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PROTOCOL DEPENDENCY OF THE BREAKPOINT
IN THE VO_2-WATT RELATIONSHIP

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M.S. degree in Kinesiology

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PROTOCOL DEPENDENCY OF THE BREAKPOINT IN THE VO_2-WATT RELATIONSHIP

By

Peter J. Osmond

A THESIS

Submitted to
Michigan State University
In partial fulfillment of the requirements
for the degree of

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ABSTRACT

PROTOCOL DEPENDENCY OF THE BREAKPOINT IN THE VO_2-WATT RELATIONSHIP

By

Peter J. Osmond

The purpose of this study was to determine whether the breakpoint in the VO_2-watt relationship (VO_{2BP}) observed during incremental exercise testing is protocol dependent. Specifically, we attempted to determine if alterations in stage duration engendered quantifiable changes on the VO_{2BP}. In addition, we assessed lactate thresholds (LTs) and ventilatory thresholds (VTs) to determine values of these variables relative to the occurrence of the VO_{2BP}. Sixteen subjects (mean age (SD) 26.8 ± 4.2 years, mean peak O_2 uptake (SD) ~3.1 ± .526 L/minute) who had no known cardiovascular disease participated in this study. All subjects performed three maximal exercise tests. These tests included incremental protocols of 1-, 3-, and 5-minute stages. All testing was performed on a cycle ergometer. Potential differences in the VO_{2BP}, LT, and VT between the three protocols were determined using a two-way, repeated measures analysis of variance. The main findings in this study were threefold: (1) there was a disparity in the relationship between the VO_{2BP} and the LT, (2) there was a significant difference between LT and VT for all protocols, and (3) the power outputs at VO_{2BP}, LT, and VT were higher during the 1-minute stage protocols than the 3- and 5-minute stage protocols.

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KEY TO ABBREVIATIONS

BTPS	Body temperature and pressure saturated
HR	Heart rate
LT	Lactate threshold
MSS	Maximal steady state
$P_{ET}CO_2$	End tidal carbon dioxide
$P_{ET}O_2$	End tidal oxygen
PO_{max}	Maximum power output
R	Respiratory Exchange Ratio
STPD	Standard temperature and pressure dry
VCO_2	Volume of carbon dioxide expired
V_E	Minute ventilation
VO_2	Volume of oxygen consumed
VO_{2BP}	Breakpoint in the VO_2-watt relationship
VO_{2max}	Maximal oxygen consumption
VO_{2peak}	Peak oxygen consumption
VO_{2sc}	Slow component of VO_2 kinetics
VT	Ventilatory threshold
H+	Hydrogen ion

DEFINITIONS

Critical power: The theoretical power output for an individual that could be maintained indefinitely, as it represents the upper limit for sustainable exercise.

Lactate threshold: The power output, during incremental exercise, at which the first abrupt change in blood lactate concentration occurs (minimum 0.5 mmol/L) and after which continues to increase with increasing power output.

Maximal steady state: The highest power output at which an individual can perform exercise while maintaining stable VO_2.

Slow component of VO_2 kinetics: The second non-linear component of the VO_2-watt relationship. It is calculated by the difference between actual VO_2 and that which is expected based upon linear regression analysis of the below-lactate threshold VO_2 response.

Ventilatory threshold: The power output at which there is an increase in V_E/VO_2 without an increase in V_E/VCO_2.

VO_2-watt breakpoint: The power output just prior to where the VO_2-watt relationship becomes non-linear. This point, which occurs above the lactate threshold, is believed to be indicative of the slow component of VO_2 kinetics.

INTRODUCTION

Overview of the Problem

The VO_2-watt relationship reflects the pattern of oxygen utilization during exercise relative to specific power outputs on a cycle ergometer. It is therefore also reflective of the energy requirements necessary for an individual to perform at a given work-rate. During continuous incremental exercise on a cycle ergometer, this relationship can be observed through an entire range of intensities up to an individual's maximum exercise capacity. In healthy individuals, the VO_2-watt relationship during incremental exercise has historically been perceived as linear (Astrand & Rodahl, 1986). This notion, however, only holds true for exercise intensities below the lactate threshold (LT). Exercising at an intensity that induces a sustained increase in blood lactate concentration is accompanied by a second, slower rise in VO_2 (Zoladz, Rademaker, & Sargeant, 1995). This second component is termed the slow component of VO_2 kinetics (VO_{2sc}), which can be defined as, and calculated by, the difference between actual VO_2 and that which is expected based on linear regression of the below LT VO_2 response. The use of linear regression techniques reveal a linear slope in the VO_2-watt relationship below the LT, followed by a non-linear component at intensities that are above the LT. However, it has not been determined whether the slow component itself conforms to an exponential or linear model. In fact, some evidence suggests that VO_{2sc} kinetics follow both exponential and linear trajectories, although there is no agreement as to the exact process (Barstow &

Mole, 1991). VO_2 kinetics above the LT demonstrate a diminution of the step pattern that is typically observed during incremental exercise. This departure from linearity reflects an increase in oxygen utilization, and thus an additional energy requirement that is above that predicted from an extrapolation of the below-lactate threshold VO_2-watt relationship. The power output just prior to where the VO_2-watt relationship goes from being linear to being non-linear is defined as the VO_2 breakpoint (VO_{2BP})(see Figure 1).

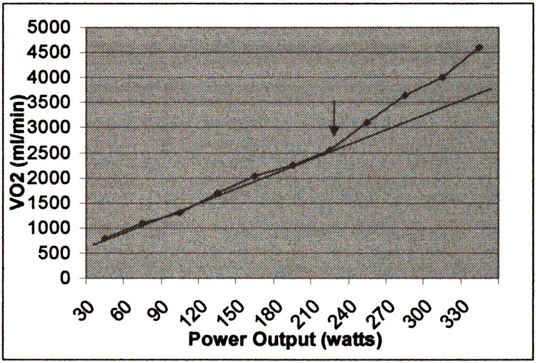

Figure 1. An example of the VO_{2BP}, indicated by the arrow. The linear regression is based on data from the below VO_{2BP} data.

Exercise that elicits a significant VO_{2SC} will be limited in duration, because it represents non-steady-state oxygen consumption (Poole, Ward, Gardner, & Whipp, 1988). The VO_2-watt breakpoint observed during constant load exercise

Whipp, 1988). The VO_2-watt breakpoint observed during constant load exercise is presumed to be a result of the slow component of VO_2 (Zoladz, Szkutnik, Majerczak, & Duda, 1998). This is important since it can be used to predict the maximal VO_2 steady state (MSS)—the point above which the slow component occurs.

Despite some research in this area and the fact that the slow component is only detectable above the LT, investigators have been unable to demonstrate a causal relationship between blood lactate concentration and VO_2 kinetics. Roston, Whipp, Cunningham, Effros, and Wasserman (1987), for example, showed the magnitude of the VO_{2sc} to be highly correlated with increases in blood lactate levels. Similarly Zoladz et al. (1998) found that the LT occurred just prior to or at the same power output as the VO_{2BP} in 23 of 26 subjects performing on a cycle ergometer. These studies suggest that the VO_{2BP} may be concurrent with the LT. However, data from Poole, Gladden, Kurdak, and Hogan (1994) suggest that although there is a relationship between LT and the slow component it is not causal. Support for this also comes from the work of Womack et al. (1995), who found that the diminution of the VO_{2sc} that occurred as a result of a 6-week cycle ergometry training program was coincident with reductions in blood lactate concentration. However, subsequent epinephrine infusion, which increased blood lactate concentration, did not increase exercise VO_2.

Previous research suggests that both the LT and the VT are altered in response to stage increment size and duration during exercise testing (Davis et al., 1982; Stockhausen, Grathwohl, Bürklin, Spranz, & Keul, 1997). Based on these studies, and assuming that the relationship between blood lactate and VO_2 is causal, one would expect that as LT and VT respond to changes in stage duration, the VO_{2BP} would respond in a similar manner. Furthermore, the influence of the VO_{2sc} itself has been reported as being dependent upon stage duration. That is, as stage duration increases, the more apparent the VO_{2sc} becomes (Zhang, Johnson, Chow, & Wasserman, 1991), and it may be undetectable for exercise involving fast work-rate increments (Whipp, 1994). A possible reason for this may be that the fast work-rate increments do not allow enough time at a particular power output for a steady state in VO_2 to occur, and therefore the VO_2-watt relationship may appear linear in the domain of heavy to severe exercise intensity. Therefore, long stage durations may be more appropriate for elucidating the VO_{2BP}. To determine the most appropriate stage duration for detecting the VO_{2BP}, subjects must perform exercise protocols of different stage durations so to compare the VO_2 and the power output at which it occurs for each test. Also, LT should be assessed to determine if changes in stage duration affect its occurrence relative to the VO_{2BP}, VO_2, and/or power output. This will provide insight into the relationship between lactate concentration and VO_2.

Need for the Study

The significance of the slow component is evidenced by its practical and clinical applications. It has been shown that a reduction in the VO_{2sc} as a result of exercise training was concurrent with improvements in walking economy in patients with peripheral arterial occlusive disease (Womack, Sieminski, Katzel, Yataco, & Gardner, 1997). This reduction in the magnitude of the VO_{2sc} is regarded as a positive adaptation to exercise training. Therefore, the VO_{2sc} can be used as a submaximal indicator of improvements in exercise tolerance. This is important since many clinical populations have difficulty in reaching the VO_{2max} criterion due to their pathologies. Furthermore, since the VO_{2BP} is believed to indicate the point at which the VO_{2sc} occurs, it can be used as a marker for assessing improvements in exercise tolerance based on the power output at which it occurs (Zoladz et al., 1998). Despite this apparent significance, the specific mechanisms that cause the VO_{2sc} are largely unknown. Typically, researchers have used the LT as a critical value, above which it is assumed the slow component occurs. From the data of Poole et al. (1994), evidence now exists that the slow component and blood lactate concentration are not causally related. They found that infusing lactate directly into a working dog muscle did not increase VO_2. Based on this, LT may not be the most appropriate indicator of the VO_{2sc}, and therefore it is important to determine the best methodology for elucidating the VO_{2BP}. In addition, it is also important to investigate how the relationships between the VO_{2BP} and LT and VT are impacted by protocol design. Currently, no study has been performed specifically for the purpose of investigating the influence of stage duration on the VO_{2BP}.

Statement of the Problem

The purpose of this study was to determine if the breakpoint in the VO_2-watt relationship is affected by stage duration during incremental exercise on a cycle ergometer.

Research Questions

This study was designed to answer the following questions: (a) will the VO_2-watt breakpoint be affected by alterations in stage duration, and (b) do these changes in protocol affect the lactate and/or ventilatory thresholds relative to the VO_{2BP}?

Hypothesis Statement

We hypothesized that the VO_{2BP} would change with stage duration. More specifically, 1) the power output at VO_{2BP} would be lowest for 5-minute stage protocol, 2) the power output at VO_{2BP} would be higher for the 3-minute than the 5-minute stage protocol, and 3) VO_{2BP} would be detected at the highest power output in the case of the 1-minute stage protocol.

REVIEW OF LITERATURE

Characteristics of the VO_2-Watt Relationship

The pattern of oxygen uptake in response to increasing workloads during cycle ergometry exercise has historically been described as linear and has been presented as such in exercise physiology textbooks (Astrand & Rodahl, 1986; DeVries & Housh, 1994; McArdle, Katch, & Katch, 1996). Despite this, there is a substantial amount of evidence that this linearity only occurs below LT and that the relationship is non-linear in the domain of exercise intensities above LT. In fact, this non-linear VO_2 response in the domain of heavy to severe exercise has been validated and accepted, and the kinetics of O_2 uptake relative to exercise intensity have been well documented (Gaesser & Poole, 1996; Whipp, 1994). Whipp (1994) characterizes VO_2 kinetics as being intensity dependent and describes three phases of the response to constant-load exercise. For moderate constant-load exercise, that is for all intensities below the LT, these phases are as follows: (a) an initial rapid response, (b) a slower, exponential response, and (c) a steady state. During light to moderate exercise intensity the steady state is typically reached in 3 to 5 minutes. An analysis of the VO_2-watt relationship during incremental cycle ergometry reveals a step pattern, which is reflective of this response at each stage. However, above the LT the kinetics of VO_2 become progressively slower at each stage, and the characteristic step pattern is increasingly damped as lactate concentration increases, which reflects an increase in VO_2 and a delayed steady state at each stage (Zhang et al., 1991). The use of linear regression techniques will then reveal a linear slope below the

LT, followed by a non-linear component at intensities above the LT, which demonstrates the diminished step pattern. The dampening of the step pattern is a result of the slow component of VO_2 kinetics and reflects a disproportionate oxygen uptake above the LT compared to that of moderate exercise.

The magnitude of the VO_{2sc} during prolonged, constant-load exercise increases as a function of time and power output and can account for as much as 1 - 1.5 L O_2 /minute during heavy exercise (Gaesser & Poole, 1996). Although the VO_{2sc} response occurs only above the LT, and despite the fact that studies have reported high correlations between lactate levels and VO_2, no research has been able to find a cause and effect relationship between them. Womack et al. (1995) found that infusing epinephrine could cause blood lactate levels to rise without subsequent increases in oxygen consumption. Similarly, Poole et al. (1994) found that direct lactate infusion did not affect the magnitude of the VO_{2sc}. These studies suggest a relationship exists between the LT and the VO_{2sc}; however, the nature of this relationship does not appear to be causal.

Significance of the VO_2 Slow Component

The VO_{2sc} can delay the attainment of a VO_2 steady state or it can drive VO_2 to a maximum value that is higher than would be expected from an observation of the below LT linearity (Zoladz et al., 1998). This is the fundamental importance of the slow component that must be examined and understood when exercise testing and prescription are considered. It is common practice for exercise physiologists to use maximal exercise testing techniques to define and prescribe exercise training as percentages of VO_{2max}. This practice is flawed if the augmented VO_2 response above the LT is not recognized, by assuming linearity up to maximum exercise capacity. This may be especially important when considering different exercise-testing modalities.

It has been reported in research involving untrained subjects that the amplitude of the VO_{2sc} is greater for cycle ergometry than for treadmill running (Jones & McConnell, 1999). This has also been found to be the case in trained athletes. Billat, Binsse, Haouzi, and Koralsztein (1998) found in elite triathletes, presumed to be trained equally in both modes of exercise, that the magnitude of the slow component was higher for cycling. These studies suggest that regardless of fitness level or familiarity with exercise modality, the VO_{2sc} generally has a greater influence during cycling ergometry. Therefore if the VO_{2sc} is not considered when exercise testing, especially during cycling exercise, then the metabolic cost of an exercise bout may be underestimated. This may then lead directly to inappropriate prescription, particularly for individuals who maintain low levels of fitness.

Despite the fact that both trained and untrained subjects have greater VO_{2sc} responses during cycling when compared to running, each individual's condition will directly influence the magnitude of the response. Jacobsen, Coast, and Donnelly (1998) reported that in comparing fit and unfit groups performing cycle ergometry, the unfit subjects consistently had greater absolute VO_{2sc} than did the fitter subjects. This suggests there is a training effect, at least for cycle exercise, in that the result is a diminished VO_{2sc}. In fact, Womack et al. (1995) found a 50% reduction in the slow component with only 2 weeks of cycle ergometry training. Since the VO_{2sc} represents an additional energy requirement at a particular power output, its delay or diminution signifies an improved economy and therefore should be considered a positive training response. Furthermore, exercise at an intensity that elicits the slow component will be temporally limited, so that attenuating the slow component may result in improved endurance performance.

Although research has not described the specific benefits of a diminished slow component to performance, some studies have successfully applied this rationale to the designing of exercise training techniques as well as to exercise testing methodology. For example, Stoudemire et al. (1996) demonstrated that subjects could remain at VO_{2max} for longer than previously thought by the systematic reduction of treadmill velocity after VO_{2max} had been reached. It is likely that the specificity of training at VO_{2max} is essential for its improvement. The longer period of time an individual can exercise at VO_{2max} during a particular training session, the more profound the effect that training session may have on the improvement of VO_{2max}. Therefore this method of systematically reducing treadmill velocity in order for VO_{2max} to be maintained could prove to be a useful training technique. This rationale could also be applied successfully to designing maximal exercise-testing protocols. Gaesser and Poole (1996) pointed out that there are a variety of power outputs that will, over time, allow for VO_{2max} to be achieved. In the severe exercise intensity domain (which typically begins at a power output that is about 50% of the difference between LT and VO_{2max}) neither lactate concentration nor VO_2 can stabilize. Therefore, constant-load exercise at any power output performed in this domain will drive VO_2 to its maximum value. This allows for versatility in exercise-testing protocols, due to the variety of power outputs that may be used, as well as provides an alternative to incremental testing. However, LT cannot be determined using such a protocol since it is performed entirely above that intensity.

Incremental exercise testing designed to determine LT and VO_{2max} can provide coaches and their athletes with additional information regarding fitness if the slow component is considered. Since the VO_{2BP} represents the boundary between steady-state and non-steady-state VO_2, one can determine the maximal steady-state power output. It has been suggested that the VO_{2BP} be used as an additional indicator of exercise capacity by determining the power output at which the VO_{2BP} occurs (Zoladz et al., 1998). Research has not determined the long-term effects of training at a power output that corresponds to the MSS, nor has it determined the best methodology for clarifying its occurrence.

The significance of the slow component for clinical populations. The kinetics of the VO_2 response to exercise above the LT for cardiac and respiratory patients also reflects the delayed attainment of the steady state and may even be more pronounced in these populations (Zhang et al., 1993). In such cases this occurs at very low work-rates, as patients are limited by their specific pathology. However, the training effect described above (which is marked by a diminished slow component and an elevated LT) is applicable to these populations (Gaesser & Poole, 1996). For patients with cardiopathology, training may not increase stroke volume and subsequent VO_{2max}, but the diminution of the slow component will allow them to exercise at slightly higher work-rates and therefore improve exercise capacity. Womack et al. (1997) studied the effect of a 4-month exercise rehabilitation program involving patients with peripheral arterial occlusive disease. They found that walking economy was significantly improved with training, and the improvement was due to the diminution of the slow component. For respiratory patients, whose maximum exercise capacity is limited by their maximum ventilatory capacity, improvements in lung function may not occur from exercise training, due to irreversible damage. However, the lowering of the ventilatory work at a particular work-rate may occur by the attenuation of the VO_{2sc} and the subsequent rise in the LT (Gaesser & Poole, 1996).

The VO_{2BP} has promise as a marker for exercise tolerance or training adaptation for clinical populations. The VO_{2max} criterion is often not achieved by patients during exercise testing (Simonton, Higginbotham, & Cobb, 1988). Therefore, the VO_{2BP} may be a more appropriate criterion on which to determine initial exercise capacity and subsequent improvements.

Protocol Effect on the LT and VT

The lactate and ventilatory thresholds are often used as predictors of endurance performance and as criteria on which exercise intensity is based. Historically these variables have been collectively termed the anaerobic threshold, which is based on the concept that measurement of gas exchange variables (i.e., VT) indicates the occurrence of lactic acidosis (i.e., LT). In recent years, however, research has shown a disparity in the occurrence of the LT and VT, providing evidence that these variables are not causally related. Chicharro, Pérez, Vaquero, Lucía, and Legido (1997) found that the VT occurred at a lower power output in 33 of 39 subjects performing a ramp protocol (25 watts/minute) on a cycle ergometer, suggesting that the increase in ventilatory response may not be caused by lactate concentration as had been previously suggested (Wasserman, Beaver, & Whipp, 1990). This dichotomy has also been observed during incremental treadmill exercise (Dickhuth et al., 1999), which suggests that this is not a phenomenon unique to a specific protocol or exercise modality.

VT may be affected by protocol design. Davis et al. (1982) compared four ramp protocols of varying work rates using a cycle ergometer. They found that the VT occurred at the same VO_2 for all protocols, but that the power output that corresponded with the VT increased as the work rate increased. Other research has reported no protocol effect on VT; however, these results either are based on units of ml/minute, rather than power output, or used stage durations of longer than 1 minute (Zhang et al., 1991). Wasserman and Whipp (1975) explained that when considering ramp protocol data, it is more appropriate to describe VT in units of ml/minute rather than in watts, due to the fact that VT always occurs at the same VO_2 but not necessarily the same power output. This may be explained by the pattern of responses in the ΔVO_2-Δwatt relationship observed at different work-rate increments. Hansen, Casaburi, Cooper, and Wasserman (1988) reported that as work-rate increased during ramp protocols from 15 to 60 watts/minute, the ΔVO_2-Δwatt slope progressively decreased. Based on Wasserman and Whipp's (1975) contention that for ramp exercise the VT corresponds to the same VO_2 regardless of protocol, the VT must then necessarily occur at a higher power output.

In contrast, Wasserman and Whipp also reported for protocols with stage durations of 1 minute or more VT can be expressed as either VO_2 or power output. Carta, Aru, Barbieri, and Mele (1991) found that the VT occurred at the same VO_2 and power output for a 30-watt/3-minute and a 10-watt/minute cycle protocol. However, the power output at VT was much higher for a 30-watt/minute protocol, while the VO_2 at VT was not significantly different from the other protocols. This suggests that this effect may be more a function of work-rate increment than of stage duration for ramp protocols. For incremental protocols of greater than 1 minute, there is no evidence to suggest that VT is affected by work-rate or stage duration. Weltman et al. (1990) found that the VO_2 and velocity at LT did not change for stage durations of 3- and 10-minutes during treadmill running. However, Stockhausen et al. (1997) defined minimum stage durations for a range of increment sizes necessary for a steady lactate concentration to be achieved. They reported that if the stage duration is too short for a particular workload increase, then a lactate steady state will not occur, and the power output at the LT may be overestimated. They determined that increment sizes of 20-, 30-, and 50-watts are required for stage durations of 3-, 4-, and 5-minutes, respectively.

An objective of the endurance athlete is to perform at the highest speed or power output, while still maintaining a constant lactate concentration. Often training intensity is based on the speed or power output that corresponds with the maximum lactate steady-state. Therefore, accuracy in determining the LT is critical to coaches and athletes for designing this type of training. The stage duration and/or work-rate used in identifying the LT may affect the speed or power output associated with its occurrence. Therefore, protocol design should be considered when accurate determination of the LT or VT is essential.

The protocol effect on parameters of aerobic function during cycle ergometry has also been extensively studied. Zhang et al. (1991) compared a ramp protocol and 1-, 2-, and 3-minute stage protocols on a cycle ergometer. Workload size was altered so that all tests were performed at the same work-rate. The authors found no significant differences between these protocols for VO_{2max}, HR, V_E, R, or VCO_2. The only notable difference was a slightly shorter total running time for the 3-minute stage test. Similar findings were reported by Davis et al. (1982), who found that various ramp slopes of 20-, 30-, 50-, and 100-watts/minute elicited consistent results for VO_{2max} and exercise economy.

It is interesting that in each of these studies discussed in the preceding paragraph, a linear VO_2 response was observed both above and below the LT in the ramp protocols (protocols of continuously increasing power output), but a non-linear response was apparent for the incremental protocols (protocols with temporally defined stages of increasing power output) above LT. In fact, as stage duration increased and work-rate subsequently decreased, the VO_2 step pattern became increasingly more apparent, but was virtually undetectable for the ramp and 1-minute protocols. Therefore, it is only during slow work-rates that evidence of the slow component of VO_2 kinetics can be observed (Whipp, 1994).

Parameters of aerobic function such as VO_{2max}, V_E, VCO_2, and economy are not affected by stage duration or changes in work-rate. However, as with LT, researchers who use exercise testing to identify the VO_{2BP} should consider the length of stage as well as the rate of work increment. However, the most appropriate stage length and/or work-rate has not yet been determined.

Assessing Maximal Steady State (MSS)

The LT has been used as a demarcation point for the upper limit of steady-state exercise as well as a critical indicator upon which to prescribe exercise intensity (Casaburi, Storer, Sullivan, & Wasserman, 1995). Due to the relationship that is often believed to exist between lactate concentration and VO_2, it has been assumed that the LT is coincident with the onset of the VO_{2sc} and therefore can be used for its detection. However, as described above, the dissociation that has been found regarding these variables has brought this hypothesis into question (Poole, Gladden, Kurdak, & Hogan, 1994; Womack et al., 1995).

It has been suggested that the maximal steady state can be determined by assessing the hyperbolic relationship between power output and endurance time to fatigue (Morton, Green, Bishop, & Jenkins, 1996; Poole, Ward, Gardner, & Whipp, 1988). Based on this relationship it is possible to determine a power output for an individual that could in theory be maintained indefinitely. This power output represents the upper limit for sustainable exercise and is termed critical power. This power output is represented in Figure 2 as the vertical asymptote.

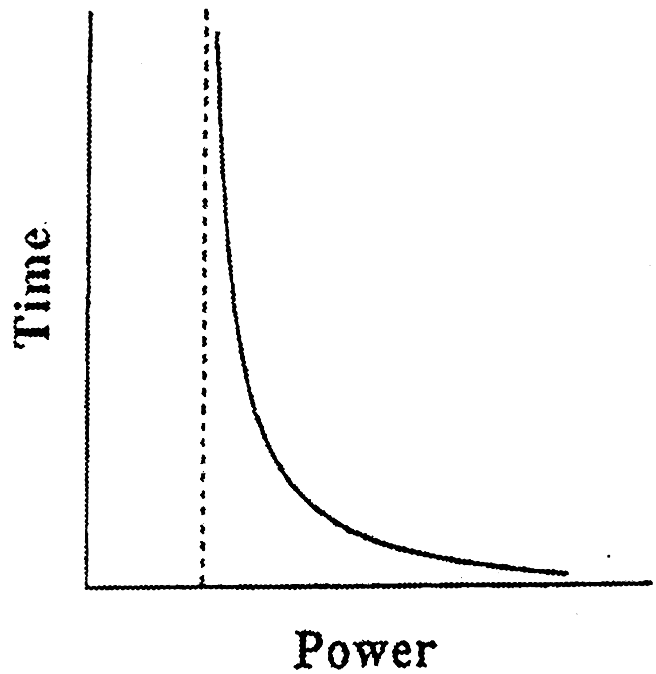

Figure 2. Critical power, represented by the dashed line. Gaesser, Carnevale, Garfinkel, Walter, & Womack (1995).

Specifically, determining critical power involves performing a series of exercise tests to fatigue, each set at a different power output. Critical power is calculated using the formula

$$T = \text{AWC} / (P\text{-CP}),$$

where T is in seconds, AWC (anaerobic work capacity) represents the total work performed, P is a constant power output, and CP is critical power.

The theoretical significance of critical power is that it represents a power output that one could maintain indefinitely. Poole et al. (1988) explained that for power outputs below the LT, steady-state VO_2 kinetics can be maintained, and consequently the duration of exercise may be prolonged. Also, exercise performed at a power output above the LT but below the critical power is marked by delayed steady-state VO_2 kinetics. It is not until one reaches a power output above calculated critical power that exercise duration is limited by a disproportionate increase in VO_2. Due to its theoretical nature, it is difficult to define critical power mathematically. The inability of subjects in various studies to maintain a calculated critical power for prolonged periods exemplifies the apparent difficulty of this calculation (McLellan & Cheung, 1992; Pepper, Housh, & Johnson, 1992).

Another problem in determining critical power is that several bouts of exhaustive exercise at different power outputs are necessary, making this technique time-consuming. Therefore, a method that requires the use of only one trial to determine MSS would be advantageous to coaches and trainers who have time constraints. Zoladz et al. (1998) suggest that the breakpoint in the VO_2-watt relationship be used as an indicator of exercise tolerance. They postulate that the VO_{2BP} has the same mechanistic basis as the slow component of VO_2 kinetics and therefore could be used as a critical point for assessing exercise capacity. That is, since the slow component represents non-steady-state VO_2, and the VO_{2BP} marks the power output above which the slow component occurs, one is then able to use the VO_{2BP} to define the MSS. They were able to detect the VO_{2BP} in 25 of 26 subjects using a single cycle protocol of 3-minute stages, with 30-watt increments. Therefore, this protocol may be appropriate for the detection of the VO_{2BP} and only requires an individual to perform one test.

Summary

The primary objective of this project is to find out whether the VO_{2BP} will be affected by alterations in stage duration. It is important to find this answer in order to provide researchers who are studying the VO_{2BP} with the most appropriate method for elucidating its occurrence. Previous research suggests that cycle ergometry may be the most appropriate mode of exercise for observing the slow component (Jones & McConnell, 1999). However, researchers have not determined which protocol may be best in elucidating the VO_{2BP}. Using stage durations of longer than 1 minute may prove to be more appropriate when attempting to identify the VO_{2BP} since the VO_2 step pattern tends to be more visible than with shorter stages. Also, stages of longer than 1 minute have been shown to have this step pattern visibly diminished above the LT and no variability in the LT and VT relative to power output or VO_2 (Zhang et al., 1991). Furthermore, due to the fact that the increase in VO_2 is a function of both time and power output in the heavy exercise domain, stages of longer than 3 minutes may engender changes in the VO_{2BP}. That is, a 3-minute stage may not be of sufficient duration for the VO_2 to rise to a detectable level. However, a 5-minute stage may be long enough so that the breakpoint is detected at the power output in which it initially occurs and not at the subsequent stage. Figure 3 shows that VO_2 continues to rise after minute 3 of exercise so that the magnitude of the VO_{2sc} is greater by minute 5. The graph also shows that 1 minute, even at the highest power output (135 watts), is not long enough to detect the VO_{2sc}.

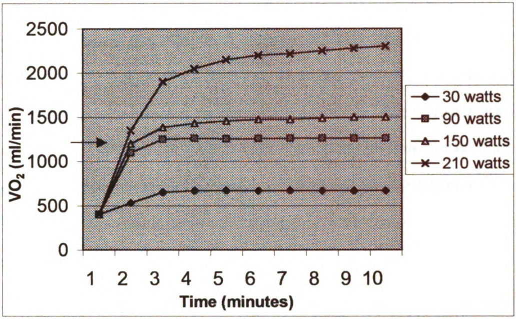

Figure 3. The VO_2 response to different constant-power exercise bouts. LT is indicated by the arrow. Above LT, VO_2 continues to rise throughout the exercise period.

METHODS

Subjects. Sixteen (8 males and 8 females) subjects (age 26.8 ± 4.2 years, height 168.9 ± 8.1cm, weight 67.4 ± 13.3 kg), who were physically active and had no known cardiovascular disease, participated in this study. Each subject signed a consent form prior to his or her participation. This study and the consent form were approved by the University Committee on Research Involving Human Subjects.

Table 1

Descriptive Data by Gender and for All Subjects

Gender	Age (years) (SD)	Height (cm) (SD)	Weight (kg) (SD)
Male	27.9 (±5.3)	173.9 (±5.8)	75.2 (±13.2)
Female	25.7 (±2.8)	164.9 (±7.0)	61.5 (±8.3)
All	26.8 (±4.2)	168.9 (±8.1)	67.4 (±13.3)

Testing. All subjects performed three maximal exercise tests on a SensorMedics 800S electrically braked cycle ergometer. These tests included three continuous incremental protocols of 1-, 3-, and 5-minute stages. All tests began at 30 watts and had 30-watt increments. This work-rate increment was chosen since it had been successfully used in conjunction with a 3-minute protocol to determine the VO_{2BP} (Zoladz et al., 1998). This study also showed that 30-watt increments are large enough so that subjects are fatigued in a reasonable amount of time. Each exercise protocol continued until the subjects reached volitional exhaustion (i.e. less than 30 minutes). Blood samples were taken prior to each test, at the end of each stage, and immediately upon completion of each test to determine lactate concentration. All samples were assessed by a YSI 2700 Select Biochemistry Analyzer. The tests were performed on three non-consecutive days and the order of the tests was randomized for each subject. LT and VT were determined via blood sampling and gas exchange data, respectively (Davis, 1985; Gaesser & Poole, 1986).

Lactate sampling and measurement methods. Blood samples were taken during the last 30 seconds of each stage, for each protocol, while the subject continued the exercise. The samples were taken via fingerstick and a very small amount of blood was placed into a heparinized capillary tube. The blood was then transferred into a micro-centrifuge tube before being presented to the lactate analyzer. Samples were assessed by a YSI 2700 Select Biochemistry Analyzer, which provided a lactate concentration value in mmol/L blood. The lactate analyzer was calibrated prior to each test. Due to the limited amount of time available to obtain blood samples during the 1-minute protocols, subjects were asked to hold a heparinized gauze pad. This prevented clotting and allowed for blood to be collected into the capillary tubes during subsequent stages. This was also the procedure for the 3- and 5-minute stage protocols.

Gas exchange measurements. The subjects breathed room air through a mouthpiece connected to a one-way valve. During exercise, expired air was analyzed breath-by-breath using a SensorMedics Metabolic Measurement Cart, which provided the following data: VO_2 (STPD), VCO_2 (STPD), V_E (BTPS), R

(VCO_2/VO_2), and end tidal PCO_2 and PO_2 ($P_{ET}CO_2$, $P_{ET}O_2$). The metabolic cart was calibrated prior to each test.

Heart rate. Heart rate was measured continuously by a Polar wireless heart rate monitor (Oulu, Finland) and was recorded prior to every test and at the end of each stage for all protocols.

Analysis of ventilatory threshold. Wasserman, Whipp, Koyal, and Beaver (1973) defined the VT as the point where one or all of the following occurred, as determined by visual inspection: (1) a distinct non-linear increase In V_E; (2) an increase in V_E/VO_2 without an increase in V_E/VCO_2; and (3) an increase in end-tidal partial pressure of oxygen ($P_{ET}O_2$) without a simultaneous decrease in end-tidal partial pressure of carbon dioxide ($P_{ET}CO_2$). Davis (1985) reported that the increase in V_E/VO_2 with no increase in V_E/VCO_2 is the most specific criterion for detecting the VT. For consistency among subjects and protocols, this was the method of detecting VT used in this study. VT was independently determined by two investigators.

Research has demonstrated that menstrual cycle phase can affect the value of VO_2 at the ventilatory threshold (Bemben, Salm, & Salm, 1995). For this reason all female subjects were tested during the follicular phase of the menstrual cycle. Follicular phase was defined as the 7 days following menstruation and was verified by the subjects reporting the end of menstruation.

Analysis of lactate threshold. Lactate concentrations were plotted against power output (watts) and visually inspected for gradual versus abrupt changes. The LT was defined as the power output prior to the first abrupt increase in lactate concentration (minimum 0.5 mmol/L), as agreed upon independently by two investigators (Zoladz et. al, 1998). Figure 4 represents an example of the visual inspection of LT.

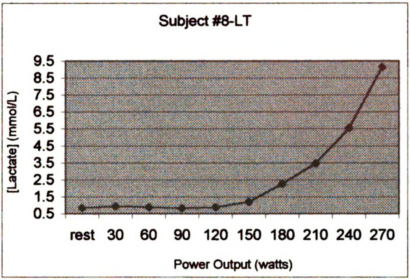

Figure 4. Blood lactate analysis. LT was defined as a 0.5 mmol/L increase. In the case of subject 8, 5-minute stage protocol LT was determined to be at 120 watts.

Analysis of VO_{2BP}. Predicted VO_2 for each power output was determined using linear regression of all the measured VO_2 data below LT. The difference between actual and predicted VO_2 was determined using a rolling sum of the error, and this was plotted against power output. An abrupt, sustained increase in the rolling sum was visually detected and was determined to be the VO_{2BP} (see Figure 5).

Coefficient of variation. Three subjects performed each protocol twice for the purpose of determining variability of the VO_{2BP}, LT, and VT. A coefficient of variation, which is the ratio of the standard deviation to the mean expressed as a percentage, was determined for power output and VO_2 (see Table 2).

Table 2

Coefficients of Variation

	VO_2	Power Output
VO_{2BP}	9.2%	13.6%
LT	5.7%	14.2%
VT	4.3%	5.7%

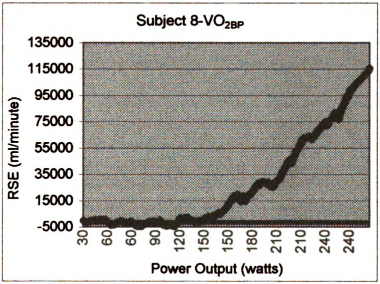

Figure 5. A plot of the rolling sum of the error of VO_2 (actual vs. estimated) against power output. The abrupt change in VO_2 at 150 watts represents the VO_{2BP}.

Statistical analysis. Differences in the power output and VO_2 corresponding to VO_{2BP}, LT, and VT between the three protocols were determined using a two-factor (protocol and threshold) repeated measures analysis of variance. Statistical significance was set at $p < 0.05$.

RESULTS

The LT, VT and VO_{2BP} were detected in all of the 48 tests performed. All subjects who participated in this study completed at least four stages of all tests (reached 150-watt stage) and achieved an average VO_{2peak} of ~3.1L/minute. Time to fatigue and PO_{peak}, on average, decreased as stage duration increased (see Table 3). ANOVA showed no significant gender x threshold or gender x stage duration interaction. Therefore the data for all 16 subjects were pooled.

Table 3.

PO_{peak}, peak stage, and time to exhaustion for each subject by protocol

	1-Minute	3-Minute	5-Minute
Subject	watts/stage#/time	watts/stage#/time	watts/stage#/time
1	270 / 9 / 8:48	240 / 8 / 22:04	210 / 7 / 33:00
2	330 / 11 / 11:14	270 / 9 / 25:16	240 / 8 / 37:51
3	330 / 11 / 10:16	210 / 7 / 19:36	240 / 8 / 35:37
4	300 / 10 / 9:13	270 / 9 / 25:04	270 / 9 / 40:22
5	240 / 8 / 8:09	240 / 8 / 21:36	210 / 7 / 30:59
6	270 / 9 / 8:36	240 / 8 / 22:09	210 / 7 / 30:59
7	240 / 8 / 7:45	180 / 6 / 17:41	180 / 6 / 27:26
8	300 / 10 / 9:59	270 / 9 / 26:11	270 / 9 / 41:08
9	240 / 8 / 7:31	180 / 6 / 16:52	180 / 6 / 25:43
10	240 / 8 / 7:18	180 / 6 / 17:59	180 / 6 / 28:53
11	210 / 7 / 6:26	180 / 6 / 17:39	180 / 6 / 27:39
12	210 / 7 / 6:39	180 / 6 / 16:14	150 / 5 / 24:20
13	180 / 6 / 5:45	180 / 6 / 15:15	150 / 5 / 21:46
14	240 / 8 / 7:43	210 / 7 / 18:59	180 / 6 / 29:59
15	240 / 8 / 7:58	180 / 6 / 17:59	180 / 6 / 27:42
16	240 / 8 / 7:12	150 / 5 / 15:00	150 / 5 / 24:58
Mean	255/8.5/7:47	210/7/19:42	199/6.6/30:31

Mean VO_{2peak} for each subject is listed in Table 4. VO_{2peak} for all subjects ranged from 34.7 ml O_2/kg/minute to 61.8 ml O_2/kg/minute, with an average for male subjects of 47.9, and an average for female subjects of 43.5 ml O_2/kg/minute.

Table 4.

Mean PO at Thresholds and Subject Characteristics

Subject	Age	Weight (kg)	Height (cm)	VO_{2peak} (ml/kg)	PO_{peak} (watts)	VO_{2BP} (watts)	LT (watts)	VT (watts)
1	29	59.6	166	55.6	250	110	90	120
2	22	87.6	175	46.9	280	120	90	170
3	34	79.1	183	44.2	250	100	80	120
4	30	69.9	179	55.9	280	100	80	130
5	31	90.6	170.5	34.7	230	110	100	100
6	28	67.3	173	48.3	230	110	50	110
7	31	89.1	168	35.9	200	90	50	90
8	18	58.5	177.4	61.8	270	150	140	150
9	26	50.7	165	51.6	190	120	40	100
10	24	53.3	152	49.2	190	110	60	120
11	26	53.2	163	49.1	180	110	80	100
12	27	53	159	43.9	170	100	50	90
13	31	69.6	176.1	36.9	210	100	60	120
14	26	70.9	168	37.6	200	100	70	100
15	22	66.9	166	41.4	200	90	60	90
16	23	60.5	161.1	38.5	180	90	60	90
Mean	27	67.5	168.9	45.7	219	107	72.5	112.5

These values fall within the ranges of age and gender norms, occurring in the 80th percentile for men and the 90th percentile for women (ACSM, 1995). Shvartz & Reibold (1990) reviewed average VO_{2max} values from various studies performed in various countries, including the U.S., over many years. They found for subjects aged 18-30 that males averaged 48-50 ml O_2/kg/minute while females averaged 41-44 ml O_2/kg/minute. Table 4 lists mean VO_{2peak} by subject, as well as, mean PO at VO_{2BP}, LT, and VT. There was no significant difference between protocols for VO_{2peak}; however, mean PO_{peak} was significantly greater for the 1-minute stage protocol compared to the 3- and 5-minute stages (see Figures 8 & 9). The average PO_{peak} attained for the 3- and 5-minute stage protocols were 82.2% and 76.7% of that reached during the 1-minute stage protocol respectively.

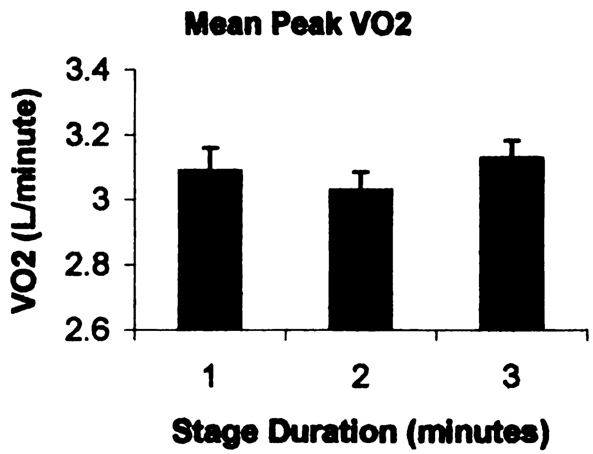

Figure 6. Mean peak VO_2 for all subjects by protocol.

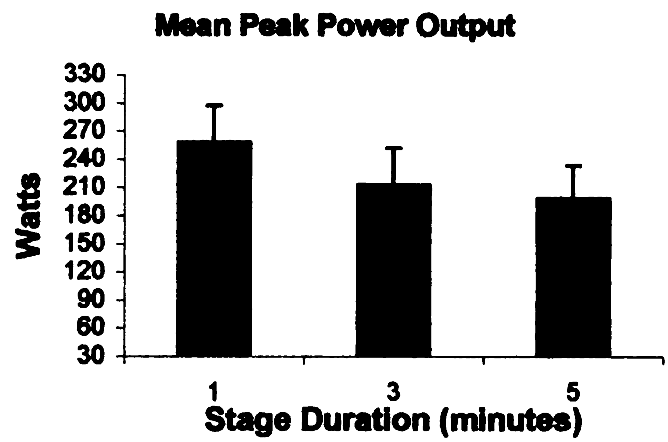

Figure 7. Mean PO_{peak} for all subjects by protocol.

ANOVA for VO_2 showed a main effect for the thresholds (VO_{2BP}, LT, VT) in which the mean VO_2 at VO_{2BP} and VT were significantly greater than the VO_2

at LT. The VO_{2BP} and VT occurred at 48.7% and 49.8% of VO_{2peak} respectively, whereas the LT occurred at 35.3% of VO_{2peak}. There was no overall effect for stage duration and no interaction between stage duration and threshold.

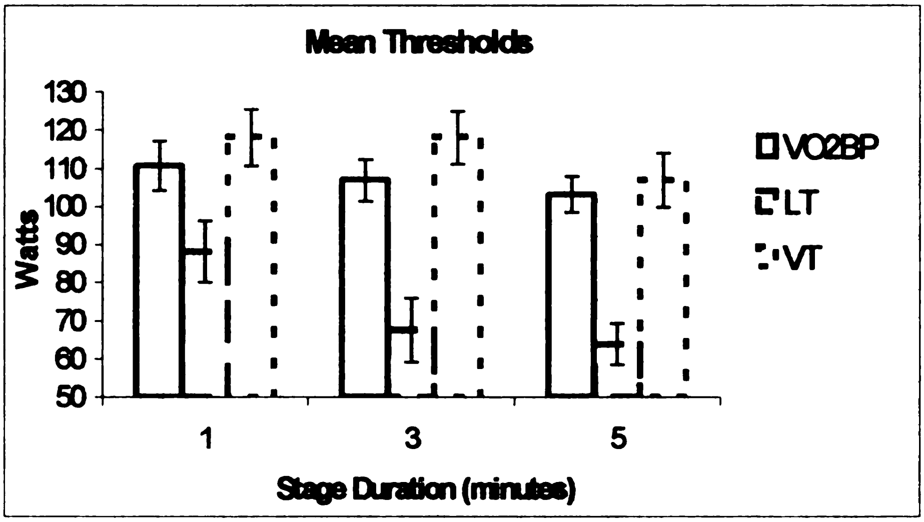

Figure 8. Mean power at VO_{2BP}, LT, and VT for all subjects.

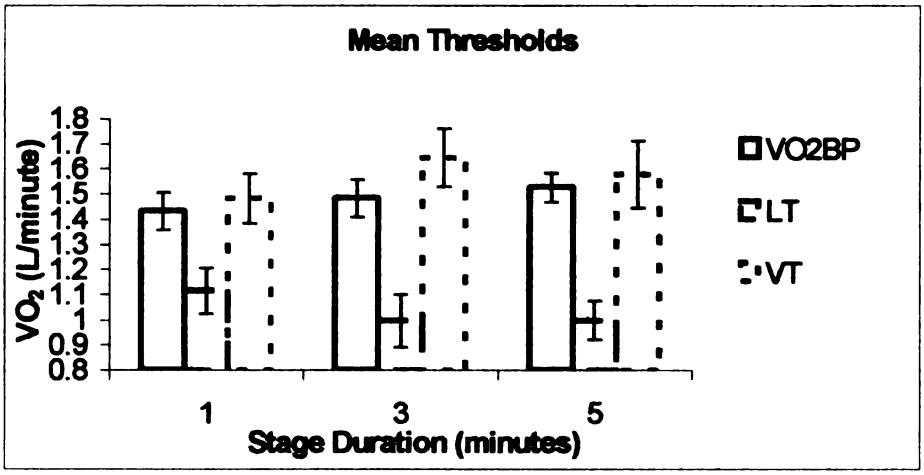

Figure 9. Mean VO_2 at VO_{2BP}, LT and VT for all subjects.

ANOVA for power output showed a main effect for threshold and stage duration, but no threshold x stage duration interaction. The mean power output at VO_{2BP} (48% PO_{peak}) and VT (51.4% PO_{peak}) were significantly greater than the power output at LT (32.8% PO_{peak}). Power outputs at the three thresholds for the 1-minute stage protocol were significantly greater than for the 3- and 5-minute stage protocols. Figures 8 and 9 show the mean power output and VO_2 for the thresholds for each protocol.

DISCUSSION

The purpose of the present study was to determine if the power output and VO_2 at the VO_{2BP}, LT, and VT are affected by stage duration during incremental cycle ergometry. In addition, we investigated potential interactions between the parameters VO_{2BP}, LT, and VT. The main findings were that the PO at VO_{2BP}, LT, and VT were higher for the 1-minute stage protocol compared to the 3- and 5-minute stage protocol. Also, there was a disparity in the relationship between the VO_{2BP} and the LT, as well as between VT and LT.

We hypothesized that the VO_{2BP} would be detectable in both 3- and 5-minute stage protocols and that it would be detectable at a lower PO in the case of the 5-minute stage protocol. We also thought it likely that the VO_{2BP} would occur at the highest PO in the 1-minute stage protocol due to the fast work-rate increment. This hypothesis was partially supported by the data in that it showed a general trend for stage duration for all thresholds (LT, VT, VO_{2BP}) with the highest PO occurring for the 1-minute stages. However there was no difference between the 3- and 5-minute stages for our group of subjects. It is possible that for a group of less fit subjects, the time delay in reaching a VO_2 steady-state may require a longer stage duration (i.e. 5-minute) for the accurate determination of VO_{2BP}.

The mean VO_{2BP} for all protocols occurred at ~49% of VO_{2peak}. This is consistent with the findings of Zoladz et al. (1998), who also found that the mean of what they termed the "VO_2 change point" occurred at 49% VO_{2peak}. In that study, the investigators used an incremental cycle protocol consisting of 30 watts/3-minute stages. They found no statistically significant difference between the power output at LT and that at the VO_{2BP}, suggesting that these parameters are concurrent. However, in the present study, there was a significant difference between the power output, as well as the VO_2 at which these parameters occurred. A potential explanation for this contrast in results may be explained by subject fitness level. The most striking difference between these studies is the fact that the former study used subjects that were considerably fitter than the subjects in our study, based on the data in Table 5. Table 5 shows data for the PO at LT, VO_{2BP}, and PO_{peak} for the 30-watts/3-minute protocols for each study. The mean PO at the LT and VO_{2BP} were higher for the Zoladz et al. group than for the subjects in this study. Also, the PO_{peak} occurred on average >2 stages higher for the subjects in the previous study. How fitness affects the relationship between LT and VO_{2BP} is not clear, and may require further investigation.

Table 5.

Mean PO for LT, VO_{2BP} and PO_{peak} for 30-watts/3-minute stage protocols.

Study	LT (W)	VO_{2BP} (W)	PO_{peak} (W)
Zoladz (1998)	125.8	136.8	279.2
Osmond	67.5	106.9	212

The results of this study support previous evidence that the relationship between VO_2 and power output is not linear in the domain of heavy to intense exercise (i.e., >LT) (Gaesser & Poole, 1996). In all of the 48 incremental exercise tests performed for this study the VO_{2BP} was detected. In each case the

VO_{2BP} occurred at, or at least one stage above, the LT. That we were able to detect the VO_{2BP} in all of the 1-minute stage tests performed is an interesting finding, since others have reported that the slow component of VO_2 kinetics may not be detectable during fast work-rate increments (Whipp, 1994). For well-trained individuals the initial fast component of VO_2 kinetics has been shown to be of shorter duration than for less trained subjects, and therefore a VO_2 steady-state is attained in less time (Jacobsen, Coast, & Donnelly, 1998). It is thus reasonable to assume then that a protocol of fast work rate increments (i.e. 30-watts/minute) may be sufficient to allow for a steady-state to be reached for these individuals, and thus may result in a detectable VO_{2BP}. Since our subjects were of average fitness, as pointed out in the previous section (see Results), this does not explain the fact that we were able to detect VO_{2BP} for all subjects for the 1-minute stage protocols. However, the 1-minute stage duration did tend to overestimate the PO and VO_2 at LT, VT, and VO_{2BP} compared to the longer stage durations.

The dissociation between the LT and the VO_{2BP} found in this study supplements the growing body of evidence that although there may be a mechanistic link between [lactate] and VO_2, the relationship is not causal (Womack et al., 1995). Womack et al. found that the diminution of the VO_{2sc} that occurred as a result of a 6-week cycle ergometry training program was coincident with reductions in blood lactate concentration. However, subsequent epinephrine infusion, which increased blood lactate concentration, did not increase exercise VO_2. In our study we also observed that although the power output and VO_2 at

LT decreased from the 1-minute stage protocol compared to the longer stage durations, the VO_{2BP} did not follow a similar pattern, as one would expect from the purported relationship. The fact that the VO_{2BP} was detected in every case, either above or at LT, suggests that the two are in some way related; however, the exact nature of this relationship remains unclear. Based on the aforementioned observations by Womack et al. (1995), it is unlikely that increased [lactate] alone causes this nonlinear increase in VO_2.

The power output at LT is apparently altered by stage duration and work-rate increment (Stockhausen et al., 1997). Stockhausen's group found that 30-watt increments necessitate the use of 4-minute stage durations in order to reach a steady state [lactate] or risk the likelihood of overestimating the power output at LT. Our results support this finding as the mean thresholds occurred at a substantially higher power output for the shortest stage duration compared to the 5-minute stage tests. Our results suggest that 3-minute stages may also be of sufficient length for accurate determination of LT (see Figures 6 and 7).

The results of our study show a disparity between LT and VT in terms of the VO_2 and power output at which they occurred, with the VT occurring at a substantially higher VO_2 and power output for all protocols (see Figures 6 and 7). Furthermore, the power output at LT was impacted by stage duration, whereas VT was unaffected. This may be due to the fact that the appearance of lactate in the blood is a time dependant variable, whereas VT is not. The fact that there was no interaction between stage duration and VT has been previously reported using 1-, 2-, and 3-minute stages (Zhang et al., 1991). The results of the present study extend this observation to 5-minute stages.

Ventilatory threshold is believed to be related to initial increments in blood lactate concentration and the subsequent buffering of lactate by increased carbon dioxide production. It should therefore occur after relatively small increases in lactate. Since lactate appearance in the blood is time dependent, whereas VT has been shown to be unaffected by stage duration, incremental exercise testing must account for both stage duration and work-rate or risk overestimating LT (Stockhausen et al., 1997). Previous research using fast work-rate increments has shown a disparity between VT and LT during cycle ergometry (Chicharro et al., 1997). This study, which utilized a 1-minute stage protocol similar to the one used in our experiment, found that the VT occurred prior to the LT. Therefore, the mean VT was lower than the LT in both power output and VO_2.

Based on this relationship, other mechanisms have been suggested to cause VT rather than lactate, such as H+. Bangsbo, Johansen, Graham, and Saltin (1993) postulated that the H+ enters the blood prior the lactate and causes the rise in V_E/VO_2 prior to the observed increase in lactate during fast work-rate incremental protocols. This, however, does not explain why we observed the LT significantly preceding the VT both in terms of PO and VO_2. In fact our data suggest that the VT and VO_{2BP} are more closely related to one another than LT. However, past investigations have shown that increases in ventilation, or the increased work of the respiratory muscles at VT, only account for a small portion of the slow component and thus does not explain this relationship (Womack et al., 1995). The cause of the delay in VT relative to the LT observed in the present study needs further investigation.

PO_{peak} was significantly higher for the 1-minute stage protocol compared to the 3- and 5-minute protocols, whereas VO_{2peak} was unaffected by stage duration. This finding is consistent with previous research involving incremental cycle ergometry (Hansen et al., 1988; Zhang et al., 1991).

The LT has been used as a primary identifier for the upper limit of steady-state exercise as well as a critical indicator that is often used for exercise training. Due to the relationship that is believed by some to exist between [lactate] and oxygen consumption, it has been assumed that the LT and the onset of the VO_{2SC} are concurrent events and therefore the LT can be used to detect the VO_{2sc}. Our observation regarding these variables brings this theory into question. The VO_{2BP} is believed to be the point above which the slow component of VO_2 kinetics occurs. VO_{2BP} is therefore a potential indicator of reduced exercise efficiency, and therefore may be used as a marker for exercise tolerance. Therefore, due to the purported relationship between lactate and VO_2, the VO_{2BP} and the LT should occur at a similar power output. However, our data show that these variables are not concurrent, as the LT occurred at a significantly lower PO and VO_2 than the VO_{2BP} for all protocols. Based on this, we conclude that it is not valid to use the LT to demarcate the occurrence of the VO_{2sc} during cycle ergometry exercise. Therefore, researchers who want to study the VO_{2sc}

need to determine the VO_{2BP} and LT independently and not regard the two as the same phenomenon.

The overestimation of LT for the 1-minute stage protocols compared to the 3- and 5-minute stage protocols suggests that this is not long enough for accurate LT determination. This should be taken into consideration when designing protocols; however, the 5-minute stage protocol causes unnecessary subject discomfort as it is not completed in as timely a fashion as the 3-minute stage test, yet yields similar results. It is our suggestion that for 30-watt increments, 3-minutes is the most appropriate stage duration for the determination of these parameters. From this protocol, accurate determination of LT, VT, VO_{2BP}, VO_{2peak}, and PO_{peak} is possible.

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