremental exercise test. Incidence of the $\dot{V}O_2$ plateau reported by previous studies has ranged from 0 to 100% (Astorino et al., 2005; Duncan et al., 1997; Froelicher et al., 1974; Rossiter et al., 2006). Much of this inconsistency can be attributed to differences in the stringency of the $\dot{V}O_2$ plateau criterion, although the incidence of the $\dot{V}O_2$ plateau has been suggested also to be largely dependent on the population under investigation, characteristics of the test protocol, and the $\dot{V}O_2$ sampling duration or data averaging method (Astorino et al., 2005; Rivera-Brown and Frontera, 1998). These factors considerably reduce the utility of the $\dot{V}O_2$ plateau as a robust method for identifying a true $\dot{V}O_{2max}$ during a continuous ramp or incremental step test. However, it should be pointed out that the $\dot{V}O_2$ plateau concept is intuitively robust and that the apparent limitations are not related to the concept itself, but to the inconsistent and often ill-conceived methodology that have been used to define it. The fact that the $\dot{V}O_2$ plateau is not always evident also does not provide evidence against its existence (Wagner, 2000).

A lack of motivation and effort may also explain the absence of a $\dot{V}O_2$ plateau, since a relatively high level of anaerobiosis and discomfort are necessary to achieve a plateau (Wyndham et al., 1959). The absence of a $\dot{V}O_2$ plateau, however, does not necessarily suggest that a maximum effort has not been given or that a true $\dot{V}O_{2max}$ was not elicited. Studies have found no difference between the maximal heart rates, respiratory exchange ratios, or post-exercise blood lactate concentrations among subjects who demonstrated a $\dot{V}O_2$ plateau compared to those who did not (Astrand, 1952; Rivera-Brown and Frontera, 1998; Rowland and Cunningham, 1992). Probably the most compelling piece of evidence highlighting the limitations of the $\dot{V}O_2$ plateau is that subjects who perform two identical continuous incremental step tests can demonstrate a $\dot{V}O_2$ plateau in only one of the tests, despite negligible differences in $\dot{V}O_{2max}$ during the two tests (Katch et al., 1982; Midgley et al., 2006; Misquita et al., 2001). This situation appears paradoxical to the well established cardiovascular/anaerobic/catastrophic model (Noakes, 2008) and suggests that $\dot{V}O_{2max}$ is limited by some other mechanism, or at least, alternative mechanisms sometimes limit $\dot{V}O_{2max}$. Finally, an important point to consider in any critique of the $\dot{V}O_2$ plateau, recently highlighted by Rossiter et al (2006), is that in the classical reports of Taylor et al. (1955) and Mitchell et al. (1958), there is no stated or implicit requirement for $\dot{V}O_2$ to plateau during a particular bout of exercise: only that during another discrete time the maximal $\dot{V}O_2$ value attained is not, or is only minimally higher, despite a higher workload. The definition of the $\dot{V}O_2$ plateau proposed by these early researchers is not therefore directly applicable to the contemporary approach for $\dot{V}O_{2max}$ determination, which invariably involves continuous ramp or incremental step protocols.

The lack of robustness of the $\dot{V}O_2$ plateau highlights the need for secondary criteria to establish whether a maximal effort has been given. If a maximum effort has been given, it is assumed that $\dot{V}O_{2max}$ has been attained, irrespective of the occurrence of a $\dot{V}O_2$ plateau (Duncan et al., 1997; Katch et al., 1982; Midgley et al., 2006). 'Traditional' secondary criteria include the attainment of arbitrary thresholds for maximal values of the respiratory exchange ratio and heart rate during the $\dot{V}O_{2max}$ test, and early post-test blood lactate concentration (Midgley et al., 2007). Poole et al. (2007) recently examined the validity of secondary criteria based upon widely adopted threshold values for the respiratory exchange ratio, heart rate and blood lactate concentration in eight, apparently healthy male subjects performing a ramp-incremented cycle ergometry test (20 W/min) to the limit of tolerance. The main finding of this investigation was that the secondary criteria could be satisfied at a $\dot{V}O_2$ much lower that the subject's eventual maximal $\dot{V}O_2$ attained in the test (even as low as 73% $\dot{V}O_{2max}$). These criteria are therefore severely limited due to their lack of specificity in identifying subjects who have not exercised to their limit of tolerance (see Figure 2 for a graphical example). Conversely, as a result of considerable between-subject variation in maximal physiological responses, some subjects may not satisfy a particular criterion even when a maximum effort is given. This is particularly problematic for the heart rate criterion based on the attainment of a percentage of the age-predicted maximal heart rate, since the scatter around the predicted maximal heart rate for any given age introduces unacceptably large prediction errors (Londeree, 1984). The above observations provide a clear mandate for rejecting currently used secondary criteria as a means of validating a true $\dot{V}O_{2max}$.

VERIFICATION PHASE

Historical perspective

The origin of the verification phase is presently unclear, but dates back at least to a book chapter by Thoden et al. (1982) published in the physiological testing guidelines of the Canadian Association of Sports Sciences. The authors originally termed the procedure the "exhaustive phase" (Thoden et al., 1982), and then later adopted the terminology “verification phase” (Thoden, 1991). Thoden et al. (1982) recommended that after 15 min of recovery from the incremental phase, a constant bout of exercise, with a workload equivalent to the last completed stage in the incremental phase, should be performed to the limits of tolerance. If the verification phase lasted more than 6 min, they recommended that upon retesting, the participant be required to undertake a verification phase at one stage higher than the last completed stage in the incremental phase. In updated guidelines, Thoden (1991) suggested a recovery of between 5-15 min in order to obtain a heart rate of 100 beats·min^{-1}, with the verification phase initially performed at a workload one stage higher than the last completed stage in the incremental phase. If the incremental phase did not last at least 8 min, the verification phase should be performed at the same workload as the last completed stage attained in the incremental phase of the test. Other notable modifications were more comprehensive guidelines regarding the intensity of the verification phase if a subject was retested at a later date. Subjects completing more than 6 min in the verification phase should perform the verification at one stage higher than the last completed stage in the incremental phase, regardless of the duration in any subsequent test. Subjects not completing a 3 min verification phase should undertake a verification phase at one stage lower than the last completed stage in the incremental phase. To the best of our knowledge, however, experiments to test the validity of these verification phase procedures were not conducted.

The earliest scientific study we have found that incorporated a verification phase was that of Morgan et al. (1989). In that study, the verification procedure consisted of 10 min recovery after the incremental phase, followed by a 2-min warm-up period and 2 min of supramaximal running. The supramaximal component was performed at one increment higher than the last completed stage in the incremental phase. Two distinguishable features of the procedure used by Morgan et al. (1989) are that the verification phase was not continued to the subject's limit of tolerance and was only performed when a $\dot{V}O_2$ plateau was not discernable in the incremental phase. The efficacy of the 2-min supramaximal run for eliciting $\dot{V}O_{2max}$ may be questioned, particularly in untrained participants with slow $\dot{V}O_2$ on-kinetics (Caputo et al., 2003). However, subsequent research has supported the premise that generally, 2 min of supramaximal exercise can be sufficient to elicit $\dot{V}O_{2max}$ (Rossiter et al., 2006). Whether the verification phase should be performed when a $\dot{V}O_2$ plateau in the incremental phase is evident is a matter for debate. Not performing the verification phase is time efficient and does not place the subject under additional unnecessary stress; however, it could be argued that the verification phase provides further confirmation and a higher level of confidence that $\dot{V}O_{2max}$ was elicited.

The verification phase has been used in subsequent experimental research, although it is certainly not a common procedure. In a survey of experimental studies published in four journals between August 2005 and July 2006, only one of 207 studies that determined $\dot{V}O_{2max}$ used the verification phase procedure (Midgley et al., 2007). This may be explained by a lack of research supporting its validity. Although the verification phase was first defined over 25 years ago, it was not until 2006 that the issue of whether the verification phase is a valid procedure for confirming a true $\dot{V}O_{2max}$ was specifically examined (see Table 1 for a summary of relevant studies).

Midgley et al. (2006) reported the utility of the verification phase for determination of a true $\dot{V}O_{2max}$ in 16 male distance runners undergoing repeat speed-incremented treadmill tests. The verification phase was performed at a speed equivalent to one stage higher than that attained during the last completed stage of the incremental phase. Figure 3 shows a Bland-Altman plot of the maximal $\dot{V}O_2$ values (30-s time-averages) attained in the incremental and verification phases for all 32 tests. The repeated measures coefficient of variation of 3.9% for the maximal $\dot{V}O_2$ during the verification phase was similar to the 3.5% obtained for the incremental phase, thereby demonstrating acceptable reproducibility. Amongst the 32 maximal tests, 26 satisfied a strict $\dot{V}O_{2max}$ verification criterion threshold of a $\dot{V}O_2$ not greater than 2% higher than the incremental phase. The 2% verification threshold was based on the technical error of measurement in $\dot{V}O_2$ determination reported by the manufacturer of the metabolic cart used to determine pulmonary $\dot{V}O_2$. However, this rather conservative criterion threshold warrants further consideration since it does not take into account acceptable short-term, within-subject biological variation in $\dot{V}O_{2max}$.

In the same year, Rossiter et al. (2006) reported the utility of the verification phase to verify the $\dot{V}O_{2max}$ of seven apparently healthy men. In that study, participants performed a ramp-incremented cycle ergometer protocol (20 W/min) to the limit of tolerance (defined as the subject being unable to maintain a pedal cadence of at least 50 rpm, despite strong verbal encouragement). The verification phase was performed after 5 min of active recovery at 20 W and consisted of cycling at 105% of the peak power output achieved in the ramp protocol. The authors concluded that the lack of significant difference between the maximal $\dot{V}O_2$ values established at different peak power outputs in the two test phases satisfy the primary criterion for $\dot{V}O_{2max}$, even though the individual test phases themselves did not exhibit a plateau. On a separate occasion, five of the subjects replicated the procedure, except the verification phase was performed at 95% peak power output. The authors suggested that both verification phase intensities appeared equally effective at verifying that $\dot{V}O_{2max}$ was elicited during the incremental phase. However, only the supramaximal verification phase can be recommended since the submaximal verification phase does not conform to the original concept of $\dot{V}O_{2max}$: that $\dot{V}O_2$ has not increased (or at least much less than expected) in response to an increased workload (Hill and Lupton, 1923).

Midgley et al. (2007) used a supramaximal verification phase to confirm that three different treadmill test protocols elicited true $\dot{V}O_{2max}$. One continuous and two discontinuous incremental phases, with mean times to exhaustion ranging from 10 to 30 min, were performed. Despite the incremental phases being distinctly different, the mean maximal $\dot{V}O_2$ values attained in the appended verification phases were almost identical. This study helps establish that in contrast to the currently used $\dot{V}O_{2max}$ criteria, the verification phase is independent of the incremental test protocol.

Foster et al (2007) recently reported the utility of the verification phase for confirming the $\dot{V}O_{2max}$ of physically active non-athletes during cycling ergometry and competitive runners during treadmill running. A notable characteristic of the $\dot{V}O_{2max}$ test procedure was the short recovery phases of 1-min for the non-athletes and 3-min for the runners, compared to previous studies that used between 5 and 10 min (Midgley et al., 2007; Midgley et al., 2006; Rossiter et al., 2006). The negligible differences between the mean maximal $\dot{V}O_2$ values attained in the incremental and verification phases indicated that short recovery phase durations do not detract from the utility of the verification procedure. A short recovery phase would be desirable since it is time-efficient. However, the effect of recovery phase duration and whether recovery is passive or active should be investigated. In relation to this, subject comfort should be an important consideration.

Two other studies incorporated the verification phase on a subsequent day to the incremental phase (Day et al., 2003; Hawkins et al., 2007). Day et al. (2003) used an average exercise intensity of 90% peak power output, whereas a recent study by Hawkins et al. (2007) used a power output equivalent to at least 130% $\dot{V}O_{2max}$. Although it has been reported that $\dot{V}O_{2max}$ can be elicited by constant load power outputs equivalent to ~95-136% $\dot{V}O_{2max}$ (Hill et al., 2002), workloads equivalent to 90% $\dot{V}O_{2max}$ have been shown to elicit maximal $\dot{V}O_2$ values significantly lower than those attained in the incremental running test (Billat et al., 1995). However, the identical mean maximal $\dot{V}O_2$ values in the incremental and verification phases reported by Day et al. (2003), does support the view that a constant load bout of exercise at 90% peak power output did indeed elicit $\dot{V}O_{2max}$. Possible explanations for this discrepancy might be differences in the exercise modality or the fitness of the subjects that were used, or differences in the incremental test protocols that meant that the subjects in these two studies could have been exercising at different relative intensities. This latter point is based on the observation that peak work rate and the work rate-$\dot{V}O_2$ relationship attained in an incremental test is somewhat dependent on the characteristics of the test protocol (Bentley and McNaughton, 2003). Performing the verification phase on a separate day is advantageous in that the subject is likely to be less fatigued, which may result in an increased time to exhaustion and increased likelihood that a maximal $\dot{V}O_2$ is elicited. However, there appears to be no reduction in the discrepancies between the mean maximal $\dot{V}O_2$ attained in the incremental and verification phases (Table 1). Furthermore, although the verification phase may be better tolerated if performed on a separate day, the additional visit to the laboratory considerably reduces the utility of this approach.

Directions for future research

Five of the six studies that have investigated the utility of the verification phase have compared the mean differences between the maximal $\dot{V}O_2$ values attained in the incremental and verification phases (Day et al., 2003; Foster et al., 2007; Hawkins et al., 2007; Poole et al., 2007; Rossiter et al., 2006). Noakes (2008) recently criticised this approach, stating that exercise testing is performed on individuals not groups, and therefore, the group mean approach does not identify subjects who might not have elicited a true $\dot{V}O_{2max}$. It is also noteworthy that the original description of the verification phase procedure by Thoden et al. (1991; 1982) did not include a criterion threshold for making a decision of whether an individual has attained a true $\dot{V}O_{2max}$. Future research should attempt to establish the most appropriate verification criterion threshold to verify a true $\dot{V}O_{2max}$.

The same-day verification phase has consisted of a single square wave exercise bout with no preceding warm-up period (Foster et al., 2007; Midgley et al., 2006; Rossiter et al., 2006). For individuals with slow $\dot{V}O_2$ on-kinetics, such as the untrained (Hickson et al., 1978) and individuals with certain pathological conditions (Nery et al., 1982; Sietsema et al., 1986), this approach may not allow sufficient time for $\dot{V}O_2$ to reach its maximum before reaching their limit of tolerance. Performing the verification phase at a very high intensity, such as the ≥130% $\dot{V}O_{2max}$ used by Hawkins et al. (2007), may exacerbate this problem. A square wave transition from rest to supramaximal exercise also may be poorly tolerated. In contrast, subjects are likely to reach their limit of exercise tolerance before $\dot{V}O_{2max}$ is attained in square wave exercise bouts that are below the severe exercise domain (i.e. below the work rate associated with the maximal lactate steady state; Poole et al., 1988). Alternative approaches could be a multi-stage verification phase that incorporates lower intensity exercise immediately before the supramaximal effort, or a brief warm-up and a short incremental verification phase, for example, starting at three stages below the last completed stage in the prior incremental phase. Regardless of the protocol, the verification phase should incorporate a workload higher than that attained in the incremental phase to conform to the original concept of $\dot{V}O_{2max}$ (Hill and Lupton, 1923).

Myers et al (1990) reported that the choice of $\dot{V}O_2$ sampling interval can have a profound effect on the $\dot{V}O_2$ value obtained. These authors reported that small sampling intervals (e.g. 5-10 s) result in unacceptable variability, whereas intervals that are too large (e.g. 60 s) may be too imprecise for accurately determining rapidly changing $\dot{V}O_2$ responses (as in a $\dot{V}O_{2max}$ test). The effect of the $\dot{V}O_2$ data sampling method on the difference between the maximal $\dot{V}O_2$ values attained in the incremental and verification phases has not been investigated. Researchers have thus far used 15-s (Rossiter et al., 2006), 20-s (Poole et al., 2007), or 30-s (Foster et al., 2007; Midgley et al., 2007; Midgley et al., 2006) time averages, or continuous 45-s Douglas bag sampling (Hawkins et al., 2007). Since the verification phase can be less than 2 min (Midgley et al., 2006; Rossiter et al., 2006), a shorter time interval may be preferable, although this may not sufficiently smooth the considerable noise inherent to $\dot{V}O_2$ data (Lamarra et al., 1987). Further research is required to investigate an optimal $\dot{V}O_2$ smoothing method that has high precision for rapidly changing $\dot{V}O_2$, whilst limiting variability around the underlying trend.

Midgley et al. (2006) suggested that maximal heart rate values for the incremental and verification phases that agree within 2 beats·min^{-1} of each other, would provide a high degree of confidence that a subject has given a maximal effort in the incremental phase. Maximal heart rate verification could replace the current heart rate criterion based on attainment of a percentage of age-predicted maximal heart rate (Howley et al., 1995). Maximal heart verification is advantageous because it is not affected by the large imprecision associated with age-predicted maximal heart rate (Londeree, 1984). The small systematic bias towards a lower maximal heart rate in the verification phase reported by Midgley et al. (2006), however, suggests that the verification procedure requires modification before maximal heart rate verification can be recommended as a valid $\dot{V}O_{2\,max}$ criterion. The authors concluded that the verification phase may have been too short for some subjects to attain their maximal heart rate and that a multi-stage verification phase incorporating lower intensity exercise may negate this problem.

A potential limitation of the verification phase is that subjects are required to exercise to the limit of their tolerance twice within the same testing session. The original recommendations made by Thoden et al. (1991; 1982) were physiological testing guidelines for elite athletes. Current research suggests that the verification phase is well tolerated in athletic as well as apparently healthy sedentary populations. However, future research should establish whether this procedure is sufficiently tolerated by other populations such as children, the elderly, the obese, and individuals with particular chronic diseases. For some of these individuals it may be considered unethical to ask them to exercise to their limit of tolerance twice in the same testing session. Moreover, individuals with low exercise tolerance may be unwilling or unable to perform the verification phase.

PERSPECTIVES

The $\dot{V}O_{2max}$ test is a widely used procedure and robust methodology for the determination of $\dot{V}O_{2max}$ is important for experimental research where invalid $\dot{V}O_{2max}$ values could alter the outcome of the research findings. The currently used criteria for confirming a true $\dot{V}O_{2max}$ have been strongly criticised in relation to their lack of validity, mainly because they are unduly influenced by the $\dot{V}O_{2max}$ test duration, exercise modality, and between-subject differences in maximal attainable physiological values. Further research is therefore needed to identify new criteria that are not influenced by these factors. One procedure that appears to yield such criteria is the verification phase; however, there has so far been relatively little research investigating the utility of this procedure. This review presents the current state of knowledge regarding the verification phase procedure, with a view that it provides a platform for future research into $\dot{V}O_{2max}$ criteria derived from the verification phase.

Table 1. Mean (SD) maximal $\dot{V}O_2$ values attained in the incremental and verification phases of $\dot{V}O_{2max}$ tests conducted during previous studies. All mean differences between incremental and verification phases, for all studies, were not statistically significant.

Reference	Incremental phase	Recovery phase	Verification phase	Verification in same testing session?	Maximal incremental phase $\dot{V}O_2$ (mL·min^{-1})	Maximal verification phase $\dot{V}O_2$ (mL·min^{-1})
Day et al. (2003)	Ramp incremented cycle ergometer test.	not applicable	90% of peak power output attained in the incremental phase.	separate day	3640 (700)	3640 (700)
Midgley et al. (2006)	Continuous treadmill test. 1 min stages.	10 min active	0.5 km·h^{-1} higher than the last completed stage in the incremental phase.	yes	4041 (455)	3994 (447)
	Repeat trial of above.	10 min active	Repeat trial of above.	yes	4010 (379)	4029 (432)
Rossiter et al. (2006)	Ramp incremented cycle ergometer test.	5 min active	95% of peak power output attained in the incremental phase.	yes	4105 (478)	4117 (528)
	Ramp incremented cycle ergometer test.	5 min active	105% of peak power output attained in the incremental phase.	yes	4149 (502)	4090 (446)

Table 1. Continued.

Reference	Incremental phase	Recovery phase	Verification phase	Verification in same testing session?	Maximal incremental phase $\dot{V}O_2$ (mL·min^{-1})	Maximal verification phase $\dot{V}O_2$ (mL·min^{-1})
Midgley et al. (2007)	Continuous treadmill test. 1 min stage durations.	5 min passive	0.5 km·h^{-1} higher than the last completed stage in the incremental phase.	yes	4093 (538)	4068 (531)
	Discontinuous treadmill test. 2 min stages, with 30-s rest between stages.	5 min passive	1 km·h^{-1} higher than the last completed stage in the incremental phase.	yes	4096 (516)	4075 (522)
	Discontinuous treadmill test. 3 min stages, 30-s rest between stages.	5 min passive	1 km·h^{-1} higher than the last completed stage in the incremental phase.	yes	3980 (488)	4071 (531)
Hawkins et al. (2007)	Continuous treadmill test. 2 minute stages.	not applicable	Work load equivalent to that requiring ≥130% $\dot{V}O_{2max}$.	separate day	63.3 (6.3)†	62.9 (6.2)†
Foster et al. (2007)	Continuous cycle ergometer test. 1 min stage durations.	1 min active	25 W higher than that attained in the last stage of the incremental phase.	yes	3950 (750)	4060 (750)
	Continuous treadmill test. 3 min stage durations.	3 min active	0.8 km·h^{-1} (females) and 1.6 km·h^{-1} (males) higher than that attained in the last stage of the incremental phase.	yes	4090 (970)	4030 (1160)
Poole et al. (2008)	Ramp incremented cycle ergometer test.	not applicable	105% of peak power output attained in the incremental phase.	separate day	4030 (100)	3950 (110)

† Reported in mL·kg^{-1}·min^{-1}. Values in mL·min^{-1} or body mass of subjects not reported in original study

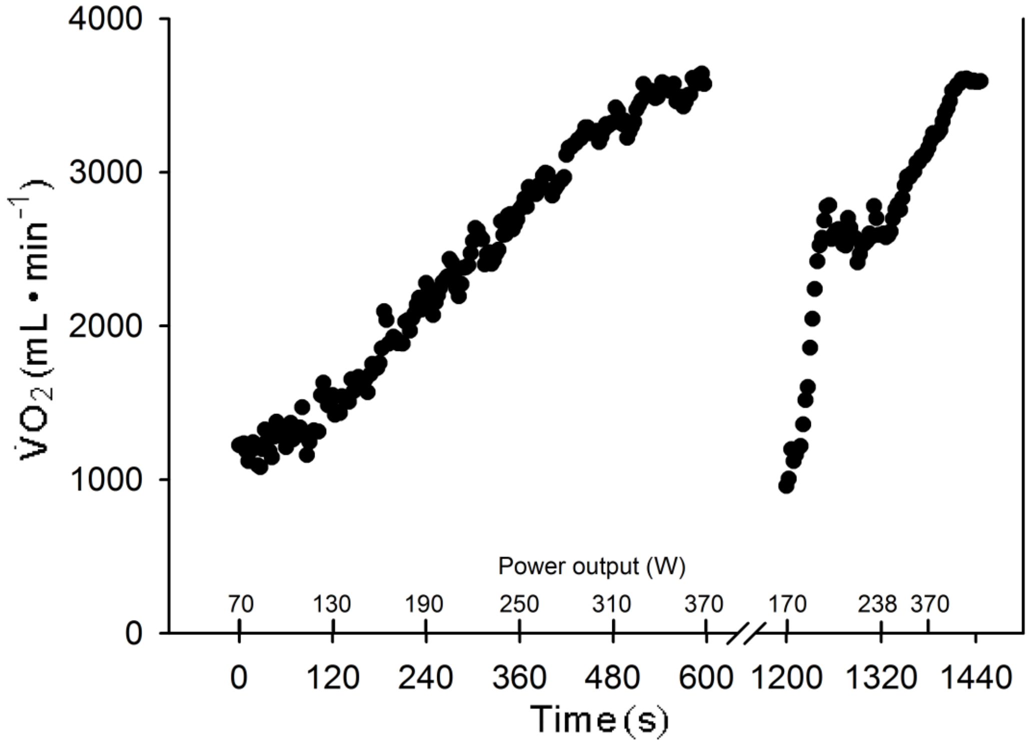

FIGURE 1. The $\dot{V}O_2$ response of one male subject to a continuous, step-incremented (30 W·min^{-1}) cycle ergometer test, incorporating subsequent recovery and verification phases. The verification phase consisted of cycling at 50% peak power output (defined as the power output associated with the last completed stage of the incremental phase) for 2 min, at 70% peak power output for 1 min, and then at one stage higher than peak power output to the limit of exercise tolerance. Note that although there was no clearly discernable $\dot{V}O_2$ plateau in the incremental phase, there was only a 0.8% difference between the maximal $\dot{V}O_2$ attained in the incremental phase (3677 mL·min^{-1}) and that attained in the verification phase (3648 mL·min^{-1}).

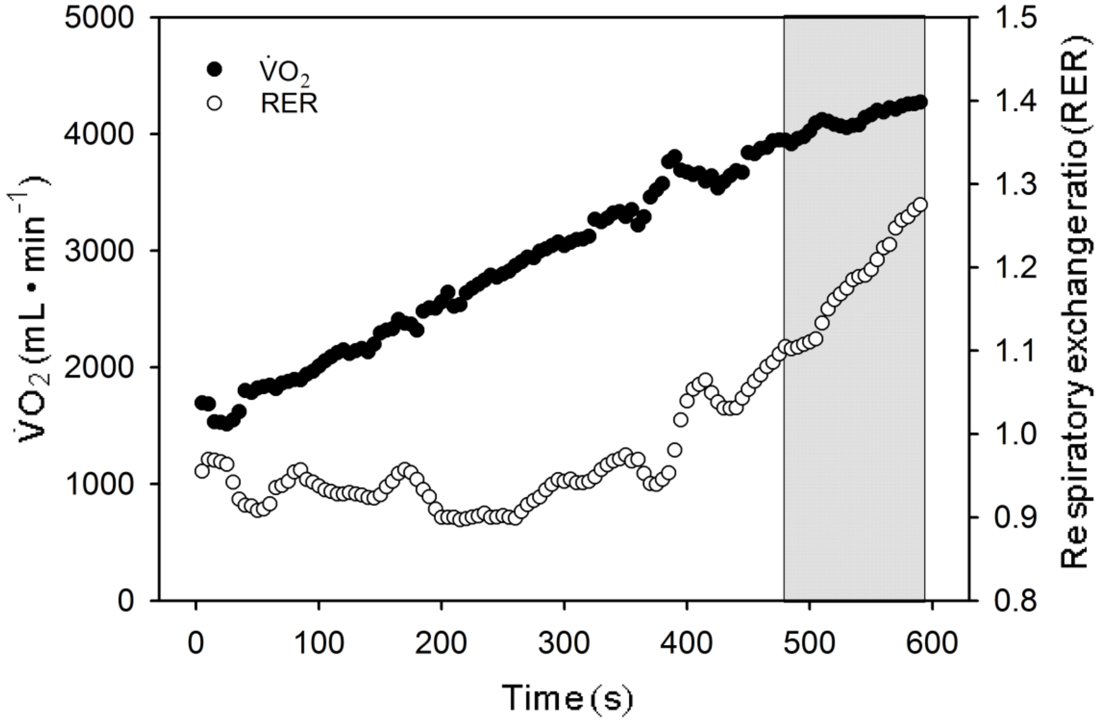

FIGURE 2. The $\dot{V}O_2$ and respiratory exchange ratio of a club-level cyclist during an incremental $\dot{V}O_{2max}$ test. Note that the cyclist would have satisfied an RER criterion of 1.10 at a $\dot{V}O_2$ of 3915 mL·min^{-1} (90% $\dot{V}O_{2max}$). The grey area represents the part of the test that would have been omitted if the subject had terminated the test at a respiratory exchange ratio of 1.10.

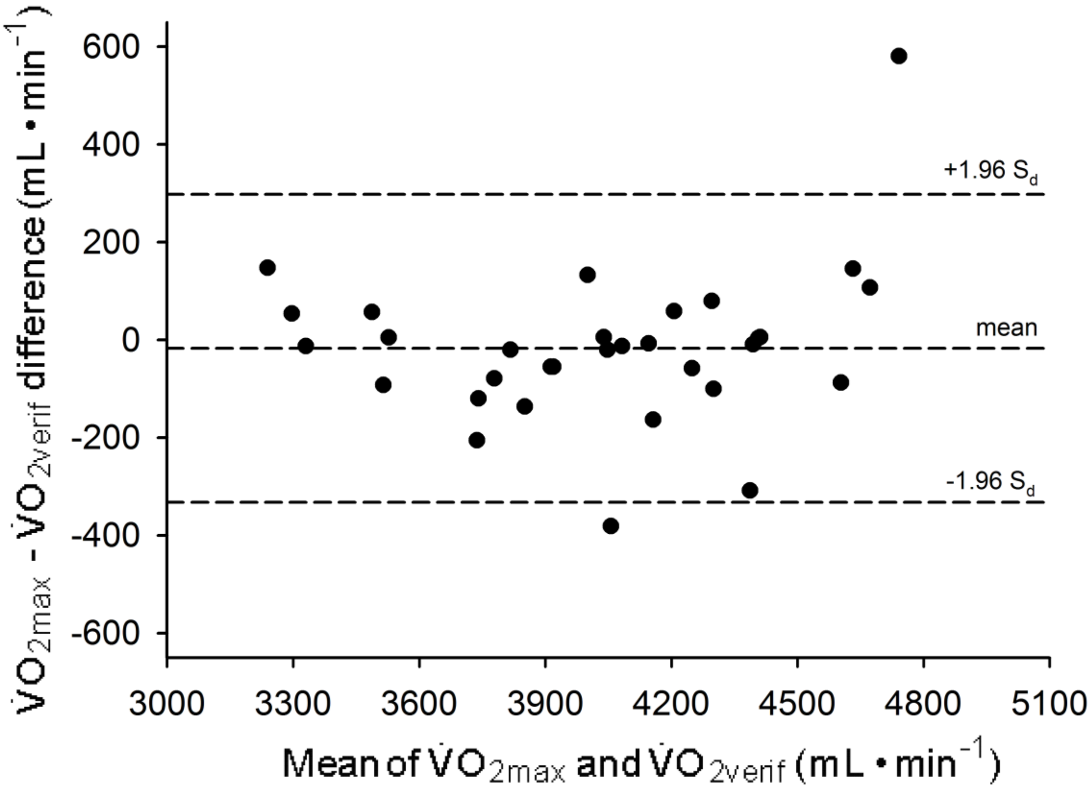

FIGURE 3. Bland-Altman plot showing individual differences between the maximal $\dot{V}O_2$ values attained in the incremental and verification phases of a $\dot{V}O_{2max}$ test plotted against their individual mean values (Midgley et al., 2006). The horizontal dashed lines represent the mean difference and 95% limits of agreement. S_d = standard deviation of the differences.

REFERENCES

Astorino TA, Willey J, Kinnahan J, Larsson SM, Welch H, Dalleck LC. Elucidating determinants of the plateau in oxygen consumption at $\dot{V}O_{2max}$. Br J Sports Med 2005: 39: 655-660.

Astrand P-O. Experimental studies of physical working capacity in relation to sex and age. Ejnar Munksgaard, Copenhagen, 1952.

ATS/ACCP. ATS/ACCP Statement on cardiopulmonary exercise testing. Am J Respir Crit Care Med 2003: 167: 211-77.

Bentley DJ, McNaughton LR. Comparison of W_{peak}, $\dot{V}O_{2peak}$ and the ventilation threshold from two different incremental exercise tests: relationship to endurance performance. J Sci Med Sport 2003: 6: 422-435.

Billat V, Renoux JC, Pinoteau J, Petit B, Koralsztein JP. Times to exhaustion at 90, 100 and 105% of velocity at $\dot{V}O_{2max}$ (maximal aerobic speed) and critical speed in elite long-distance runners. Arch Physiol Biochem 1995: 103: 129-135.

Caputo F, Mello MT, Denadai BS. Oxygen uptake kinetics and time to exhaustion in cycling and running: a comparison between trained and untrained subjects. Arch Physiol Biochem 2003: 111: 461-466.

Cumming GR, Borysyk LM. Criteria for maximum oxygen uptake in men over 40 in a population survey. Med Sci Sports 1972: 4: 18-22.

Day JR, Rossiter HB, Coats EM, Skasick A, Whipp BJ. The maximally attainable $\dot{V}O_2$ during exercise in humans: the peak vs. maximum issue. J Appl Physiol 2003: 95: 1901-1907.

Donnelly JE, Jakicic J, Roscoe M, Jacobsen DJ, Israel RG. Criteria to verify attainment of maximal exercise tolerance test with obese females. Diabetes Res Clin Pract 1990: 10 Suppl 1: S283-S286.

Duncan GE, Howley ET, Johnson BN. Applicability of $\dot{V}O_{2max}$ criteria: discontinuous versus continuous protocols. Med Sci Sports Exerc 1997: 29: 273-278.

Foster C, Kuffel E, Bradley N, Battista RA, Wright G, Porcari JP, Lucia A, Dekoning JJ. $\dot{V}O_{2max}$ during successive maximal efforts. Eur J Appl Physiol 2007: 102: 67-72.

Froelicher VF, Jr., Brammell H, Davis G, Noguera I, Stewart A, Lancaster MC. A comparison of three maximal treadmill exercise protocols. J Appl Physiol 1974: 36: 720-725.

Gonzalez-Alonso J, Calbet JA. Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. Circulation 2003: 107: 824-830.

Hawkins MN, Raven PB, Snell PG, Stray-Gundersen J, Levine BD. Maximal oxygen uptake as a parametric measure of cardiorespiratory capacity. Med Sci Sports Exerc 2007: 39: 103-107.

Hickson RC, Bomze HA, Hollozy JO. Faster adjustment of O_2 uptake to the energy requirement of exercise in the trained state. J Appl Physiol 1978: 44: 877-881.

Hill AV, Long CNH, Lupton H. Muscular exercise, lactic acid and the supply and utilisation of oxygen. Parts VII-VIII. Proc R Soc Lond B Biol Sci 1924: 97: 155-176.

Hill AV, Lupton H. Muscular exercise, lactic acid, and the supply and utilization of oxygen. Q J Med 1923: 16: 135-171.

Hill DW, Poole DC, Smith JC. The relationship between power and the time to achieve $\dot{V}O_{2\,max}$. Med Sci Sports Exerc 2002: 34: 709-714.

Howley ET, Bassett DR, Jr., Welch HG. Criteria for maximal oxygen uptake: review and commentary. Med Sci Sports Exerc 1995: 27: 1292-1301.

Katch VL, Sady SS, Freedson P. Biological variability in maximum aerobic power. Med Sci Sports Exerc 1982: 14: 21-25.

Lamarra N, Whipp BJ, Ward SA, Wasserman K. Effect of interbreath fluctuations on characterizing exercise gas exchange kinetics. J Appl Physiol 1987: 62: 2003-2012.

Londeree BR. Influence of age and other factors on maximal heart rate. J Cardiac Rehabil 1984: 4: 44-49.

Midgley AW, McNaughton LR, Carroll S. Time at VO_{2max} during intermittent treadmill running: test protocol dependent or methodological artefact? Int J Sports Med 2007: 28: 934-939.

Midgley AW, McNaughton LR, Carroll S. Verification phase as a useful tool in the determination of the maximal oxygen uptake of runners. Appl Physiol Nutr Metab 2006: 31: 541-548.

Midgley AW, McNaughton LR, Polman R, Marchant D. Criteria for determination of the maximal oxygen uptake: A brief critique and recommendations for future research. Sports Med 2007: 37: 1019-1028.

Misquita NA, Davis DC, Dobrovolny CL, Ryan AS, Dennis KE, Nicklas BJ. Applicability of maximal oxygen consumption criteria in obese, postmenopausal women. J Womens Health Gend Based Med 2001: 10: 879-885.

Mitchell JH, Sproule BJ, Chapman CB. The physiological meaning of the maximal oxygen intake test. J Clin Invest 1958: 37: 538-547.

Morgan DW, Baldini FD, Martin PE, Kohrt WM. Ten kilometer performance and predicted velocity at VO2max among well-trained male runners. Med Sci Sports Exerc 1989: 21: 78-83.

Mortensen SP, Damsgaard R, Dawson EA, Secher NH, Gonzalez-Alonso J. Restrictions in systemic and locomotor skeletal muscle perfusion, oxygen supply and VO2 during high-intensity whole-body exercise in humans. J Physiol 2008: 586: 2621-2635.

Mortensen SP, Dawson EA, Yoshiga CC, Dalsgaard MK, Damsgaard R, Secher NH, Gonzalez-Alonso J. Limitations to systemic and locomotor limb muscle oxygen delivery and uptake during maximal exercise in humans. J Physiol 2005: 566: 273-285.

Myers J, Walsh D, Sullivan M, Froelicher V. Effect of sampling on variability and plateau in oxygen uptake. J Appl Physiol 1990: 68: 404-410.

Nery LE, Wasserman K, Andrews JD, Huntsman DJ, Hansen JE, Whipp BJ. Ventilatory and gas exchange kinetics during exercise in chronic airways obstruction. J Appl Physiol 1982: 53: 1594-1602.

Niemela K, Palatsi I, Linnaluoto M, Takkunen J. Criteria for maximum oxygen uptake in progressive bicycle tests. Eur J Appl Physiol Occup Physiol 1980: 44: 51-59.

Noakes TD. How did A V Hill understand the $\dot{V}O_{2\,max}$ and the "plateau phenomenon"? Still no clarity? Br J Sports Med 2008: 42: 574-580.

Noakes TD. Maximal oxygen uptake as a parametric measure of cardiorespiratory capacity: comment. Med Sci Sports Exerc 2008: 40: 585.

Poole DC, Ward SA, Gardner GW, Whipp BJ. Metabolic and respiratory profile of the upper limit for prolonged exercise in man. Ergonomics 1988: 31: 1265-1279.

Poole DC, Wilkerson DP, Jones AM. Validity of criteria for establishing maximal O_2 uptake during ramp exercise tests. Eur J Appl Physiol 2007: 102: 403-410.

Rivera-Brown AM, Frontera WR. Achievement of plateau and reliability of $\dot{V}O_{2\,max}$ in trained adolescents tested with different ergometers. Pediatr Exerc Sci 1998: 10: 164-175.

Rossiter HB, Kowalchuk JM, Whipp BJ. A test to establish maximum O_2 uptake despite no plateau in the O2 uptake response to ramp incremental exercise. J Appl Physiol 2006: 100: 764-770.

Rowland TW, Cunningham LN. Oxygen uptake plateau during maximal treadmill exercise in children. Chest 1992: 101: 485-489.

Shephard RJ, Allen C, Benade AJ, Davies CT, Di Prampero PE, Hedman R, Merriman JE, Myhre K, Simmons R. The maximum oxygen intake. An international reference standard of cardiorespiratory fitness. Bull World Health Organ 1968: 38: 757-764.

Sietsema KE, Cooper DM, Perloff JK, Rosove MH, Child JS, Canobbio MM, Whipp BJ, Wasserman K. Dynamics of oxygen uptake during exercise in adults with cyanotic congenital heart disease. Circulation 1986: 73: 1137-1144.

Stachenfeld NS, Eskenazi M, Gleim GW, Coplan NL, Nicholas JA. Predictive accuracy of criteria used to assess maximal oxygen consumption. Am Heart J 1992: 123: 922-925.

Taylor HL, Buskirk E, Henschel A. Maximal oxygen intake as an objective measure of cardio-respiratory performance. J Appl Physiol 1955: 8: 73-80.

Thoden JS. Testing aerobic power. In: MacDougall JD, Wenger HA and Green HJ (eds) Physiological testing of the high-performance athlete. Human Kinetics, Champaign, IL, 1991, 107-173.

Thoden JS, MacDougall JD, Wilson BA. Testing aerobic power. In: MacDougall JD, Wenger HA and Green HJ (eds). Mouvement Publications, Inc, Ithaca, NY, 1982, 39-54.

Wagner PD. New ideas on limitations to $\dot{V}O_{2\,max}$. Exerc Sport Sci Rev 2000: 28: 10-14.

Wyndham CH, Strydom NB, Maritz JS, Morrison JF, Peter J, Potgieter ZU. Maximum oxygen intake and maximum heart rate during strenuous work. J Appl Physiol 1959: 14: 927-936.