THE RELATIONSHIP OF THE HEART RATE THRESHOLD TO THE VENTILATORY THRESHOLD IN TRAINED CYCLISTS

by

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The purpose of this study was to assess the relationship of the heart rate threshold (HRT) to the ventilatory threshold (T_{VENT}) in trained cyclists. Twenty-one endurance trained cyclists (mean ± SD values: age = 26.2 ± 5.6 years; weight = 76.2 ± 8.2 kg; height = 179.1 ± 6.3 cm; VO_2 max. = 67.6 ± 4.7 ml · kg · min^{-1}) volunteered to participate in this study. Each subject completed a maximal cycle ergometer test to volitional fatigue. The procedure utilized a ramped protocol on an electronically braked cycle ergometer with initial resistance set at 50 watts (W) · min^{-1} with a 30 W · min^{-1} increase. Ventilatory variables (Ve, VO_2, VCO_2) and power were measured on-line with averages reported every twenty seconds. Heart rate (HR) was measured using a portable cardio-telemetric monitor and was observer recorded every twenty seconds. T_{VENT} was assessed using the excess CO_2 (ExCO_2) elimination curve. The HRT was assessed using a mathematical model (MM) that incorporates the natural log of HR data points to produce a curvilinear fit through these points. The first order derivative of the upper portion of the logistic curve delineated the HRT. Statistical significance was set a priori at p < 0.01. Paired t-tests indicated that there were no significant differences (p > 0.01) between HR values at HRT (171.7 ± 9.6 beats · min^{-1}) and T_{VENT} (169.8 ± 9.9 beats · min^{-1}) or VO_2 values at HRT (53.6 ± 4.2 ml · kg · min^{-1}) and T_{VENT} (52.2. ± 4.8 ml · kg · min^{-1}). However, power values at HRT (318.7 ± 30.7 W) were significantly different from those at T_{VENT} (334.8 ± 36.7 W). Pearson product-moment zero-order correlation coefficient demonstrated significant relationships between HRT and T_{VENT} for the physiological variables of HR (r = 0.92, p < 0.001), VO_2 (r = 0.72, p < 0.001) and power (r = 0.77, p < 0.001). These findings indicate that HR and VO_2 at the HRT are not significantly different from those values at T_{VENT} in trained cyclists.
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CHAPTER I
INTRODUCTION TO THE PROBLEM

The characterization of exercise performance and prescription embodies the assessment of several physiological variables. These variables primarily include oxygen consumption (VO2), carbon dioxide (VCO2), blood lactate (BLAC), ventilation (VE), heart rate (HR), speed, and power, and are acknowledged as a reflection of metabolic intensity for a given workload. These assessments take place in an exercise laboratory and are usually confined to sport-specific progressive intensity protocols.

Physiological appraisal that is important for the endurance athlete is the assessment of the so-called "anaerobic threshold" (Wasserman and McIlroy, 1964; Wasserman et al., 1973). This threshold is accepted as a measurement of the ability to perform at optimal intensity for prolonged periods of time when expressed as velocity, power or fraction of VO2 max. at this juncture (Billat, 1996). Further clarification characterizes it as a "critical intensity" workload or "transition threshold" identified by demarcations in blood lactate and/or ventilatory variables, respectively acknowledged as the lactate threshold (TLAC) or ventilatory threshold (TVENT) (Anderson and Rhodes, 1991; Loat and Rhodes, 1996). These transition thresholds are related to maximal prolonged endurance capability (Loat and Rhodes, 1996), examples of which include extended performance in long distance running (Farrell et al., 1979; McKenzie and Rhodes, 1984; Powers et al., 1983; Tanaka et al., 1983) and time trial cycling (Nichols, Phares and Buono, 1997; Coyle et al., 1991; Hoogeveen, Hoogsteen and Schep, 1997; Hopkins and McKenzie, 1994).

The paucity of qualified exercise science laboratories and substantial costs of frequent testing can restrict the use of such appraisals to those who are financially disposed and/or those elite athletes involved in funded testing programs. Monitoring transition thresholds using either
lactate or ventilatory analysis during training or competition therefore, could be considered impractical. However, HR is a variable that can be readily monitored outside of the laboratory setting. The advent of accurate, inexpensive, portable cardio-telemetric devices or heart rate monitors has made the assessment of exercise HR convenient and relatively easy to execute by both athlete, non-athlete and coach.

Exercise HR appears to occupy a linear relationship with oxygen consumption (Arts and Kuipers, 1994; Astrand and Rodahl, 1977;) and power output during incremental testing (Arts and Kuipers, 1994; Hawley and Noakes, 1992). Regression equations for different exercise modes based upon the relationship between %VO₂ max. and % of maximal HR are useful for exercise prescription (Londeree et al., 1995). It would be logical to conclude then that HR could be incorporated as a variable by which to assess, monitor and determine exercise intensities (Boulay et al., 1997; Gilman and Wells, 1993; Jeukendrup and van Dieman, 1998). Since transition thresholds are related to endurance performance, the relationship of HR to these thresholds may provide a framework for such training prescriptions (Dwyer and Bybee, 1983).

HR values for such prescription are measured in relation to power or speed at transition threshold intensities (Dwyer and Bybee, 1983; Parkhouse et al., 1982). This is to say that HR may be implemented only after critical workloads have been established from incremental testing (Arts and Kuipers, 1994). However, the relationship between HR and power/VO₂ does not always manifest itself as linear and may have curvilinear profiles during the latter stages of work (Brooke and Hamley, 1972; de Wit et al., 1997). Interpretations of HR to workload therefore, may not be as clear.

The utility of HR alone as an alternative method to identify critical work intensities has been suggested by Conconi et al. (1982). These investigators developed a simple field test that incorporated sequential increases in running speed (RS). HR monitoring during the test evinced a
progressive shift in HR from a linear to curvilinear trend. This "deflection" occurred at near maximal speeds. Conconi et al. (1982) labeled this loss of linearity between HR and RS the "deflection velocity" and demonstrated that this critical HR value coincided with the lactate threshold. From these observations Conconi et al. (1982) hypothesized that HR could be used to assess the lactate threshold during training and competition. Physiological variables related to and concurrent with this deflection point are referred to in the literature as the heart rate threshold (HRT).

Subsequent research has confirmed this HR breakaway and convergent relationship to either lactate or ventilatory thresholds (Bunc and Heller, 1992; Bunc et al., 1995; Bunc Heller and Leso, 1988; Gaisl and Hofmann, 1991; Gaisl and Weisspeiner, 1987; Hofmann et al., 1994; Hofmann et al., 1997), but other studies have demonstrated no such relationship (Francis et al., 1989; Jones and Doust, 1997; Kuipers et al., 1988; Tokmakidis and Leger, 1992, 1988). The reliability of the HRT has also been questioned since HR deflection does not always present itself, even across repeated within-subject testing (Jones and Doust, 1995). There is no clear consensus in the scientific literature that the HRT is reliable and is a valid assessment of transition thresholds; however, it should be noted that HRT is utilized by some coaches with a fair measure of success (Jones and Doust, 1997).

The axial problem of HRT is the detection of the HR breakpoint (Hofmann et al., 1994). Visual inspection has been the traditional method of assessment and is still accepted since the breakpoint often readily presents itself. However, in cases where HRT is not as evident, the location thereof may be prone to subjective error or estimation. This could lead to false HRT values and may be a source of the discrepancies in the literature. Validation of HRT is not possible unless there is clarity of breakpoint. Very recently, mathematical models have been introduced to help with HRT assessment (Hofmann et al., 1994; Kara et al., 1996; Petit, Nelson
and Rhodes, 1997). These models have enabled a more objective assessment of HRT without subjective influences.

The value of such a testing modality is evident in as much as it allows the athlete to perform multiple analyses of the HR-transition threshold relationship within the appropriate training environment. Furthermore, this HRT test is noninvasive and reduces laboratory involvement.

**JUSTIFICATION**

The utility of HRT as a noninvasive method to monitor transition thresholds could enable both athlete and coach to assess and prescribe exercise intensity based on HR if the relationship between HRT and transition thresholds can be resolved. Several investigations have attempted to authenticate this hypothesis, but with disparate findings. The central problem of HRT still appears to be the objective assessment of the deflection in HR (Hofmann et al., 1994a).

Recently Petit, Nelson, and Rhodes (1997) validated a mathematical model (MM) based on a logistic function that evaluates the HRT/running speed relationship. Running speeds at HRT were used to predict ten kilometer running performances with high correlations (r=0.98, p<0.01) between actual and predicted times. Significant correlations were noted for running speed and HR across HRT and \( T_{VENT} \). Additionally, this MM has demonstrated high reproducibility and high reliability of HRT (Bodner, Rhodes and Coutts, 1998) when applied to incremental cycle ergometry. The MM analyzes HRT by fitting a log curve to the HR data points. Instead of a graphical deflection, a point on the logistic curve is located that distinguishes the HRT/transition threshold relationship. The primary advantage of this model is that the HRT is objectively identified without subjective interpretation of breakaways.

Although field tests have been used to locate HRT in elite cyclists (Conconi et al., 1988b; Droghetti et al., 1985), no attempt has been made to examine the relationship of the HRT to
T\textsuperscript{VENT} in highly trained cyclists utilizing ramped cycle ergometry. For cyclists, power output is perhaps the best indicator of exercise intensity, but HR monitoring and measuring is less difficult (Jeukendrup and van Diemen, 1998). The assessment of HRT in trained male road and off-road cyclists using the MM (Petit, Nelson and Rhodes 1997) with an established T\textsuperscript{VENT} protocol (Anderson and Rhodes, 1989; Langill and Rhodes, 1993; Loat and Rhodes, 1996; Volkov et al., 1975) can further clarify the relationship or lack thereof between these variables.

**STATEMENT OF PURPOSE**

The purpose of this investigation was to assess the relationship between the HRT and the T\textsuperscript{VENT} as they are related to HR, VO\textsubscript{2} and power in male competitive road and off-road cyclists.

**HYPOTHESES**

**Primary**

1. There will be no significant difference between the HR\textsubscript{HRT} and HR\textsubscript{T\textsuperscript{VENT}}.

2. A significant relationship will be evident between HR\textsubscript{HRT} and HR\textsubscript{T\textsuperscript{VENT}}.

**Secondary**

1. A significant relationship will be evident between VO\textsubscript{2}\textsubscript{HRT} and VO\textsubscript{2}\textsubscript{T\textsuperscript{VENT}} and Power\textsubscript{HRT} and Power\textsubscript{T\textsuperscript{VENT}}.

2. There will be no significant difference between Power\textsubscript{HRT} and Power\textsubscript{T\textsuperscript{VENT}}.

3. There will be no significant difference between VO\textsubscript{2}\textsubscript{HRT} and VO\textsubscript{2}\textsubscript{T\textsuperscript{VENT}}.
CHAPTER II
REVIEW OF SELECTED LITERATURE

Summary

Heart rate (HR) is a viable mode to express work intensity. This viability is based upon the linear relationship between HR and work assessed by progressive incremental testing. It is conceivable therefore that HR can be used in exercise prescription. The advent of portable HR monitors encourages coaches and athletes to incorporate HR monitoring as an integral part of regular training.

Early research suggests that the HR-work relationship may not always evince a complete linear trend but often retains a curvilinear aspect near the end-stages of incremental work. Initial research concerning this HR breakpoint involved a running field test in which running speed at the HR breakaway was termed the "deflection velocity". HR deflection at this velocity was hypothesized to noninvasively assess the lactate threshold (TLAC). This phenomenon is now referred to in the literature as the heart rate threshold (HRT).

Physiological mechanisms explaining the deflection in HR are not understood. Augmentation of lactacid mechanisms is suggested as one possibility. The intrinsic myocardial function expressed as left ventricular ejection fraction also demonstrates coincidence with the deflection point. Neural and catecholamine influences do not appear to affect HRT.

Some researchers question the validity of HRT to assess critical work intensities. The HRT may not be a physiological necessity but instead represent an artifact of the protocol or the beginning in the plateau of maximum HR. Strong relationships are reported between HRT and TLAC or ventilatory thresholds (TVENT), however this is not consistent in all investigations. HRT relationship to steady state exercise remains equivocal. Methodological differences appear to contribute to low HRT reproducibility across independent studies but is not a cogent explanation
for low reproducibility within subjects. HRT reliability is affected by changes in training status, hydration levels and glycogen depletion. This article reviews the HRT. Historical development and relationship to transition thresholds are highlighted.

1. Introduction

The characterization of exercise performance embodies the assessment of several physiological variables. Evaluations of such testing provide feedback for training programs and modifications. These variables primarily include oxygen consumption (VO₂), carbon dioxide (VCO₂), blood lactate (BLAC), ventilation (VE), heart rate (HR), speed, and power. Sensitive laboratory equipment and trained personnel are required for accurate assessments of ventilatory variables as well as BLAC and power. The paucity of qualified exercise science laboratories and substantial costs of repeated testing often restrict the use of such appraisals to those who are financially disposed and/or those athletes in funded testing programs.

Exercise HR is related to oxygen consumption (Astrand and Rodahl, 1977). Regression equations for different exercise modes based upon the relationship between %VO₂ max. and % of maximal HR are useful for exercise prescription (Londeree et al., 1995). Furthermore, HR has been proposed as a viable method by which to assess, monitor and prescribe exercise intensities (Boulay et al., 1997; Gilman and Wells, 1993; Jeukendrup and Van Diemen, 1998). The creation of accurate, inexpensive portable cardiotelemetric devices or heart rate monitors has made the assessment of exercise HR readily available and relatively easy to implement by both athlete, non-athlete and coach.

The endurance athlete is particularly interested in the relationship of HR to the “anaerobic” threshold (Wasserman et al., 1973). This threshold is described as a “critical intensity” workload or “transition threshold” otherwise known as the lactate threshold (TLAC) or ventilatory threshold (TVENT) (Anderson and Rhodes, 1991; Loat and Rhodes, 1996). These
transition thresholds are related to maximal prolonged endurance ability (Loat and Rhodes, 1996). Unfortunately, associating HR with this intensity still requires laboratory involvement.

The hypothesis that a HR-work relationship alone can be used to discriminate critical work intensities was first suggested by Conconi et al. (Conconi et al., 1982). This disclosure was significant since the methodology incorporated a simple progressive intensity test that could be carried out in field settings. A deviation in HR-work slope or “deflection” in HR described this value. Practically, this HR test is appealing since it may minimize laboratory involvement.

This HR phenomenon was originally labeled the “deflection velocity” but has recently been termed the “heart rate threshold” (HRT) (Bunc et al., 1995; Hofmann et al., 1994a; Hofmann et al., 1994b; Hofmann et al., 1994c; Gaisl and Hofmann, 1990; Nikolaizik et al., 1998; Thorlund, Podolin and Mazzeo, 1994). The HRT is popular in Europe and is incorporated to assess training programs and evaluate endurance capacity (Jones and Doust, 1997). Evidence suggests that HRT is related to transition thresholds; however, there are challenges to the validity and also the reliability of the HRT concept.

It will be the purpose of this review to examine the HRT in terms of its inception and probe its controversial nature as a mode to assess critical intensity thresholds.

2. Heart Rate and Anaerobic Threshold

Prolonged exercise capability requires the utilization of a relatively large fraction of $\text{VO}_2$ and this is related to $\text{BLAC}$ concentrations during selected exercise levels at submaximal intensity (Billat, 1996). Transition thresholds are accepted as a measurement of the ability to perform at an optimal intensity for prolonged periods of time when expressed as velocity, power or fraction of $\text{VO}_2 \text{ max.}$ at the lactate threshold (Billat, 1996). Since $\text{TVENT}$ is coincidentally related to and possibly causally related to $\text{TLAC}$, a similar relationship to endurance performance may be
assumed and can be found in the literature (Hopkins and McKenzie, 1994; Powers et al., 1983; Rhodes and McKenzie, 1984).

The acceptance of a relationship between transition thresholds and optimal endurance performance, either simulated in the laboratory or in real competition infers that this exercise intensity represents some type of pivotal juncture with respect to endurance competition and could be incorporated into training methodology. The challenge for the exercise physiologist and coach therefore is to accurately allocate training programs using TLAC or TVENT as a reference point.

Selected intensities at various percentages of running speed (RS) at the TLAC is one type of prescription modality (Coen et al., 1991). This is pragmatic when the training situation is controlled and speed can be calculated (a track or pool, for example); however, exercise prescription based on a speed-TLAC relationship can be arduous if speed is not readily resolved. For cyclists, speed is largely affected by environmental factors such as temperature, humidity, wind, as well as changes in terrain. For the cyclist then, power assessment may be a better indicator of exercise intensity (Jeukendrup and Van Diemen, 1998). Recent technological developments that assess cycling power outside of the laboratory setting may help to refine this mode of training in the future (Jeukendrup and Van Diemen, 1998). However, these authors concede that power output may not always be used to maintain a specific exercise intensity because of its variability during exercise.

Parkhouse et al. (1982) suggest that HR may be utilized as a competent indicator of transition thresholds and therefore HR represents a variable by which these threshold exercise intensities are prescribed. Greater focus and attention is being given to the potential use of HR as a means to monitor high intensity endurance exercise (Boulay et al., 1997; Gilman, 1996; Gilman and Wells, 1993). Individualized training programs may be created based on the relationship of
HR to \( T_{VENT}, \) \( TLAC \) and \( VO_2 \) max. (Gilman and Wells, 1993). Associating HR to TLAC or \( T_{VENT} \) still requires laboratory involvement; this presents an obstacle for the athlete who does not have access to an exercise laboratory and/or requires repeated testing.

3. Historical Development of the Heart Rate Threshold

3.1 Early Observations

The HR response during a progressive intensity test generally manifests itself in a linear relationship when coupled to oxygen consumption. This linear relationship is not influenced by age, sex, or training state (Astrand and Rodahl, 1977). The slope of this relationship might vary, however, depending on the fitness state of the individual. Training workloads using HR as an index may be established based upon this linear relationship providing that extrinsic (e.g. environmental) and intrinsic (e.g. stress, same muscle groups) conditions must remain constant (Astrand and Rodahl, 1977).

However, early observations suggest that HR response to incremental testing does not always evince this linear coupling (Brooke and Hamley, 1972). Findings indicated that the HR/workload relationship among a group of racing cyclists was in most cases both linear and curvilinear. An example of this finding is given in Figure 1. Assessment of this HR/physical work curve divulged three distinct sequential phases: an anticipatory phase that demonstrated a somewhat stochastic HR response, a linear phase where the slope of HR was consistent, and a curvilinear phase where the slope of HR/workload decreased and deviated from the linear trend (Brooke and Hamley, 1972).

3.2 Conconi Test

This curvilinear aspect of the HR-work relationship also appeared in the work of Conconi et al. (1982) who suggested that HR alone could be employed as an alternative method to assess critical performance or work intensities. This hypothesis was based upon the observations that
Figure I Heart Rate Deflection and Ventilatory Threshold
the beginning of the curvilinear response of HR during incremental testing coincided with TLAC. The procedure became popularized as the "Conconi test".

Their original investigation involved well-trained distance runners (n = 210) who participated in a running field test. The test incorporated an initial RS of 12-14 km/h with an attendant speed increase every 200m (0.5 km · h\(^{-1}\) average increase) until further increases were no longer possible. HR was recorded during the last 50 m of every segment. When HR values were examined post-test there was a distinct shift in the nature of HR response from a linear to curvilinear trend. These results were similar to those of Brooke and Hamley (1972). This deflection in HR occurred at near maximal speeds. Conconi et al. (1982) originally labeled this loss of linearity between HR and RS the "deflection velocity".

Conconi et al. (1982) also purported that the deflection velocity and TLAC (measured by BLAC) were coincidentally related (r = 0.99; n = 10). They hypothesized that TLAC could be measured by the RS relationship, with the possibility of HR (specifically the HR at the departure from linearity) evaluating TLAC. This was demonstrated by incorporating a somewhat unconventional blood lactate profile from ten subjects at three RS above and below the individualized deflection velocity. During this procedure, each RS was maintained for 1200m and venous blood samples were extracted five minutes after the completion of each run. Each running fraction was interspersed with a fifteen-minute recovery period.

These BLAC profiles were superimposed onto the corresponding HR-RS graph. After BLAC values were plotted, straight lines connected the lactate points above and below the deflection velocity, respectively. The intersection of these lines resolved the RS at which TLAC occurred. Comparison of RS at deflection velocity and TLAC suggested that this critical HR value...
coincided with TLAC. From these observations Conconi et al. (1982) suggested that in runners at least the HR-RS relationship could be used to monitor TLAC during training and competition.

4. Heart Rate Threshold

The findings of Conconi et al. (1982) suggested a practical alternative or complementary test for transition threshold acquisition and encouraged further research of the HR deflection phenomenon.

Terminology for this phenomenon is varied in the literature. The term “deflection velocity” is also reported in the literature as the “heart rate break point” (Ribeiro et al., 1985) “heart rate deflection point” (de Wit et al., 1997; Jones and Doust, 1995; Kara et al., 1996; Mahon and Vaccaro, 1991; Zacharogiannis and Farrally, 1993) “slope variation point” (Maffuli, Sjodin and Ekblom, 1987) “heart rate performance curve” (Hofmann et al., 1997; Pokan et al., 1993; Pokan et al., 1995) or the “heart rate threshold” (Bodner, Rhodes and Coutts, 1998; Bodner et al., 1999; Bunc et al., 1995; Hofmann et al., 1994a; Hofmann et al., 1994b; Hofmann et al., 1994d; Thorlund, Podolin and Mazzeo, 1994). In each instance the designation refers to a specific physiological variable or intensity at HR deflection. For clarification purposes, this review will refer to the deflection phenomenon as the heart rate threshold (HRT).

It should be noted that Conconi et al. (1982) were referring to RS coincident with HR deviation and their validation research focused primarily on the relationships between speed at deflection and average speed during competition. The HR deflection point was used to identify this critical workload. This might question the overall applicability of the deflection velocity if speed cannot be acquired. The assumption is made that HR will provide the cue, however Conconi et al. (1982) have never clearly addressed this speed aspect.

The notion that HR at HRT can be used to control training intensity (i.e. coincident with transition thresholds) is a recent, but viable one (Hofmann et al., 1994b). The HR variable would
make the most sense in terms of feedback to the athlete since it is a unique, intrinsic function and reflects metabolic intensity. Investigations subsequent to Conconi et al. (1982) have scrutinized the HRT in light of physiological variables such as power, speed, VO₂, and BLAC as well as HR. Furthermore, the generalizability of the HRT phenomenon in various subject populations and in disparate sporting activities has also been examined.

4.1 Subjects

The assessment of HRT has involved some variability in terms of subject characteristics. Most studies however have incorporated younger, healthy individuals. One unique study did examine the relationship of HRT to several metabolic thresholds in cystic fibrosis patients (Nikolaizik et al., 1998). Training or cardiovascular fitness state has been one inclusion criterion that has assembled some type of partition between subject populations. This criterion is sensible since there are reported differences in cardiac function between endurance trained and untrained individuals (di Bello et al., 1996; Gledhill, Cox and Jamnik, 1994). Trained athletes (Brooke and Hamley, 1972; Cellini et al., 1986; Conconi et al., 1982; Droghetti et al., 1985; Droghetti, 1986; Hofmann et al., 1994b; Jones and Doust, 1995; Kuipers et al., 1988; Petit, Nelson and Rhodes, 1997; Tokmakidis and Leger, 1988; Tokmakidis and Leger, 1992) and untrained individuals (Bunc et al., 1995; Francis et al., 1989; Hofmann et al., 1994a; Hofmann et al., 1994c; Hofmann et al., 1994c; Hofmann et al., 1994c; Pokan et al., 1993; Ribeiro et al., 1985; Thorlund, Podolin and Mazzeo, 1994) have been assessed for HRT validation.

Age is another criterion that has been addressed in HRT investigations. Children (Ballarin et al., 1989; Baraldi et al., 1989; Gaisl and Hofmann, 1990; Gaisl and Weisspeiner, 1987; Sallo, 1996), adolescents (Ballarin et al., 1989), university students (Hofmann et al., 1997) and middle-aged men (Bunc and Heller, 1992; Hofmann et al., 1996) represent the chronological spectrum.
Very few studies utilized adult females in their subject pool. Some investigations incorporated gender-mixed samples but in those cases females comprised a very small minority (Cellini et al., 1986; Droghetti et al., 1985; Droghetti, 1986; Hofmann et al., 1994b; Kuipers et al., 1988; Nikolaizik et al., 1998; Zacharogiannis and Farrally, 1993). Only two studies have specifically analyzed the adult female HRT response (Bunc et al., 1995; Hofmann et al., 1994a). Table 1 provides a summary of subject populations.

4.2 Field and Laboratory Assessment

Field tests have been one focus of assessing HRT. Running (Tokmakidis and Leger, 1988; Tokmakidis and Leger, 1992; Ballarin et al., 1989), swimming (Cellini et al., 1986), rowing (Droghetti, 1986), cycling (Conconi et al., 1988; Droghetti et al., 1985), canoeing, cross-country skiing, roller skating, ice-skating, walking (Droghetti et al., 1985), and kayaking (Hofmann et al., 1994b) have all been evaluated. Field protocols are summarized in Table 2.

Although field testing perhaps better resembles the athlete’s environment, laboratory testing allows for a more controlled setting to analyze HRT. Procedures utilized in the laboratory have approximated the same increases in exercise intensity used in the Conconi et al. (1982) protocol. Research has primarily incorporated cycle ergometry (Bodner, Rhodes and Coutts, 1998; Bodner et al., 1999; Bunc and Heller, 1992; Bunc et al., 1995; Francis et al., 1989; Gaisl and Hofmann, 1990; Gaisl and Weisspeiner, 1987; Hofmann et al., 1994a; Hofmann et al., 1994c; Hofmann et al., 1996; Kuipers et al., 1988; Pokan et al., 1993; Pokan et al., 1995; Ribeiro et al., 1985; Sallo, 1994; Thorlund, Podolin and Mazzeo, 1994) but has also included rowing ergometry (Droghetti, 1986) and treadmill running (Gaisl and Hofmann, 1990; Gaisl and Weisspeiner, 1987; Jones and Doust, 1995; Maffuli, Sjodin and Ekblom, 1987; Mahon and Vaccaro, 1991; Zacharogiannis and Farrally, 1993). Laboratory protocols are summarized in Table III.
4.3 Methodology

Methodological procedures involved in HRT assessment require some genre of progressive intensity testing. Modifications of the Conconi et al. (1982) protocol have allowed its implementation into the exercise laboratory. This has evinced some procedural disparities with HRT assessment. Part of the difficulty relates back to the fact that the original HRT testing was performed in the field and utilized only running as a modality. Subsequent to the work of Conconi et al. (1982), HRT investigations utilized a variety of sports both in the field and in the laboratory. The complexities of juxtaposing field testing to laboratory testing makes any concrete interpretation of HRT arduous, if not impossible. However, prudence suggests that if HRT is a normal physiological occurrence then it should be observed throughout all categories of progressive intensity testing including field and laboratory measurements (Jones and Doust, 1995).

The original HRT field protocol (1982) has been revised and clarified recently (Conconi et al., 1996). The updated procedures necessitate the increase in exercise intensity to be representative of a uniform time-based acceleration. Specifically, this requires an augmentation in workload such that HR does not increase by more than eight beats \( \cdot \) min\(^{-1}\). In cases where speed is the modality, the point of transition between submaximal and maximal exercise intensity should be characterized by an accelerated rate of increase until volitional exhaustion. This point may be determined intrinsically by the athlete or by the investigator monitoring external signs of impending fatigue. Furthermore, a correlation coefficient of \( r \geq 0.98 \) for the linear portion of the HR-work relationship is considered a critical component for successful HRT assessment (Conconi et al., 1996).
4.3.1 Detection of Heart Rate Deflection

HRT is normally characterized by a decrease in the slope of the HR-work relationship. This is visually manifest as a curvilinear response and is reported in the range of 88-94% of maximum HR (Bunc and Heller, 1992; Hofmann et al., 1994; Hofmann et al., 1997; Kara et al., 1996; Ribeiro et al., 1985; Zacharogiannis and Farrally, 1993). However, a very small percentage of deflections (7.9%) demonstrate an inverse or increase in slope after deflection (Hofmann et al., 1997). A phasic flattening of HR response at the HRT followed by a linear rise with a different slope is another variation of this phenomenon (Maffuli, Sjodin and Ekblom, 1987).

Visual inspection is considered an acceptable method for HRT determination. The demarcation of change in slope during progressive testing is the hallmark of HRT; however, not all demarcations readily present themselves (Francis et al., 1989; Ribeiro et al., 1985). Disparate results in the literature concerning the deflection point may be related to interindividual observational differences. This may confound true or accurate HRT assessments.

Attempts have been made to make this arbitration more objective. The majority of investigations have incorporated subjective visual analysis to assess HRT (Cellini et al., 1986; Conconi et al., 1982; Droghetti et al., 1985; Gaisl and Weisspeiner, 1987; Jones and Doust, 1997; Ribeiro et al., 1985; Thorlund, Podolin and Mazzeo, 1994; Tokmakidis and Leger, 1988; Tokmakidis and Leger, 1992; Zacharogiannis and Farrally, 1993) but others have applied linear regression models (de Wit et al., 1997; Kuipers et al., 1988; Mahon and Vaccaro, 1991), two-compartment linear regression (Bunc et al., 1995; Bunc and Heller, 1992; Bunc, Heller and Leso, 1988), computer-aided linear regression (Hofmann et al., 1994; Hofmann et al., 1994) and mono-segmental exponential and bi-segmental logarithmic analyses (Tokmakidis and Leger, 1992).
<table>
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<tr>
<th>STUDY</th>
<th>POPULATION</th>
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<tr>
<td>Ballarin et al. (1989)</td>
<td>children and adolescents</td>
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<td>Baraldi et al. (1989)</td>
<td>children</td>
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<td>Bodner et al. (1999)</td>
<td>trained cyclists</td>
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<td>Bodner, Rhodes and Coutts (1998)</td>
<td>healthy, active males</td>
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<td>Bunc and Heller (1992)</td>
<td>untrained middle-aged men</td>
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<td>Bunc, Heller and Leso (1988)</td>
<td>trained male runners; untrained males</td>
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<tr>
<td>Bunc et al. (1995)</td>
<td>female students with no regular training</td>
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<tr>
<td>Cellini et al. (1986)</td>
<td>trained swimmers</td>
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<td>Conconi et al. (1982)</td>
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<td>Droghetti (1986)</td>
<td>trained rowers</td>
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<td>Droghetti et al. (1985)</td>
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<td>Gaisl and Hofmann (1990)</td>
<td>male and female children</td>
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<td>Gaisl and Weisspeiner (1987)</td>
<td>male and female children</td>
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<td>Hofmann et al. (1994(^a))</td>
<td>female physical education students</td>
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<td>male sport students</td>
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<td>Hofmann et al. (1996)</td>
<td>healthy young and older males</td>
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<td>Hofmann et al. (1997)</td>
<td>male students; trained athletes</td>
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<tr>
<td>Jones and Doust (1995)</td>
<td>trained male distance runners</td>
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<td>Jones and Doust (1997)</td>
<td>trained male distance runners</td>
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<td>Kara et al. (1996)</td>
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<td>trained athletes; sedentary individuals</td>
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<td>Maffuli, Sjodin and Ekblom (1987)</td>
<td>well-trained males</td>
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<td>male children</td>
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<td>Nikolaizik et al. (1998)</td>
<td>male and female cystic fibrosis patients</td>
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<td>Petit, Nelson and Rhodes (1997)</td>
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<td>male sport students</td>
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<td>Pokan et al. (1993)</td>
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<td>Ribeiro et al. (1985)</td>
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<td>Thorlund, Podolin and Mazzeo (1994)</td>
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<td>Tokmakidis and Leger (1988)</td>
<td>elite male runners</td>
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<td>Tokmakidis and Leger (1992)</td>
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<td>Zacharogiannis et al. (1993)</td>
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<td>Study</td>
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<td>Baraldi et al. (1989)</td>
<td>treadmill</td>
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<td>Bodner et al. (1999)</td>
<td>cycle ergometry</td>
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<td>Bodner, Rhodes and Coutts (1998)</td>
<td>cycle ergometry</td>
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<td>Bunc and Heller (1992)</td>
<td>cycle ergometry</td>
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</table>
| Bunc, Heller and Leso (1988) | treadmill, cycle ergometry | treadmill: 13 km·h⁻¹ (5% inclination) with 1 km·h⁻¹ increase  
 |                      |                        | cycle ergometer: physical work capacity of 170 beats·min⁻¹ plus 20W start with 20W·min⁻¹ increase |
| Bunc et al. (1995) | cycle ergometry        | 40W start with 10W·min⁻¹ increase at 70 rev·min⁻¹                         |
| de Wit et al. (1997) | cycle ergometry        | Constant Duration test: power value = 120 - 130 beats·min⁻¹ start with mathematically calculated stage increase every min  
 |                      |                        | Constant Distance Test: 0.50-1.50 W·kg body weight start; stage 1 = 2 min.; stage 2 = 1 min.; stages 3-5 = 50 seconds; stage 6-end = 40 seconds |
| Droghetti (1986)  | rowing ergometry       | Men: 170 - 200W start with 10 - 15W·min⁻¹ increase  
 |                      |                        | Women: 150W start with 8 - 12.5W·min⁻¹ increase                           |
| Francis et al. (1989) | cycle ergometry        | 50 rev·min⁻¹ at 100W start with 5 rev·30 seconds increase                 |
| Gaisl and Hofmann (1990) | cycle ergometry        | cycle ergometer: 10W start with 10W·min⁻¹ increase; 40W start with 10W·min⁻¹ increase (females); 60W start with 10W·min⁻¹ increase (males)  
<p>|                      |                        | treadmill (5% grade): 7 - 8 km·h⁻¹ start with speed increase every 200m; 6 km·h⁻¹ start with 0.5·km·h⁻¹ increase every min |
| Gaisl and Weisspeiner (1987) | cycle ergometry       | 0 W start with 10W·min⁻¹ increase                                         |
| Hofmann et al. (1994) | cycle ergometry        | 40W start with 10W·min⁻¹ increase                                         |</p>
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<tr>
<td>Hofmann et al. (1994&lt;sup&gt;d&lt;/sup&gt;)</td>
<td>cycle ergometry</td>
<td>40W start with 20W increase every 90 seconds; cadence fixed at 70 rev·min&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td>Hofmann et al. (1997)</td>
<td>cycle ergometry</td>
<td>40W start with 20W·min&lt;sup&gt;-1&lt;/sup&gt; increase</td>
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<td>Jones and Doust (1997)</td>
<td>treadmill</td>
<td>3.33m·sec&lt;sup&gt;1&lt;/sup&gt; start at 1% inclination with 0.14m·sec&lt;sup&gt;1&lt;/sup&gt; increase</td>
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<tr>
<td>Jones and Doust (1995)</td>
<td>treadmill</td>
<td>3.33m·sec&lt;sup&gt;1&lt;/sup&gt; start with 0.14m·sec&lt;sup&gt;1&lt;/sup&gt; increase every 200m</td>
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<tr>
<td>Kara et al. (1996)</td>
<td>cycle ergometry</td>
<td>40W start; electronically braked resistance</td>
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<tr>
<td>Kuipers et al. (1988)</td>
<td>cycle ergometry</td>
<td>60% predetermined maximal workload with 10W·min&lt;sup&gt;-1&lt;/sup&gt; increase</td>
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<td></td>
<td>treadmill</td>
<td>20 min. warmup; 10 km·h&lt;sup&gt;-1&lt;/sup&gt; start with 0.5 km·h&lt;sup&gt;-1&lt;/sup&gt; increase every 30 sec</td>
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<tr>
<td>Maffuli, Sjodin and Ekblom (1987)</td>
<td>treadmill</td>
<td>Borg scale “very light” or “fairly light” start with 0.083 - 0.16 m·sec&lt;sup&gt;1&lt;/sup&gt; for 1, 2 and 4 min. stages</td>
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<tr>
<td>Mahon and Vaccaro (1991)</td>
<td>treadmill</td>
<td>3 miles·h&lt;sup&gt;-1&lt;/sup&gt; at 0% inclination with 0.5 miles·h&lt;sup&gt;-1&lt;/sup&gt; increase until 5-7 miles·h&lt;sup&gt;-1&lt;/sup&gt;; 2.5% increase in elevation thereafter</td>
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<td>Nikolaizik et al. (1998)</td>
<td>cycle ergometry</td>
<td>males: 50W start with 10W·increment&lt;sup&gt;-1&lt;/sup&gt; increase</td>
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<td>females: 30W start with 10W·increment&lt;sup&gt;-1&lt;/sup&gt; increase</td>
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<td>proportional time reduction per stage</td>
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<td>Pokan et al. (1995)</td>
<td>cycle ergometry</td>
<td>40W start with 20W·min&lt;sup&gt;-1&lt;/sup&gt; increase</td>
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<td>Pokan et al. (1993)</td>
<td>cycle ergometry</td>
<td>40W start with 20W increase every 90 seconds</td>
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<td>Ribeiro et al. (1985)</td>
<td>cycle ergometry</td>
<td>30W start with 30W·min&lt;sup&gt;-1&lt;/sup&gt; increase; cadence fixed at 70 rev·min&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td>25W start with 25W·min&lt;sup&gt;-1&lt;/sup&gt; increase</td>
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<td>Thorlund, Podolin and Mazzeo (1994)</td>
<td>cycle ergometry</td>
<td>60W start with 30W·2 min&lt;sup&gt;-1&lt;/sup&gt;; cadence fixed at 60 rev·min&lt;sup&gt;-1&lt;/sup&gt;</td>
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<td>Zacharogiannis et al. (1993)</td>
<td>treadmill</td>
<td>predetermined speed at start with 1.0 km·h&lt;sup&gt;-1&lt;/sup&gt; increase every min</td>
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<td>Hofmann et al. (1994&lt;sup&gt;e&lt;/sup&gt;)</td>
<td>cycle ergometry</td>
<td>40W start; 20W·min&lt;sup&gt;-1&lt;/sup&gt; increase</td>
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<td>Study</td>
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<tr>
<td>Ballarin et al. (1989)</td>
<td>running</td>
<td>Outdoor: 5-7 km·h$^{-1}$ with speed increase every 100m&lt;br&gt;Indoor: figure-eight course with slow speed increase</td>
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<tr>
<td>Cellini et al. (1986)</td>
<td>swimming</td>
<td>speed increase every 50m</td>
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<td>Conconi et al. (1982)</td>
<td>running</td>
<td>12-14 km·h$^{-1}$ start with 0.5 km·min$^{-1}$ increase</td>
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<td>Droghetti et al. (1985)</td>
<td>multi-sport</td>
<td>Canoeing and Rowing: water speed 36m·h$^{-1}$ with speed increase every 200m&lt;br&gt;Cross Country Skiing (Asphalt): 1680m distance (5.5% grade) with speed increase every 140m&lt;br&gt;Cross Country Skiing (Snow): speed increases on frozen lake&lt;br&gt;Cycling: speed increase every 335m in velodrome&lt;br&gt;Ice Skating: 400m track with speed increase every lap&lt;br&gt;Roller-skating: 325m asphalt track with speed increase every lap&lt;br&gt;Walking: 400m track with speed increase every 200m</td>
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<tr>
<td>Hofmann et al. (1994$^b$)</td>
<td>kayaking</td>
<td>HR 130 beats·min$^{-1}$ start with 5 beat·min$^{-1}$ increase</td>
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<tr>
<td>Petit, Nelson and Rhodes (1997)</td>
<td>running</td>
<td>10.3 km·h$^{-1}$ start with speed increase every 200m</td>
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<tr>
<td>Tokmakidis and Leger (1992)</td>
<td>running</td>
<td>9 km·h$^{-1}$ start; pre-recorded audio cassette signaled speed increases</td>
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<tr>
<td>Tokmakidis and Leger (1988)</td>
<td>running</td>
<td>9 km·h$^{-1}$ start with 1 km·h$^{-1}$ increase to 14 km·h$^{-1}$; 0.5 km·h$^{-1}$ increase thereafter</td>
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</table>
Recently, mathematical modeling of classical HRT behavior has also been administered to assist with HR breakpoint assessment. A third order curvilinear regression equation (Kara et al., 1996) and logistic function (Bodner, Rhodes and Coutts, 1998; Bodner et al., 1999; Petit, Nelson and Rhodes, 1997) have been incorporated to describe the often observed curvilinear attribute of HR during the latter stages of incremental testing. The direction and degree of HR deflection has also been assessed by incorporating a second degree polynomial representation of HR data points (Hofmann et al., 1994c; Hofmann et al., 1997; Pokan et al., 1993; Pokan et al., 1995). These modeling techniques have demonstrated success detecting HRT.

4.3.2 Transition thresholds

The expression of transition thresholds in the HRT literature is diverse and has contributed to the challenges of validation. Some investigators (Cellini et al., 1986; Droghetti et al., 1985) utilized the unconventional multistage protocol created by Conconi et al. (1982), however most inquiries applied simultaneous protocols. The second lactate turnpoint (LTP2) (Davis et al., 1983) after the initial rise in \( \text{BLAC} \) concentration defined the \( \text{TLAC} \) for most studies (Bunc et al., 1995; Hofmann et al., 1994a; Hofmann et al., 1994d; Hofmann et al., 1997; Jones and Doust, 1997; Nikolaizik et al., 1998; Pokan et al., 1995; Ribeiro et al., 1985; Thorlund, Podolin and Mazzeo, 1994) however, a fixed blood lactate of 4 mmol \( \cdot \) L\(^{-1}\) has also been used as a standard (Gaisl and Hofmann, 1990; Gaisl and Weisspeiner, 1987; Kuipers et al., 1988; Maffuli, Sjodin and Ekblom, 1987). Only one study incorporated the first lactate breakaway as the lactate threshold (Tokmakidis and Leger, 1988).

\( \text{TVENT} \) is accepted as one criterion to describe critical work intensities (Loat and Rhodes, 1996) and its noninvasive nature makes it an appealing choice for comparison to HRT.
5. Mechanisms of Heart Rate Deflection

Logically, the validation of HRT depends on a direct relationship between HR and metabolism because HR deflection is used as an indication of metabolism intensity (Pessenhofer et al., 1991). The physiological mechanisms advocating the HRT relationship to transition thresholds have not been fully elucidated. Potential explanations have focused primarily on load-dependent myocardial function.

5.1 Conconi hypothesis

Originally, Conconi et al. (1982) cited the observations of Pendergast et al. (1979) who demonstrated that above transition thresholds the attendant increase in VO₂ was smaller than the increase in workrate. Conconi et al. (1982) hypothesized that this may be true for runners and that a concomitant increase in HR may also not follow a linear relationship to work intensity. Conconi et al. (1982) proposed that HRT is partially reflective of an increased reliance on anaerobic glycolytic mechanisms to increase ATP production at high workloads above transition thresholds. This increase in ATP production occurs independently of oxygen uptake. These investigators reasoned that the linear rise in work intensity increases faster than HR (i.e. after the HR breakpoint) beyond the anaerobic threshold and is reliant upon “anaerobic” production of ATP. Logically, it would follow that this deflection in HR could evaluate the onset of the transition from aerobically generated power to additional power developed by anaerobic glycolytic pathways. The additional ATP generated by anaerobic pathways, Conconi et al. (1982) proposed, is necessary because VO₂ and HR do not increase in accordance with power when approaching maximal work levels during progressive testing. The HRT therefore is related to the inability of HR and cardiac output to account for the total increase in VO₂ above transition thresholds.
5.2 Myocardial Function

HRT may not represent a physiological substrate in as much as it may represent a coupling of cardiovascular control mechanisms (Pessenhofer et al., 1991). The first physiological rationale for abrupt changes in HR behavior during incremental exercise appeared in the work of Pokan et al. (1993). Their findings suggested a relationship between myocardial function and the HRT (Pokan et al., 1993). Myocardial function was assessed using radionuclide ventricular scintigraphy and expressed as left ventricular ejection fraction (LVEF). Twelve of the fifteen subjects examined demonstrated a deflection in HR or nearly linear response to incremental cycle ergometry. The other three exhibited an increase in the slope of HR at higher work intensities. LVEF characteristically reached highest values before maximal workloads were attained but evinced both linear and breakaway responses as well. In some cases LVEF increased slightly or leveled off after the breakaway. This pattern was interpreted as augmented myocardial function and was significantly related to HR deflection ($r = -0.673$, $p < 0.01$). More linear HR responses on the other hand demonstrated a marked decrease in LVEF after breakpoint.

These investigators hypothesized that the absence of deflection in HR was related to a diminution in myocardial function. The increase in cardiofrequency possibly compensated for the shortcomings in LVEF and maintained the obligatory cardiac output. Conversely, in subjects where increases or flattening of LVEF responses after deflection did not require HR augmentation, chronotropic HR response was curtailed somewhat.

Similar results were observed by Hofmann et al. (1994) who noted disparate LVEF responses between subjects with and without HR deflection. Again, the decrease in LVEF at breakpoint was more conspicuous in those subjects without HR deflection. There were significant correlations and no significant differences between power and HR at LVEF breakpoints and HR and power at the onset of HR deflection ($r = 0.628$ and $r = 0.884$, $p < 0.001$,
respectively). This was also true for HR at TLAC and HR at HRT and LVEF breakpoints (r = 0.847, p < 0.01; r = 0.690, p < 0.05). This decrease in LVEF in both groups was significantly related to the TLAC.

Age differences may be related to different LVEF behavior. Older males (50 ± 10 years) appear to express greater decreases in LVEF and greater increases in end systolic volume beyond the lactate threshold than do younger males (23 ± 2 years) utilizing similar incremental cycle ergometry (Hofmann et al., 1996). Younger males displayed classical HRT, whereas older males demonstrated an inverse response. Cardiac output increased throughout testing in both groups which suggests that increased HR frequency may be necessary to compensate for possible age-related losses in myocardial function.

Varying degrees of LVEF are related to both the type of HR deflection and the TLAC, but this does not imply cause and effect. The hypothesis can be made, however that the augmentation of glycolytic mechanisms culpable for HR deflection are related to the intrinsic function of the heart. A limited cardiac output due to diminution of myocardial function above the lactate threshold may contribute to a retarded oxygen uptake (Hofmann et al., 1994). This reduction in oxygen uptake demands that glycolytic pathways must be strongly activated to meet the energy needs for increased power production during the latter stages of heavy incremental work. This hypothesis is a reverse model of the hypothesis raised by Conconi et al. (1982).

Age may be a potential factor in the difference in direction of deflection, but it is important to note that Hofmann et al. (1997) observed a completely linear response or inverse deflection in a small percentage of healthy young subjects. Additionally, Bunc and Heller (1992) observed a HRT in the majority of middle-aged men (51.8 ± 5.4 years). Physiologically, this limitation in LVEF and HR responses may be related to differentiated catecholamine sensitivity of the myocardium (Hofmann et al., 1994d).
5.3 Neural and Catecholamine Influences

Slight modulations in HR deflection have been observed in individuals under the influence of parasympathetic blockade (Hofmann et al., 1994); however parasympathetic regulation does not appear to be a cogent explanation for HR deflection. The results of this study may be supported by recent evidence that demonstrates that exercise intensities corresponding to 50-60% of maximal oxygen consumption are devoid of vagal influences on HR (Tullpo et al., 1998). Cardioacceleration beyond this point is mediated completely by the sympathetic drive.

Hormonal preponderance of HR acceleration appears to be minimal at low exercise intensity (Perini et al., 1993). Reduction in vagal activity combined with increased activity of cardiac sympathetic nerves is primarily responsible for further incremental HR accretion (Maciel et al., 1986). However, during steady state exercise circulating levels of catecholamines (Breuer et al., 1993; Perini et al., 1993) and increased temperature of cardiac pacemaker tissue (Tullpo et al., 1998) play a more dominant role in sustaining tachycardia.

It is reasonable to hypothesize that catecholamines may be a constituent in the mechanism(s) of HR deflection since they contribute to the tachycardic response during exercise. (Pokan et al., 1995). Time courses of plasma epinephrine (E) and norepinephrine (NE) concentrations juxtaposed with both regular and inverse HR deflections during cycle ergometry however, display no significant relationship. At the same time, a significant relationship was noted between the time course of plasma E concentration and blood lactate concentrations (r = 0.723, p < 0.005). Time course of plasma catecholamine concentrations appeared to be independent of HR deflection behavior.

This is the only study relating HRT to catecholamine time courses. A study such as this is difficult to interpret because the mechanisms fundamental to cardiac control are rationalized from inquiries relating to dynamic sustained exercise. Control mechanisms governing
cardiodynamics during progressive intensity exercise presents another assortment of uncertainties because of a metabolic state that is continuously in flux (Perini et al., 1993).

6. Validity

The notion that HRT assesses critical or transition intensity thresholds is appealing. HRT testing can provide a simple means to accomplish this within the realm of endurance athletics. Although HRT is widely and successfully used by coaches (de Wit et al., 1997) there is no clear consensus in the literature that it provides a valid assessment of transition thresholds.

6.1 Physiological Occurrence or Artifact of Protocol?

Some researchers raise doubts that the HRT is a normal physiological occurrence (Pokan et al., 1993; Ribeiro et al., 1985). Ribeiro et al. (1985) reported difficulties detecting HRT in 50% of their subjects and suggested that the biological origin of the deflection point is somewhat dubious. They asserted that the deviation in HR linearity is not physiologically indispensable.

To interpret the occurrence of a deflection, some investigators contend that the fixed-distance stage protocols may be responsible (Jeukendrup et al., 1997). Since stage distances are constant, any accretion in exercise intensity must arise from an increase in speed. This however, effectively decreases the duration of the stage, especially near the end of the test. The time interval of each stage will decrease progressively to the extent that the circulatory system cannot effectively adapt to the increasing workload. This will be physically manifest as a lagging in HR response and visually observed as a deflection in linearity. This decreased continuance of the stage coincident with ineffective cardiovascular adaptation implies that HR deflection is an artifact of the protocol (Jeukendrup et al., 1997).

This explanation is disputed by Conconi et al. (1997) who reported that in runners, the final acceleration during incremental staging occurs after the HR deflection has been observed. The time lag between the onset of deflection and the beginning of the final acceleration to
complete the test is sufficient to allow for cardio-circulatory adaptation. Conconi et al. (1997) purport that this adaptation can occur within ten to twenty seconds if the adjustment in speed increments are 0.5 km·h\(^{-1}\) or less.

Additionally, Conconi et al. (1997) defends the use of increased cadence as a means by which to assess the HRT. Their primary argument is that from a physiological perspective increased cadence is used by mammals (including man) to increase work intensity (unaided by mechanical devices). This explanation, however, fails to account for HR deflections that occur with cycle ergometry when cadence is fixed (Hofmann et al., 1994\textsuperscript{d}; Ribeiro et al., 1985) or when cadence is self-selected (Bodner, Rhodes and Coutts, 1998; Bodner et al., 1999; Bunc et al., 1995; Hofmann et al., 1994\textsuperscript{a}). Furthermore, confirmations of HRT during fixed stage protocols utilizing the cycle ergometer and treadmill (Hofmann et al., 1994\textsuperscript{d}; Jones and Doust, 1995) appear to contradict the suggestion that deflections are the result of protocol. It is true that most fixed stages involve one-minute sessions that require rapid cardiovascular adaptation. However, within-subject analysis of HRT by Maffuli, Sjodin and Ekblom (1987) demonstrated reproducible HR deflections across one, two and four minute stages of treadmill ergometry.

6.2 Plateau of Maximum HR

HRT may denote the beginning of the plateau of maximum HR (Jones and Doust, 1995). Regression analysis applied to their HR data on elite runners suggested that oxygen consumption at HRT would have been equivalent to 93% of peak VO\(_2\). These investigators proposed that since exercise workloads at a relative intensity of 95% VO\(_2\) max. are characteristic of the beginning of the plateau in maximum HR, HRT could be construed as the beginning of that plateau. Direct measurements of gas exchange parameters in runners however, suggests that VO\(_2\) at HRT corresponds to only 78.5% of VO\(_2\) max. (Maffuli et al., 1987). Similar results were obtained by
Bodner et al. (1999) who observed that oxygen consumption at HRT in well-trained cyclists is approximately 77.0% of maximal values.

6.3 Relationship to Transition Thresholds

Pivotal for HRT validation is its relationship to TLAC or TVENT. These relationships are expressed as power, speed, HR or VO₂ at these thresholds. Validity of HRT is inconclusive because of sundry results in the literature.

Where HRT is confirmed, strong correlations (r > 0.80) relating HRT and transition thresholds are reported (Bunc et al., 1995; Bunc and Heller, 1992; Bunc, Heller and Leso, 1988; Gaisl and Hofmann, 1990; Gaisl and Weisspeiner, 1987; ; Hofmann et al., 1994d; Hofmann et al., 1997; Zacharogiannis and Farrally, 1993). Strong correlations (r = 0.905, p < 0.001; r = 0.889, p < 0.001) for HR and power between HRT and TLAC (respectively) in 213 healthy young male subjects utilizing cycle ergometry (Hofmann et al., 1997). This finding is important since the relationships were inclusive of inverse deflections as well. These authors suggest that HRT may be useful from a training prescription perspective, but cautioned universal applicability since a deflection was not observed in 6.2% of cases.

Conversely, low correlations between speed at TLAC and HRT have also been observed (Tokmakidis and Leger, 1988; Tokmakidis and Leger, 1992). These poor correlations may have been the result of the method of assessment. Mathematical linear regression models applied to the HR data possibly ignored the effect of the non-linear HR component characteristic of the beginning of the exercise regimen. Linear regression models that include this portion may bring about erroneously high HRT values (Hofmann et al., 1997). Interestingly, in the Tokmakidis and Leger study (1988), HR at HRT and TLAC were strongly correlated (r = 0.85) and not significantly different.
Some research suggests that running velocity at HRT is 13.4% higher than that at TLAC (Tokmakidis and Leger, 1988). These values are almost identical to those of Jones and Doust (1997) who also reported a 13% higher average running velocity at HRT than at TLAC. These variables however, were significantly correlated ($r = 0.73$). Zacharogiannis and Farrally (1993) also reported that velocity, $VO_2$ and %HRmax values at HRT are significantly higher than TVENT (8.26%, 7.2% and 9.5% respectively) despite significant correlations between these values.

The discontinuous multistage lactate threshold protocol implemented by Conconi et al. (1982) may also introduce an experimental bias that accounts for the high degree of relationship and coincidence of RS at HRT and RS at TLAC (Tokmakidis and Leger, 1988; Tokmakidis and Leger, 1992). This protocol requires the acquisition of the intersection of two regression lines of blood lactate concentrations corresponding to three RS above and below the RS at HR deflection. According to Tokmakidis and Leger (1988) this point will always arrive close to RS at HRT. Furthermore, the incorporation of this two-compartment linear model to determine the blood lactate breakaway is not valid for BLAC responses since they often manifest a curvilinear inclination (Tokmakidis and Leger, 1988). Conconi et al. (1988) disagree with Tokmakidis and Leger (1988) and suggest that the intersection of lactate lines may occur at any point on the graph up to the first speed above the deflection. They remain firm in their conviction that the intersection of these lines resulted from augmented lactate concentration above the deflection velocity.

While discontinuous protocols may be subject to criticism, there is evidence to support the validity of HRT when threshold assessments are conducted within and are concurrent with the graded test itself. Strong relationships have been observed between HRT and transition thresholds when such assessments are undertaken (Bunc et al., 1995; Bunc and Heller, 1992; Bunc, Heller and Leso, 1988; de Wit et al., 1997; Gaisl and Hofmann, 1990; Gaisl and
Weisspeiner, 1987; Hofmann et al., 1994; Hofmann et al., 1997; Pokan et al., 1993; Pokan et al., 1995; Zacharogiannis and Farrally, 1993). Figure I demonstrates the apparent coincidence between HR and TVENT breakpoints during graded cycle ergometry.

The disparity of power outputs at HRT across varied nutritional states however, suggests that HRT validity may be questionable even if threshold assessment is concurrent. HRT does not appear to provide a stable assessment of TLAC across normal and glycogen-depleted conditions (Thorlund, Podolin and Mazzeo, 1994). These investigators conclude therefore that there is no causal relationship between HRT and TLAC. This finding jeopardizes the usefulness of HRT applied to prolonged training or competition because glycogen reserve reduction is inevitable and potentially chronic with such activities (Thorlund, Podolin and Mazzeo, 1994). However, Conconi et al. (1997) state that the disparity in RS or power across HRT testing following prolonged training does not disqualify the validity of HRT nor its usefulness. Rather, these investigators suggest that HRT may be used to signal modifications in the nutritional status of the athlete in such instances.

Evidence linking HR behavior and lactate kinetics is unsubstantiated, according to Tokmakidis and Leger (Tokmakidis and Leger, 1988; Tokmakidis and Leger, 1992). These investigators suggest that physiologically it is puzzling that HR behavior should account for the interplay of lactate kinetics (production and removal) during incremental exercise.

This dissociation between metabolism and cardiovascular implication is evident in the assessment of HRT in cystic fibrosis (CF) patients (Nikolaizik et al., 1998). Individuals with CF present a unique situation with respect to HRT. Their cardiovascular function is normal, however oxygen diffusion across the alveolar-capillary interface is compromised because of the nature of the interstitial lung disease. Hypoxemia associated with this poor oxygen diffusion may lead to a reduced capacity for exercise due to premature metabolic acidosis. Results of HRT assessment
showed relatively significant relationships between HRT and LTP2 ($r = 0.84, p < .01$) but the mean HRT was 19% higher than LTP2 (Nikolaizik et al., 1998). It is clear that HRT-based exercise prescription would result in workloads that are too strenuous for CF patients.

This data presents new obstacles for a physiological explanation of HRT. The deflection point is hypothesized to represent a function of physiological substrate (Conconi et al., 1982; Conconi et al., 1996). The intrinsic myocardial characteristics associated with oxygen uptake kinetics have also been hypothesized to help explain the HRT phenomenon. However, neither of these theories appear to be congruent with HRT in CF patients.

6.3.1 Steady State Exercise

Incremental testing contributes to a metabolic state that is continuously in transition (Perini et al., 1993). However, the identification of physiological variables at transition thresholds derived from these tests reflects a similar metabolic state that occurs during maximal steady state exercise (Aunola and Rusko, 1992; Yamamoto et al., 1992). Additionally, endurance performance based on transition thresholds confirms this relationship (Hopkins and McKenzie, 1994; Rhodes and McKenzie, 1984; Powers et al., 1983; Coyle et al., 1991; Farrell et al., 1979; Tanaka et al., 1983). HRT validity can be strengthened if extrapolated to steady state testing, however these studies are few in number.

According to Hofmann et al. (1994a) it is possible that steady state intensities may be augured from traditional, non-steady HRT assessments. BlAC concentrations, $Ve$, $VO_2$ and surface EMG of working muscle were found to be at steady state during successful twenty minute cycle ergometry at workloads equivalent to 10% lower than power at HRT in untrained female students (Hofmann et al., 1994a). This was not observed at 10% above power at HRT (with the exception of EMG). No subjects were able to complete the twenty-minute task. A similar study demonstrated that $VO_2$ and HR values at HRT were significantly related to but not
significantly different from those obtained during steady state cycling at $T_{VENT}$ in trained cyclists (Bodner et al., 1999).

Strong correlations between RS at deflection and average speed during a 5000m race ($r = 0.93$, $n = 19$), marathon ($r = 0.95$, $n = 55$) and one hour race ($r = 0.99$, $n = 31$) have been observed, but HR was not included in the assessment (Conconi et al., 1982). Some sports have demonstrated relationships between deflection speed and average race speed (Droghetti et al., 1985). Similar to Conconi et al. (1982), any potential significant differences between deflection speed and average race speed were not reported, however.

Significant differences in HR at HRT and $T_{LAC}$ were observed by Jones and Doust (1997) despite a relatively strong correlation ($r = 0.89$, $p < 0.05$). Concerning this study, seven subjects attempted to complete a 30-minute run at $0.14 \text{ m } \cdot \text{s}^{-1}$ below running speed at HRT. Only one was able to complete this task. $B_{LAC}$ levels in all subjects increased continually until volitional fatigue and final mean HR was equivalent to 99% $HR_{MAX}$.

Contrary to the findings of Jones and Doust (1997), Hofmann et al. (1994$^b$) demonstrated that in white water kayakers, steady state HR and $B_{LAC}$ levels during twenty minute sessions were not significantly different from those values at HRT. HR at HRT and steady state HR in twelve cases were strongly correlated ($r = 0.882$, $p < 0.001$) and not significantly different.

Only one study has used HRT to predict competitive performance. Petit, Nelson and Rhodes (1997) applied an objective mathematical model (MM) to Conconi field test results to assess HRT in a group of runners. No significant differences were observed for HR, running speed and predicted performance times between field test and subsequent treadmill evaluations. Additionally, highly significant relationships were reported between HRT predicted times and actual times for 10 kilometer running performance ($r = 0.98$, $p < 0.01$).
7. Reproducibility and Reliability

Methodological discrepancies between investigations appear to have congested the interpretation of HRT (Francis et al., 1989) and may be construed as a cause of low-reproducibility. For example, constant stage duration as conducted in laboratory testing rather than a fixed-distance/stage reduction protocol characterized in field testing might account for the low incidence of HRT and scope of HRT variability and in the literature (Jones and Doust, 1995).

It is also evident from the literature that there is a limitation to the HRT since a clear visual deflection point does not always present itself. Success discerning the breakaway has been documented (Ballarin et al., 1996; Conconi et al., 1982; Droghetti, 1986) but others report successful breakpoints in 94% (Hofmann et al., 1997), 93% (Bunc and Heller, 1992), 89% (Gaisl and Weisspeiner, 1987) 72% (Ribeiro et al., 1985) 68% (Kara et al., 1996) 57% (Nikolaizik et al., 1998), 46% (Kuipers et al., 1988) of their subjects, or no demonstrable deflection point (Francis et al., 1989). This suggests that HRT may not be reproducible across dissimilar populations. Indeed, the evidence for HRT reproducibility appears to be equivocal. Ribeiro et al. (1985) observed that only 50% of subjects demonstrated HRT when assessed for reproducibility. However, TVENT was confirmed in all subjects. This finding is comparable to the results of Jones and Doust (1995) who reported that only 40% of their subjects exhibited a clear curvilinear shift in HR during incremental treadmill testing. The 60% remaining showed either no HRT (26.7%) or displayed HRT in only one of the tests (33.3%). Similar results (45%, 31% and 24%, respectively) were reported by De Wit et al. (1997).

A deficiency of repeatable HRT could be attributed to differences among the training or fitness status of subjects (Ribeiro et al., 1985). Endurance athletes have a highly trained anaerobic capacity and motivated disposition that contributes to the effort necessary to achieve
supramaximal exercise intensities required for successful test completion. Lesser-trained individuals could lack the volition to finish and may quit prematurely (Jones and Doust, 1995). As a result, the completed test may not be of an appropriate length to acquire HRT.

This hypothesis is supported by Ribeiro et al. (1985) and Francis et al. (1989) whose subject pools were composed primarily of healthy, active, but relatively untrained subjects. This appears to be a sensible hypothesis, but one study utilizing homogeneous groups of well-trained individuals demonstrated the same reproducibility difficulties (Jones and Doust, 1995).

Not all HRT investigations have demonstrated disparate reproducible results. Conconi et al. (1982) tested 147 runners between three and 80 times each and reported strong reproducibility, but did not quantify the data, unfortunately. Other investigators (Ballarin et al., 1996) have also demonstrated reproducible HRT in heterogeneous and homogeneous populations using a modified Conconi protocol. Incorporating cycle ergometry, Bodner, Rhodes and Coutts (1998) noted that HRT derived by mathematical modeling was reproducible for HR ($r = 0.84$, $p < .001$) and power ($r = 0.95$, $p < .001$). This relationship was strengthened by the fact that no significant differences were observed across repeated testing. Maffuli, Sjodin and Ekblom (1987) also reported that HR deflection was reproducible in trained runners with a test-retest correlation of $r = 0.97$. Additionally, and perhaps more importantly, the HR deflection point was reproducible if the length of the stage of the protocol was one, two or four minutes in length.

Repeated testing may result in some variance in the regression slopes of the HR-workload response, however some researchers allege that the convergence of the HR breakpoints across repeated testing is not differentiated (Ballarin et al., 1996). Conversely, the individual metabolic response to graded testing may influence the reliability but not the reproducibility of HRT. This infers that HRT may be observed across repeated testing (reproducibility) but power, speed or HR at the deflection at the breakpoints may be significantly different. HRT reliability appears to
be influenced by factors such as glycogen depletion (Thorlund, Podolin and Mazzeo, 1994; Maffuli, Sjodin and Ekblom, 1987) and hydration (Maffuli, Sjodin and Ekblom, 1987). These observations are supported by Conconi et al. (1996) who suggest that the HRT-TLAC relationship may be modified if glycogen levels are disturbed. Variability in HRT is demonstrated following a marathon performance (Maffuli, Sjodin and Ekblom, 1987; Conconi et al., 1996). Changes in location of HRT however are not related to low-test reproducibility, but rather to an alteration in nutritional states (Conconi et al., 1996). HRT testing should be conditional upon training status and basal diet to minimize reproducibility difficulties (Maffuli, Sjodin and Ekblom, 1987).

Reproducibility studies that have published both HR and work intensities have only examined test-retest responses over two sessions. Lack of repeatable deflections has been interpreted to indicate that HRT is not reliable (Jones and Doust, 1995). However, within-subject multiple HRT testing could provide a better assessment of overall HRT reproducibility. Presently there is no quantified reliability study in the literature that has conducted multiple repeated HRT tests.

The cornerstone of reliability of HRT is the objective definition of HR deflection. Validation becomes problematic if reliable assessments of HRT are unavailable. The ability to detect HR slope transitions is the weakest aspect of HRT investigation (Hofmann et al., 1994a). Visual analysis is acceptable, however it is prone to subjective interpretation which may lead to errant or diverse HRT values. Mathematical modeling of HR behavior however, provides an objective option for HRT determination (Petit, Nelson and Rhodes, 1997).

The unique, noninvasive nature of HRT testing and its applicability in the field or laboratory settings makes it a favorable modality to assess critical work intensities. However, transition threshold assessment by means of the HRT has not been confirmed. Physiological
mechanisms that describe the nature of the HR deflection are not clear but appear to be related to intrinsic myocardial function.

Evidence is equivocal concerning HRT validity; however, several studies demonstrate a high degree of relationship to either TLAC or TVENT. HRT reproducibility is not consistent in the literature; this includes research across studies and within subjects. Reliability of HRT appears to be affected by training status and nutritional state. The detection of the HR breakaway point is suggested as the weak link in HRT investigations. Disparate findings of the HRT-transition threshold relationship warrant further research with particular attention given to physiological mechanisms and HRT relationship to steady state exercise.
CHAPTER III

METHODS AND PROCEDURES

Subject Characteristics

Twenty-one well-trained male, elite (Canadian Cycling Association Category 1-2-3) competitive road or Professional/Elite off-road endurance cyclists volunteered for this study. Off-road cyclists were also included in this investigation since the majority of their aerobic endurance training (80%) is conducted on the road. Recruitment and testing commenced between the months of March and September which is the equivalent of the racing season in British Columbia. All cyclists satisfied the inclusion criteria definition of well-trained: a minimum of two years competitive racing experience, a maximum oxygen uptake (VO$_2$ max.) of $\geq 60$ ml $\cdot$ kg $\cdot$ min$^{-1}$, cycling endurance training (on road) a minimum of 8 hours training per week, and within the selected age range of 18 - 40 years. Subjects completed a Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology) along with written informed consent. This study was approved by the Research Ethics Board of the University of British Columbia.

Anthropometric Measurements

Height (cm) (Holtain Ltd.) and weight (kg) (Mettler-Toledo, Worthington, Ohio) were measured before ergometry. Height was measured without shoes and weight was assessed wearing cycling shorts and T-shirt only.

Cycle Ergometry

All subjects performed a maximal graded exercise test at the J.M. Buchanan Exercise Science Laboratory at the University of British Columbia. The procedure utilized a ramped protocol on an electronically braked cycle ergometer (Sensormedics 800 Ergometer, SensorMedics, Yorba Linda CA). Initial resistance was set at 50 watts (W) incorporating a 30W $\cdot$ min$^{-1}$ increase. Analysis of pilot research (Bodner, Rhodes and Coutts, 1998) demonstrated that
this protocol satisfied the methodological criteria set forth by Conconi et al. (1996) to allow sufficient cardio-circulatory adaptation (≤ 8 beats • min⁻¹ increase in HR per stage) for augmented workloads.

Individual cycle seat heights (measured from the center of the crank spindle to the level aspect of the cycling saddle) were acquired from the subjects and transferred to the seat height on the cycle ergometer. Pedals from the subjects' bicycles were also compatible with the Sensormedics 800 cycle ergometer, allowing the cyclists to use their own cleated cycling shoes. All subjects completed an individual warmup before commencing ergometry. Cadence was self-selected, however subjects were informed to keep pedal revolutions above 40 • min⁻¹ since cadence below this would effect an inaccurate power output. Verbal encouragement was rendered throughout test duration.

Subjects were instructed to refrain from strenuous exercise the day of and 24 hours before testing and to arrive at the lab at least two hours post-absorptive. Fluids were allowed up until the time of testing.

**Ventilatory Threshold Determination**

1. **Nutritional Considerations**

   Competitive cyclists normally maintain a high carbohydrate (CHO) diet during training for maintenance of liver and muscle glycogen levels. However, because of possible disparity between lactate threshold and ventilatory threshold when CHO stores are lowered (Neary et al., 1985) all subjects were encouraged to consume (or maintain) a high CHO diet as they normally would during the course of a racing season for the week preceding testing.

2. **Ventilatory Threshold**

   Minute ventilation (Ve), VO₂, VCO₂ and RER were measured on-line employing breath-by-breath analysis with averages reported every twenty seconds (SensorMedics Vmax Series
Room temperature and barometric pressure were recorded by the Sensormedics Vmax Series 2900 for each testing session. Attainment of VO\textsubscript{2} max. was accepted when three of the following criteria were met: 1) oxygen consumption stopped increasing in a linear manner with increasing workload 2) RER of \( \geq 1.10 \) 3) HR within 10 beats \( \cdot \text{min}^{-1} \) of age-predicted maximum 4) volitional fatigue (based on inability to maintain minimum cadence of 40 revolutions \( \cdot \text{min}^{-1} \)) (Bannister et al., 1993).

The ventilatory threshold (\( T_{\text{VENT}} \)) was incorporated to represent critical work or transition threshold (Loat and Rhodes, 1996) and was defined utilizing the excess CO\textsubscript{2} (EXCO\textsubscript{2}) elimination curve (Anderson and Rhodes 1991; Langill and Rhodes 1993; Loat and Rhodes 1996; Volkov et al. 1975) using the following equation:

\[
\text{Excess CO}_2 = VCO_2 \times (RQ \times VO_2)
\]

where \( CO_2 \) is the total expired CO\textsubscript{2}, \( O_2 \) is the total expired O\textsubscript{2} and \( RQ \) is the resting respiratory quotient. A set \( RQ \) value of 0.75 was used to assess the EXCO\textsubscript{2} elimination curve (Volkov et al., 1975).

In graphs where discernment of EXCO\textsubscript{2} breakaways were inconclusive, the ventilatory equivalent of oxygen uptake (\( VE/VO_2 \)) (Wasserman et al., 1973) was incorporated to aid with threshold assessment. Both EXCO\textsubscript{2} and \( VE/VO_2 \) have been used to determine critical intensity thresholds in elite racing cyclists (Anderson and Rhodes, 1989). Independent analyses of the EXCO\textsubscript{2} and \( VE/VO_2 \) breakpoints were resolved by two trained exercise physiologists. In cases where there was a divergence in breakaway points, a third independent assessment was sought.

Once the time of ventilatory breakaway was established, the physiological values for HR, \( VO_2 \) and power were assessed by interpolation.
Heart Rate

HR values were assessed utilizing HR telemetry (Polar Electro, Finland) and observer recorded every 20 seconds. Polar HR monitors are accurate to within ± one beat · min⁻¹ or ± 1% of maximal HR, whichever is greater.

Mathematical Model

Heart rate threshold (HRT) was assessed using a validated mathematical model (MM) (Petit, Nelson and Rhodes, 1997) that is based upon a logistics function. This model incorporates the natural log of HR data points to produce a curvilinear fit through these points (Appendix A). The first order derivative of the upper portion of the logistic curve is used to find the relevant point of change which represents the HRT/TVENT relationship (Appendix B). Based upon pilot research, the power output approximating 60% of maximal HR satisfies the starting point of the upper portion of the logistic curve for well-trained cyclists (Bodner et al., 1999) and was used as the initial point of derivation. The MM calculated a table of derivatives corresponding to this power output and at every 1 watt increase, respectively. The MM also calculated a specific HR for these power values. The derivative point (DP) of 0.8 was originally validated to represent the HRT in runners (Petit, Nelson and Rhodes, 1997). Pilot research (Bodner, Rhodes and Coutts, 1998) also demonstrated that HR and power values at a DP of 0.8 were significantly related to those at TVENT using cycle ergometry. The DP of 0.8 was therefore used to represent the HRT in this study.

The physiological value of VO₂ at HRT was assessed by interpolation by cross-referencing the HR at HRT to the time course of HR during the incremental test.

Statistical Analysis

Paired t-tests were used to identify any significant differences between at HRHRT and HRTVENT, VO₂HRT and VO₂TVENT and PowerHRT and PowerTVENT. Pearson product-moment zero-
order correlation coefficient demonstrated any significant relationships. Statistical significance was set a priori at \( p < 0.01 \).

**Delimitations**

This study is delimited by:

1. The sample type: male, elite road and off-road cyclists
2. The testing period relative to the cycling training schedule.

**Limitations**

This study is limited by:

1. Data collection capabilities of the Sensormedics Vmax Series 2900 and Polar Heart Rate monitor.
2. Individual metabolic and HR response to exercise protocol.
3. Determination of the ventilatory threshold by visual inspection.
4. Nutritional state: Thorlund, Podolin and Mazzeo (1994) suggested that an alteration in nutritional states (normal and glycogen-depleted) could effect a disparity between HRT and lactate threshold. Controlling for the nutritional state of the subjects was therefore considered a limitation.
5. Homogeneous population of well-trained cyclists.

**Definition of Terms**

For the purpose of clarification, the following definitions and abbreviations were considered appropriate throughout this study:

**Heart Rate Threshold (HRT)** - the shift in slope in HR from its linear trend during incremental increases in workload. This demarcation manifests itself as a decrease in slope in the majority of HRT responses however, in a very small number of cases, an increase in the slope following deflection may also occur (Hofmann et al., 1997). Additionally, a “flattening” response after
deflection with sequential change in slope has also been observed (Maffuli, Sjodin and Ekblom, 1987). Physiological variables of HR, speed, power or VO₂ related to this deflection point further define the HRT.

**Ventilatory Threshold (TVENT)** - defined as a breakpoint in ventilatory variables during incremental exercise that represents a critical work intensity. For this study the excess CO₂ (ExCO₂) elimination curve described TVENT. ExCO₂ is defined as the measure of nonmetabolic CO₂ produced in relation to the amount of non-metabolic O₂ consumed as energy for a given workload.

**Mathematical Model (MM)** - logarithmic application to HR data points derived from incremental cycle ergometry to locate the HRT. The first derivative (0.8) of this log curve describes the HRT-TVENT relationship. See Appendix A and B for a detailed description.
CHAPTER IV
RESULTS AND DISCUSSION

RESULTS

Selected anthropometric, performance and cardiovascular variables of the subjects (N = 21) are presented in Table IV. Mean age (± SD) for the subjects was 26.2 ± 5.6 years and ranged between 18 and 40 years. This encompasses the spectrum of senior, veteran and masters level cyclists in the Canadian Cycling Association. The subjects are defined as well-trained represented by the high VO₂ max. values. The mean absolute oxygen uptake value (mean ± SD) was 5.12 ± 0.52 L · min⁻¹ (range: 4.14 - 5.91 L · min⁻¹) while the relative value was 67.6 ± 4.7 ml · kg · min⁻¹ (range: 57.7 - 75.6 ml · kg · min⁻¹). Mean maximal power output (± SD) was 469.3 ± 42.1 watts (range: 388 - 548 watts). Additionally, the average number of hours (mean ± SD) engaged in on-bike training per week for their particular phase of training cycle was 13.3 ± 2.9 (range: 10-20) and the average number of years involved in competitive racing was 5.4 ± 3.1 (range: 2-15).

Statistical analysis of relevant data is presented in Table VI. Paired t-tests revealed non-significant t-values for HR at HRT (HRHRT) (171.7 ± 9.6 beats · min⁻¹) and HR at TVENT (HRTVENT) (169.8 ± 9.9 beats · min⁻¹) (t₀.₀₁/₂, 20df = 2.17; p > 0.01) and VO₂ at HRT (VO₂HRT) (53.6 ± 4.2 ml · kg · min⁻¹) and VO₂ at TVENT (VO₂TVENT) (52.2 ± 4.8 ml · kg · min⁻¹) (t₀.₀₁/₂, 20df = 1.88; p > 0.01). Power at HRT (PowerHRT) (334.8 ± 36.7 watts) and Power at TVENT (PowerTVENT) (318.7 ± 30.7 watts) were significantly different, however (t₀.₀₁/₂, 20df = -3.15; p < 0.01). All aforementioned scores presented as mean ± SD.

HR, VO₂ and power at HRT represented 89.1%, 79.2% and 67.9% of maximum values, respectively. At TVENT HR, VO₂ and power represented 88.1%, 77.1% and 71.3% of maximum
values, respectively. Individual data for selected physiological variables at HRT and TVENT are represented in Table V.

Pearson product-moment (zero-order) correlation coefficients (Table VII) demonstrated significant relationships for HR_{HRT} - HR_{TVENT} (r = 0.92, p < .001), VO_{2HRT} - VO_{2TVENT} (r = 0.72, p < .001) and Power_{HRT} - Power_{TVENT} (r = 0.77, p < .001) between HRT and TVENT which are illustrated by Figures II, III and IV, respectively. The summary of hypothesis testing is highlighted in Table VIII.
<table>
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<th>Age (yr)</th>
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<th>Weight (kg)</th>
<th>VO$_2$ max. (ml·kg$^{-1}$·min$^{-1}$)</th>
<th>Power$_{\text{MAX}}$ (watts)</th>
<th>HR$_{\text{MAX}}$ (beats · min$^{-1}$)</th>
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<td>60.8</td>
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<td>138.5</td>
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| Mean    | 26.2    | 179.1      | 76.2        | 67.6                            | 469.3                       | 192.7                          | 163.2                          |
| (SD)    | (5.6)   | (6.3)      | (8.2)       | (4.7)                           | (42.1)                      | (8.6)                          | (24.1)                          |
Table V  Selected Physiological Variables at HRT and TVENT

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<tr>
<th>Subject</th>
<th>HRT (beats • min(^{-1}))</th>
<th>TVENT (beats • min(^{-1}))</th>
<th>Power (watts)</th>
<th>VO(_2) (ml • kg • min(^{-1}))</th>
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<td>21</td>
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<td>297</td>
<td>332</td>
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</table>

Mean | 171.7 | 169.8 | 318.7 | 334.8 | 53.6 | 52.2 |
(SD)  | (9.6) | (9.9) | (30.7) | (36.7) | (4.2) | (4.8) |
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<th>HRT</th>
<th>TVENT</th>
<th>p</th>
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</thead>
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<tr>
<td>HR (beats · min⁻¹)</td>
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<td>169.8 ± 9.9</td>
<td>&gt; .01</td>
</tr>
<tr>
<td>VO₂ (ml · kg⁻¹ · min⁻¹)</td>
<td>53.6 ± 4.2</td>
<td>52.2 ± 4.8</td>
<td>&gt; .01</td>
</tr>
<tr>
<td>Power (watts)</td>
<td>318.7 ± 30.7</td>
<td>334.8 ± 36.7</td>
<td>&lt; .01</td>
</tr>
<tr>
<td>Variable</td>
<td>r</td>
<td></td>
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<tr>
<td>---------------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>HR (beats • min⁻¹)</td>
<td>0.92 (p &lt; .001)</td>
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<td></td>
</tr>
<tr>
<td>VO₂ (ml • kg⁻¹ • min⁻¹)</td>
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<td></td>
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<tr>
<td>Power (watts)</td>
<td>0.77 (p &lt; .001)</td>
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</table>
Table VIII  Summary of Hypothesis Testing

Primary

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<th>Dependent Variable</th>
<th>Hypothesis</th>
<th>Result</th>
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<td>HR (beats • min.(^{-1}))</td>
<td>HR_{HRT} = HR_{VENT}</td>
<td>fail to reject null hypothesis</td>
</tr>
<tr>
<td></td>
<td>significant correlation</td>
<td>supported</td>
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Secondary

<table>
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<th>Dependent Variables</th>
<th>Hypothesis</th>
<th>Result</th>
</tr>
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<td>VO(_2) (ml • kg • min(^{-1}))</td>
<td>VO(<em>2)</em>{HRT} = VO(<em>2)</em>{VENT}</td>
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</tr>
<tr>
<td></td>
<td>significant correlation</td>
<td>supported</td>
</tr>
<tr>
<td>Power (watts)</td>
<td>Power_{HRT} = Power_{VENT}</td>
<td>reject null hypothesis</td>
</tr>
<tr>
<td></td>
<td>significant correlation</td>
<td>supported</td>
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</table>
Figure II Correlation between HR at Heart Rate Threshold and HR at Ventilatory Threshold

\[ y = 0.9512x + 6.4761 \]
\[ r = 0.92 \]
Figure III Correlation between VO2 at Heart Rate Threshold and VO2 at Ventilatory Threshold

\[ y = 0.8146x + 8.5398 \]

\[ r = 0.72 \]
Figure IV Correlation between Power at Heart Rate Threshold and Power at Ventilatory Threshold

\[ y = 0.9247x + 40.095 \]

\[ r = 0.77 \]
DISCUSSION

The main purpose of this investigation was to assess the relationship between the HRT and TVENT in male competitive road and off-road cyclists. The physiological variables of HR, VO₂ and power were assessed across these thresholds. The cyclists who participated this study were characterized as either provincial and/or national class according to the Canadian Cycling Association.

High maximal oxygen uptake values (VO₂ max.) (> 65 ml · kg · min⁻¹) characterize the subjects as elite endurance cyclists (Anderson and Rhodes 1991; Coyle et al., 1991; Hoogeveen et al. 1997; Hopkins and McKenzie, 1994; Lopategui et al., 1986; Sjogaard 1984; Wilber et al. 1997). Additionally, these athletes are able to utilize a large fraction of VO₂ max. (80-90%) during prolonged work (Coyle et al., 1991; Hopkins and McKenzie, 1994).

Physiological variables such as VO₂ max. (mean ± SD = 5.12 ± 0.52 L · min⁻¹; 67.6 ± 4.7 ml · kg · min⁻¹) and percent of VO₂ max. utilized at TVENT (77.2%) were comparable with those in the relevant literature for trained cyclists (Coyle et al. 1988; Hopkins and McKenzie, 1994; Lopategui et al. 1986; Wilber et al., 1997). Maximal power output (469.3 ± 42.1 watts) and power output at TVENT (334.8 ± 36.7 watts) were also similar to the findings of relevant investigations (Hawley and Noakes, 1992; Hopkins and McKenzie, 1994; Wilber et al., 1997).

HRT is a testing modality that is purported to assess critical work intensities at TLAC and TVENT (Conconi et al., 1982). Conconi et al. (1982) originally proposed that a deflection in HR during incremental testing was related to these critical work intensities. From a practical point of view, HRT is an attractive threshold assessment method since it is noninvasive and may be conducted in field situations.

Visual analysis of HR-power or speed data can be used to identify a HR deflection point which adds to the feasibility of the method. However, the usefulness of such an acquisition may
be questioned because the divergence from linear to curvilinear trends of HR response occasionally lack distinction. The present study utilized a validated mathematical model (MM) (Petit, Nelson and Rhodes, 1997) that compensates for potentially obscure changes in HR slope and provides an objective assessment of HRT.

HR is considered a useful and reliable variable to monitor exercise intensity (Boulay et al., 1997; Gilman and Wells, 1993; Jeukendrup and Van Diemen, 1998) and the advent of accurate, portable HR monitors allows for easy regulation of cardio-frequency telemetry. This feasibility of HR monitoring in the field has practical ramifications for cyclists. HR at HRT (HR_{HRT}) may be monitored during training to provide an index or parameter by which to mark work intensities close to, above or below TLAC or TVENT. However no published study has assessed the HRT-TV_{VENT} relationship in elite cyclists.

The fitness state of the cyclists in this study is characteristic of the subjects in a large portion of the HRT literature. Highly trained runners were assessed by Conconi et al. (1982) in the original HR deflection investigation and have been assessed in subsequent HRT studies (Jones and Doust, 1995, 1997; Maffuli, Sjodin and Ekblom, 1987; Petit, Nelson and Rhodes, 1997; Tokmakidis and Leger 1988; 1992; Zacharogiannis and Farrally, 1993). Cyclists (Argentieri et al., 1988; Conconi et al., 1988; Droghetti et al., 1985), swimmers (Cellini et al., 1986), rowers (Droghetti 1986), cross-country skiers (Droghetti et al., 1985) canoeists (Droghetti et al., 1985) and kayakers (Hofmann et al., 1994) account for the spectrum of sporting activities of trained athletes involved in HRT investigations. Despite the focus on trained populations, a series of HRT studies have also included untrained populations (Bunc, Heller and Leso, 1988; Bunc et al., 1995; Francis et al., 1989; Hofmann et al., 1994; Hofmann et al., 1994; Kuipers et al., 1988; Pokan et al., 1993; Ribeiro et al., 1985; Thorlund, Podolin and Mazzeo, 1994).
Heart Rate Assessment at Heart Rate Threshold (HRT)

HR is the most pertinent and practical variable for cyclists as it is readily monitored and reflects relative exercise intensity (Dennis and Noakes, 1998). In the elite cyclists assessed, a mean HR of 171.7 ± 9.6 beats • min⁻¹ was observed at HRT. HR_TVENT (169.8 ± 9.9 beats • min⁻¹) was highly related to HR_HRT (r = 0.92, p < 0.001). HR_HRT was greater than HR_TVENT by 1.9 beats • min⁻¹ but these values were not significantly different (p > 0.01). HR_HRT approximated 89.1% of maximal HR (HR_MAX) (range 85.3 - 92.7%) which is consistent with the known literature wherein mean HRT ranges between 88-94% of HR_MAX (Bunc and Heller, 1992; Hofmann et al., 1994d; Kara et al., 1996; Ribeiro et al., 1985; Zacharogiannis and Farrally, 1993). HR_TVENT represented 88.1% of HR_MAX. This value is slightly higher than those reported in trained road, off-road and track cyclists where HR_TVENT ranged between 84.5 - 87% HR_MAX (Craig et al., 1993; Wilber et al., 1997).

The results of this study are supported in the literature. Significant relationships between HR_HRT and HR_TLAC or HR_TVENT with correlation coefficients exceeding r = 0.80 have been reported (Baraldi et al., 1989; Bunc and Heller, 1992; Bunc, Heller and Leso, 1988; Bunc et al., 1995; Gaisl and Hofmann 1990; Hofmann et al., 1994d; Hofmann et al., 1997; Maffuli, Sjodin and Ekblom, 1987; Mahon and Vaccaro, 1991; Ribeiro et al., 1985). Hofmann et al. (1997) reported correlation values of r = 0.89 (p < 0.001) between HR_HRT and HR_TLAC (167 ± 9 and 168 ± 10 beats • min⁻¹, respectively) in 213 male subjects utilizing cycle ergometry. Other cycle ergometry studies by Hofmann et al. (1994a; 1994d) also demonstrated significant relationships between HR_HRT and HR_TLAC (r > 0.85) with no significant differences between HR values. Similar results were obtained by Bunc et al. (1995) where 24 females were assessed for HRT utilizing cycle ergometry. Values reported for HR_HRT and HR_TVENT were 170.8 ± 5.5 and 168.3 ±
4.8 beats • min\(^{-1}\) respectively. These values were also significantly related (r = 0.81) and not significantly different.

In terms of steady state cycling, HR\(_{HRT}\) in trained cyclists (168.7 ± 6.9 beats • min\(^{-1}\)) was related to but not significantly different from HR\(_{TVENT}\) at the ten (164.3 ± 10.4 beats • min\(^{-1}\); r = 0.817, p < 0.05) and fifteen minute (166.4 ± 11.9 beats • min\(^{-1}\); r = 0.796, p < 0.05) intervals during twenty minute cycle ergometry at a power output equivalent to that at TVENT (Bodner et al., 1999).

Studies involving trained runners have also demonstrated relationships in HR values at HRT and TVENT. Petit, Nelson and Rhodes (1997) observed that HR\(_{HRT}\) and HR\(_{TVENT}\) were significantly related (r = 0.79, p < 0.01) but not significantly different (178 ± 7.7 and 180 ± 9.9 beats • min\(^{-1}\), respectively). Similar results were obtained by Bunc, Heller and Leso (1988) between HR\(_{HRT}\) and HR\(_{TVENT}\) (177.0 ± 6.0 and 176.0 ± 6.0 beats • min\(^{-1}\), respectively) (r = 0.93; p < 0.01) in trained runners.

However, not all HRT studies have shown high relationships and agreement at HRT. Jones and Doust (1997) observed that HR\(_{HRT}\) overestimated HR\(_{TLAC}\) by 14 beats • min\(^{-1}\) when assessed by visual analysis. This disparity between HR\(_{HRT}\) and HR\(_{TLAC}\) may be partially explained by the methods used to acquire HR deflection. Conconi et al. (1982) originally reported that the deflection in HR could be assessed by visual inspection. However, studies that support HRT validity rely upon investigators who have experience determining HR breakpoints (Ballarin et al., 1996). It has been recently suggested that analysis of HRT is best carried out by experienced observers (Ballarin et al., 1996) since inexpert observers may be prone to error. Additionally, there are no established criteria for visual analysis of HR deflection aside from the fact that the change in slope in the HR-power/speed relationship occurs at some point.
It is possible that the most obvious point of deflection to the untrained eye might be the beginning of the plateau in maximum HR. This possibly occurred in the study of Jones and Doust (1997) wherein independent observers were assigned to identify the HRT, with the first clear departure in HR from a linear trend given as a criterion. This drastic overestimation of HRT would also explain why their trained runners were unable to complete a thirty minute steady state running test at an intensity just below that derived from HRT.

Tokmakidis and Leger (1992) also reported that $\text{HR}_{\text{HRT}}$ was greater than $\text{HR}_{\text{TLAC}}$ by approximately 12 beats · min$^{-1}$. In this case, methodological differences determining TLAC may have attributed to disparities between $\text{HR}_{\text{HRT}}$ and $\text{HR}_{\text{TLAC}}$. In their study, Tokamakidis and Leger (1992) used the first significant increase in blood lactate to indicate TLAC. However, Hofmann et al. (1994; 1997) report that HRT occurs between the first rise in blood lactate concentration above resting levels and the final maximal power value attained. Specifically, the point of deflection is very near the second abrupt rise in blood lactate or the second lactate turnpoint (LTP$_2$) (Davis et al., 1983, Skinner and Mclellan, 1980). Both Tokmakidis and Leger (1992) and Hofmann et al. (1997) used linear regression breakpoint analysis to locate HRT. However, Hofmann et al. (1997) began their regression analysis at the point of initial rise in blood lactate whereas Tokmakidis and Leger (1992) incorporated all HR data points. This, according to Hofmann et al. (1997) might lead to exceptionally high HRT values due to the nature of linear regression.

Zacharogiannis and Farrally (1993) reported a significant relationship between $\text{HR}_{\text{HRT}}$ and $\text{HR}_{\text{TVENT}}$ when expressed as %HR$_{\text{MAX}}$ in runners ($r = 0.70$, $p < 0.01$) during treadmill testing. However, the mean values were significantly different (172 ± 13 and 161 ± 12 beats · min$^{-1}$, respectively) with $\text{HR}_{\text{HRT}}$ overestimating $\text{HR}_{\text{TVENT}}$ by 11 beats · min$^{-1}$. In this case it is possible that the treadmill protocol may have affected the HRT-TVENT relationship. Running speed was
increased by 1 km·h⁻¹ every three minutes which is dissimilar to other treadmill protocols whereby running speed is increased every minute. These longer stages procured a prolonged testing time that ranged from 30-45 minutes. Since HR was averaged during the last minute of each three minute stage, it is conceivable that an upward drift in HR (Kindermann, 1979) may have increased overall the HR values reported at the deflection points.

**Oxygen Consumption (VO₂) at the Heart Rate Threshold (HRT)**

The present study demonstrated that oxygen uptake values at HRT and TVENT were significantly related (r = 0.72, p < 0.001). VO₂ at HRT and TVENT are significantly related in both treadmill and cycle ergometry studies. Bunc and Heller (1992) reported relationships between VO₂₇HRT and VO₂₇TVENT of r = 0.71, (p < 0.001) and r = 0.72, (p < 0.001) in healthy untrained middle-aged men. These correlations are consistent with the results of the present study. The literature reports correlations between VO₂₇HRT and VO₂₇TVENT ranging from 0.71 - 0.95 (Bunc and Heller, 1992; Mahon and Vaccaro, 1991; Zacharogiannis and Farrally, 1993; Bunc et al., 1995; Bunc, Heller and Leso, 1988).

The findings of Hofmann et al. (1994a) show that continuous cycling at an intensity equivalent to Power₇HRT minus 10% demonstrates that VO₂ appears to reach steady state values that are slightly below VO₂₇HRT. However, at Power₇HRT plus 10%, VO₂ values increase steadily, approaching VO₂ max. In trained cyclists, steady state cycling at Power₇TVENT demonstrate VO₂ values that are related to but not significantly different from VO₂₇HRT at the ten (r = 0.819, p < .05) and fifteen minute (r = 0.872, p < .05) time intervals (Bodner et al., 1999).

There were no significant differences between VO₂₇HRT and VO₂₇TVENT in the present study. The findings of Bunc et al. (1995) and Bunc Heller and Leso (1988) also demonstrate non-significant differences in VO₂ values between HRT and TVENT. However, Zacharogiannis and Farrally (1993) reported that VO₂ at HRT was significantly greater (p < 0.01) than that at TVENT.
(42.42 ± 3.81 and 45.29 ± 3.99 ml • kg • min⁻¹, respectively) despite a significant correlation (r = 0.92) between the two variables. Jones and Doust (1997) calculated VO₂ values of approximately 93% of VO₂ peak at HR deflection.

The reason for these greater VO₂ values at HRT is most likely due to the fact that VO₂ values are assessed by interpolation, and are therefore dependent upon the time of the HR breakway. As described in the previous section, an overestimation of HRT relative to TVENT or TLAC possibly due to protocol or visual analysis would necessitate a concurrent overestimation of oxygen uptake values.

The present study showed that the cyclists exhibited a mean oxygen uptake value at HRT (53.6 ± 4.2 ml • kg • min⁻¹) that was equivalent to 79.2% of VO₂ max. The literature indicates that VO₂ values at HRT demonstrate a wider scope of % max values unlike HR_HRT which appears to be confined to a narrow range approximating 90% HR_MAX (Hofmann et al., 1997). Percentages of VO₂ max. at HRT range from 59.2% to 85.9% (Bunc et al., 1995; Bunc, Heller and Leso, 1988; Kara et al., 1996; Maffuli et al., 1987; Thorlund, Podolin and Mazzeo, 1994; Zacharogiannis 1993). Generally, this extent is consistent with the relative training status of the subjects tested. The trained cyclists in this study displayed higher %VO₂ max. values at HRT similar to those in highly trained runners of Maffuli, Sjodin and Ekblom (1987) (78.5% VO₂ max.) Zacharogiannis and Farrally, (1993) (83.9% VO₂ max.) and Bunc, Heller and Leso (1988) (85.9% VO₂ max.).

Lower % VO₂ max. values at HRT characterize untrained male subjects (67.4 - 68.5%) (Bunc and Heller, 1992; Bunc, Heller and Leso, 1988) with the lowest values pertaining to middle-aged men. Similarly, Kara et al. (1996) reported that in untrained males oxygen consumption at HRT averaged between 71.2 to 73.9% VO₂ max. Untrained female subjects elicited HRT ranging from 70.3% (Hofmann et al., 1994a) to 72.2% of VO₂ max. (Bunc et al.,
1995) and physically active young men in the study of Thorlund, Podolin and Mazzeo averaged only 59.2% of VO\textsubscript{2} max. at HRT.

**Power Output at the Heart Rate Threshold (HRT)**

Power output in cycling is the most direct indicator of exercise intensity (Jeukendrup and Van Diemen 1998). Loat and Rhodes (1996) have demonstrated in trained cyclists that power output at T\text{VENT} appears to assess work intensities that may be maintained for at least one hour. For the purposes of this study the power value at HRT (Power\textsubscript{HRT}) was assessed as a legitimate variable for HRT validation.

In the present study, the mean Power\textsubscript{HRT} (318.7 ± 30.7 watts) was equivalent to 67.9% of maximal power (Power\text{MAX}) values. This percentage is similar to but slightly less than the values reported in other HRT investigations. Power\text{HRT} in those studies ranged from 71.0 - 74.9% of Power\text{MAX} (Bunc et al., 1995; Bunc and Heller, 1992; Hofmann et al., 1994\textsuperscript{d}; Hofmann et al., 1997). All of these investigations incorporated healthy, but not endurance-trained subjects and this was demonstrated by the smaller mean Power\textsubscript{HRT} values (range: 158 - 227 watts).

In the cyclists studied a significant correlation (r = 0.77, p < 0.001) was observed between Power\textsubscript{HRT} and Power at T\text{VENT} (Power\text{TV\text{VENT}}). This relationship is supported in the literature. Bunc and Heller (1992) reported HRT-T\text{VENT} power relationships in younger (r = 0.70) and older (r = 0.73) middle-aged men. Correlation coefficients (r's) of greater than 0.90 have been reported for power variables between HRT and T\text{VENT} (Bunc, Heller and Leso, 1988) or TL\text{AC} (Bunc et al., 1995; Hofmann et al., 1994\textsuperscript{d}; Hofmann et al., 1997; Ribeiro et al., 1985). In each of the aforementioned investigations no significant differences were observed between Power\textsubscript{HRT} and Power\text{TV\text{VENT}} or Power\text{TL\text{AC}}.

However, the present study demonstrated a significant difference (p < 0.01) between Power\textsubscript{HRT} and Power\text{TV\text{VENT}} (334.8 ± 36.7 watts). HRT underestimated T\text{VENT} by 16.1 ± 23.4
watts. Pilot work also demonstrated that Power\textsuperscript{TVENT} was underestimated by approximately 14 watts by the MM derived HRT during cycle ergometry in trained male subjects (Bodner, Rhodes and Coutts, 1998). The methodological procedures used to assess HRT and T\textsubscript{VENT} may explain the significant difference between Power\textsubscript{HRT} and Power\textsubscript{TVENT} in the present study. Visual inspection of T\textsubscript{VENT} requires that the physiological variables of HR, power and VO\textsubscript{2} be assessed by interpolation based on the time of ventilatory breakaway. These values are reported every twenty seconds (metabolic cart protocol). The result is a specific value for HR and power at T\textsubscript{VENT}. The MM on the other hand, indexes a linear increase in power to HR data that is fit to a logistic growth curve. The logistic curve characterizes HR such that it increases at an increasing rate and then increases at a decreasing rate. MM-generated HR values will therefore increase at a decreasing rate at or near the deflection point while power continues to increase linearly. Since the MM indexes power values at one watt intervals, this procures a larger range of power values distributed over very small increases in HR. Therefore, HR values at HRT and T\textsubscript{VENT} may be relatively close, but power outputs at these thresholds may exhibit a greater degree of variability due to the nature of the MM. This might account for the larger overall disparity between Power\textsubscript{HRT} and Power\textsubscript{TVENT} but explain the smaller, non-significant difference between HR\textsubscript{HRT} and HR\textsubscript{TVENT}.

One other study has demonstrated a significant difference between power values at HRT and T\textsubscript{LAC}. Kuipers et al., (1988) reported a deflection in 6 of 13 subjects during cycle ergometry. Of the 6 subjects who displayed a HR breakpoint, power outputs at HRT (286 ± 32 watts) were approximately 36 watts greater than those at a fixed blood lactate value of 4 mmol \cdot L\textsuperscript{-1} (250 ± 51 watts). The reason for this disparity is again related to the application of linear regression and visual analysis to locate the HR breakpoint. The characteristics of the HR response must be taken into consideration if linear regression is used to clarify the HRT (Hofmann et al., 1997). If the
regression line includes the initial stochastic response of HR characteristic of low work intensities (Brooke and Hamley, 1972) then this will affect the slope of the regression line, possibly leading to an overestimation of the HR breakpoint. Graphical data presented by Kuipers et al. (1988) suggests that the HRT was overestimated because the initial start in the plateau of maximal HR was identified as the HRT. Since power values at HRT are assessed by interpolation, this would explain the disparity between HRT and TLAC.

**Physiological Mechanisms of Heart Rate Deflection**

The physiological mechanisms that characterize the HRT phenomenon remain unresolved. Conconi et al. (1982) originally hypothesized that the deflection in HR was partially representative of an increased reliance on anaerobic glycolytic pathways. During progressive testing, power/speed and VO\textsubscript{2} increase in a linear manner; however, HR appears to lag behind, manifesting itself as a deflection in HR. The “extra” ATP necessary to generate power production during the latter stages of incremental work originates from the augmentation of anaerobic lactacid mechanisms that coincide with the HR breakpoint. Oxygen consumption, however, continues to increase at a rate higher than that for HR and cardiac output (Conconi et al., 1982) possibly due to a rightward shift in the oxyhaemoglobin dissociation curve as a result of increased lactic acid concentrations (Conconi et al., 1996).

The HR deflection phenomenon is perceived by some to be a normal physiological variation in the control of cardiac output during progressive intensity testing (Hofmann et al., 1997). Pokan et al. (1993) acknowledged a significant correlation ($r = -0.67$, $p < 0.01$) between the HR deflection point and augmented myocardial function expressed as the left ventricular ejection fraction (LVEF). Individuals exhibiting these breakpoints in HR demonstrated less of a drop in LVEF beyond TLAC than individuals who were characterized as having a more linear response in HR. Furthermore, significant relationships were observed between LVEF breakpoints
and HR at TLAC (HR_{TLAC}) \( (r = 0.69, p < 0.05) \) and between HR_{TLAC} and HR_{HRT} \( (r = 0.85, p < 0.01) \). These results do not imply cause and effect, however. Further research is warranted for mechanisms of HR deflection.

**Methodological Considerations**

The original HRT protocol (Conconi et al., 1982) required increases in work intensity based upon distance rather than time. This methodology is criticized by some who suggest that a deflection in HR may be an artifact of the protocol (Jeukendrup et al., 1997). However, several investigations report the HR deflection phenomenon during fixed stage incremental work (Bunc et al., 1995; Gaisl and Hofmann, 1990; Gaisl and Weisspeiner, 1987; Hofmann et al., 1994c; Hofmann et al., 1994d; Pokan et al., 1993; Pokan et al., 1995; Ribeiro et al., 1985). This suggests that HRT may not be protocol-dependent. A ramped cycling protocol was selected for this study based on the reasoning that HR deflection may not be an artifact of protocol, but rather a biological occurrence. Thus, if there is a physiological basis for HR deflection, HR slope changes should also materialize during ramped work.

Successful HRT evaluation requires an increase in HR of no more than eight beats \( \cdot \) min\(^{-1}\) with a HR-work linear relationship of \( r \geq 0.98 \) (Conconi et al., 1996). This criterion is founded on time-based cardioacceleration and may represent work intensity increases that allow sufficient time for the cardiovascular system to adapt (Conconi et al., 1997). Pilot research demonstrated that ramped cycle ergometry with work intensity increases of 30 W \( \cdot \) min\(^{-1}\) satisfies this criteria (Bodner, Rhodes and Coutts, 1998). A ramped protocol is attractive for subjects since it allows for self-selection of cadence during increases in work intensity and accommodates an individualized adaptation to increased workloads.

The present study analyzed \( \text{TVENT} \) and HRT simultaneously, a procedure followed by the majority of HRT investigations (Baraldi et al., 1989; Bunc et al., 1995; Bunc and Heller, 1992;
Bunc, Heller and Leso, 1988; Francis et al., 1989; Hofmann et al., 1994; Hofmann et al., 1994; Hofmann et al., 1997; Kara et al., 1996; Nikolaizik et al., 1998; Pokan et al., 1993; Pokan et al., 1995; Ribeiro et al., 1985). Droghetti et al. (1985) and Conconi et al. (1988) used an unconventional lactate threshold protocol wherein a discontinuous assessment of blood lactate profiles were obtained at predetermined cycling speeds above and below the speed at HRT to identify the lactate threshold.

**HRT Reproducibility: Models of Depiction and Implications**

The present study utilized an objective mathematical model (MM) to assess HRT. This model incorporates a logistic function fit to the HR-power data to describe the curvilinear nature of the HR-work response in a mathematical configuration. The MM adds to the practicality of HRT testing in that it provides an objective evaluation of the HRT and consistently provides a value for HRT.

Disparate results within the literature concerning HRT acquisition have been attributed to methodological divergence used to identify the deflection point. Subjective determinations of HRT used in conjunction with various threshold concepts (i.e. \( T_{VENT} \) and \( T_{LAC} \)) may be the cause for contradictory HRT results.

Historically, visual inspection of the HR deflection point was used by Conconi et al. (1982) to elucidate HRT with apparent success and is one of the practical cornerstones of this testing modality. Visual inspection is still an accepted method of analysis, is widely used in HRT investigations (Ballerin et al., 1989; Cellini et al., 1986; Conconi et al., 1982; Conconi et al., 1988; Droghetti et al., 1985; Droghetti, 1986; Gaisl and Weisspeiner, 1987; Jones and Doust, 1997; Mahon and Vaccaro, 1991; Nikolaizik et al., 1998; Ribeiro et al., 1985; Thorlund, Podolin and Mazzeo, 1994; Tokmakidis and Leger, 1988), and is purported to be as accurate as computer-determined results if experienced observers render judgement (Ballarin et al., 1996).
There are limitations to this method however, especially when clear demarcations in HRT are not readily apparent. In such instances, accurate evaluations of HRT may necessitate either expert observers or mathematical analysis (Ballarin et al., 1996). The MM used in the present study however, extends the practical nature of HRT such that HRT assessments may be utilized by coaches or athletes who lack the expertise locating deflection in HR.

Previous research indicates that this MM is capable of characterizing the HRT (Petit, Nelson and Rhodes, 1997). The reliability of this model has also been substantiated. Pilot data utilizing cycle ergometry revealed that HRT derived from the MM is reproducible for HR (r = 0.84, p < 0.01) and power (r = 0.95, p < 0.001) across repeated testing (Bodner, Rhodes and Coutts, 1998). Objectivity is the strength of this MM to assess HRT since HRT information is retrieved from the mathematical analysis and not from visual graphical interpretation.

Linear regression models have been used to help with HRT assessment (de Wit et al., 1997; Francis et al., 1989; Kuipers et al., 1988; Tokmakidis and Leger, 1992) which may allow for greater clarity in the discernment of the HR breakpoint. However, in cases where the dissociation between linear and curvilinear aspects of HR-power relationships are indistinct or where the entire HR response is characterized by a curvilinear mien, linear regression may be an ineffective method to discern the demarcation in HR slope shift (Francis et al., 1989; Kuipers et al., 1988). Two-part discontinuous linear regression models can, however, can be utilized for curvilinear HR responses and have successfully discriminated the HR deflection point (Bunc et al., 1995; Bunc and Heller, 1992; Bunc, Heller and Leso, 1988; Hofmann et al., 1994a; Hofmann et al., 1994d; Jones and Doust, 1995). Kara et al. (1996) have accounted for the curvilinear nature of the HR response by applying a third order curvilinear regression curve to the HR-power data and reported successful HRT assessments.
Linear responses to incremental protocol have been observed but do not appear to be commonplace (Hofmann et al., 1997). However, linear responses may limit the universal application of HRT. Regression modeling of HRT may not be able to discriminate a HR breakpoint if the HR curve appears to be linear. The MM however, can compensate for linear responses such that it will produce a value for HRT based upon the logistic transformation of the HR-power-speed data. However, it is unclear to what extent linear HR responses limit the MM.

**Heart Rate Threshold: Implications for Cycling Training**

The present study involved elite cyclists and demonstrated significant relationships between HR, VO$_2$ and power between HRT and $T_{VENT}$. The relationships between $HR_{HRT}$ and $HR_{TVENT}$ observed in this study do not imply cause and effect. In terms of practical application however, HRT may provide an index of work intensity that closely approximates that at $T_{VENT}$. The MM provides a rapid, simple, objective means by which to evaluate HRT from progressive intensity testing. Since the testing time for HRT evaluation ranges from fifteen to twenty minutes, HRT assessments may be incorporated into the weekly training regimen of the cyclist.

Comparing the results of this study to other HRT research using trained cyclists as subjects is an arduous, if not impossible task. The reason for this is that the data available concerning HRT in elite cyclists is scant and investigations have occurred in field settings using a cycling track (velodrome) (Droghetti et al, 1985; Conconi et al., 1988$^b$) or outdoor, uphill segments (Conconi et al., 1988$^b$). Results have been reported in terms of speeds at HRT rather than $HR_{HRT}$. However, where speed variables have been reported, significant relationships are observed between speed at HRT and average cycling speeds for selected events. Cycling speed at HRT was highly related to ($r = 0.99, n = 6$) the average speed maintained during a one hour time trial (Conconi et al., 1988$^b$).
HRT acquisition using the Conconi et al. (1988b) method necessitates a cycling track or velodrome to increase cycling speed. HR is highly correlated to cycling speed (Boulay, 1995) but is not as reliable as power to assess exercise intensity since terrain and environmental conditions (i.e. hills, prevailing winds) influence speed resolutions (Jeukendrup et al., 1998). Therefore HRT speed variables on a velodrome are limited to flat terrain and will vary accordingly, depending upon environmental conditions, most notably windspeed.

However, HR_{HRT} values can be assessed utilizing cycling speed and may be used in training prescription (Conconi et al., 1988b). Cyclists without access to a velodrome, however will be disadvantaged. Hills of sufficient length ($\geq 1.8$ km) with a constant grade are also successful implements for HRT assessment (Conconi et al., 1988b). A more viable and possibly practical HRT method incorporates the use of a cycling windload trainer (Argentieri et al., 1988). A windload trainer is a device upon which cyclists attach their bicycles. Resistance is applied using either fans (air resistance) or magnetic braking. These devices are common among cyclists because they provide a training venue during inclement winter weather. Argentieri et al. (1988) reported no significant differences between cycling speeds at HRT and those derived at end-tidal oxygen breakaways ($r = .99$) when HRT was assessed using a windload trainer.

HRT demonstrates variability under conditions of glycogen depletion or dehydration (Maffuli, Sjodin and Ekblom, 1987; Thorlund, Podolin and Mazzeo, 1994; Conconi et al., 1997). While this has been construed by some as evidence to invalidate HRT (Thorlund, Podolin and Mazzeo, 1994), others have suggested that this type of variability should be expected and may be used to identify changes in nutritional status (Conconi et al., 1997), pathologic or environmental alterations (Ballarin et al., 1996) across training time courses. However, this is primarily hypothetical speculation at this point since there have been no published investigations on the effects of training, environment or pathology on HRT.
In summary, the analysis of this study demonstrates that the selected physiological variables of HR, VO₂ and power at HRT derived by an objective MM are significantly correlated to those at TVENT. This study of 21 well-trained endurance cyclists demonstrated no significant differences between HRT and TVENT for HR and VO₂. However, a significant difference for power was observed. Further research is required to assess and compare selected physiological variables at HRT derived from incremental testing to steady state work or performance in cyclists.
CHAPTER V

SUMMARY AND CONCLUSIONS

SUMMARY

Conconi et al. (1982) were the first researchers to develop a noninvasive test utilizing HR alone as a modality to assess TLAC. These investigators observed a decrease in the change in slope of HR during a progressive running field test. This slope differentiation exhibited appeared to coincide with TLAC. Running velocities at this HR deflection point were highly related to average speeds during endurance races (r > 0.90). These data were interpreted to validate this "heart rate threshold" (HRT) as a noninvasive method to identify critical work intensities.

Subsequent investigations have lead to equivocal results in terms of the validity of HRT. Methodological differences have accentuated these disparities with the central problem being the accurate assessment of the deflection in HR.

Mathematical analysis of the HR response during incremental exercise has helped with HRT assessment. Recently a mathematical model (MM) has been developed to objectively assess the HRT (Petit, Nelson and Rhodes, 1997). The present study incorporated this MM to assess the HRT in elite cyclists and to compare the physiological variables of HR, VO₂ and power to those at ventilatory threshold (TVENT).

Twenty-one competitive, highly-trained road or endurance off-road cyclists (mean age 26.2 years) with a mean VO₂ max. of 67.6 ml · kg · min⁻¹ participated in one graded cycle ergometer test to assess both the HRT and TVENT. TVENT was assessed using the excess CO₂ elimination curve and the HRT was determined using a MM that incorporated a logistic function fit to the HR-power data. HR, VO₂ and power at TVENT were assessed by interpolation to ventilatory breakpoint. HR and power variables were calculated by the MM for HRT, however VO₂ values at HRT were assessed by interpolation to the HRHRT.
Statistical analysis using paired t-tests and Pearson product-moment zero order correlation coefficients demonstrated significant relationships between HRT and T\text{VENT} for the selected variables of HR, VO\textsubscript{2} and power. There were no significant differences between HRT and T\text{VENT} for HR or VO\textsubscript{2}. However, Power\textsubscript{HRT} and Power\textsubscript{T\text{VENT}} were significantly different.

The relationship between HRT and T\text{VENT} does not necessitate cause-and-effect. However, this coincidental relationship in terms of HR variables may be have practical applications for cyclists such that HR may be used as an training index to identify critical work intensities.

**CONCLUSIONS**

1. There were no significant differences between HRT and T\text{VENT} for the variables of HR and VO\textsubscript{2} (p > .01)

2. Power values at HRT and T\text{VENT} were significantly different (p < .01)

3. Significant relationships were observed between HRT and T\text{VENT} for the variables of HR (r = 0.92, p < .001), VO\textsubscript{2} (r = 0.72, p < .001) and power (r = 0.77, p < .001).

**RECOMMENDATIONS**

1. Additional validation studies with the MM:
   a.) prolonged work using power outputs generated at HRT by the MM
   b.) application of the MM to other endurance sports (rowing, cross-country skiing, swimming, etc.)

2. The relationship between physiological variables at HRT derived by incremental testing and those during steady state cycling performances have not been thoroughly investigated. In particular, the influence of cardiovascular drift on HR values at HRT is worthy of investigation.
3. The use of a cycle windload trainer to assess HRT produces methodological challenges that need to be addressed. The comparison and analysis of HRT derived from windload trainer to cycle ergometry will enhance the applicability of HRT in the field.

4. Longitudinal studies that involve the effect of training and competition on HRT have not been researched.

5. The reproducibility of HRT (i.e. multiple within-subject HRT investigations) requires further study.

6. Influence of cycling cadence upon HR has yet to be addressed. This has important implications for HRT protocol.

7. Physiological mechanisms of HR deflection are not fully understood and require further investigation.
BIBLIOGRAPHY


Fitting a Logistic Growth Curve to the Heart Rate - Power Output Data from Graded Cycle Ergometry

The heart rate - power output data from graded cycle ergometry are fit to a logistic growth curve to allow for more objective analysis. This is accomplished with the following logistic growth function:

\[ y = \frac{1}{ab^x + c} \]

For analysis of the heart rate - power output data the logistic function must be transferred into its linear form. The following steps accomplish this:

1. In terms of the heart rate \(H\) at a given power output \(w\), the logistic growth function is computed as:

\[ H_w = \frac{1}{ab^w + 1/m} \]

\(m = \text{maximum heart rate}\)

2. The non-linear logistic growth function is transferred to a linear format:

\[ \frac{1}{H_w} - \frac{1}{m} = ab^w \]

3. The logarithms of each side of the equation are calculated:

\[ \ln \left( \frac{1}{H_w} - \frac{1}{m} \right) = \ln a + (\ln b) w \]

4. This linear format of the logistic growth curve can now be used in a regression of the converted heart rate - power output data from graded cycle ergometry. Calculation of the intercept \(a\) and the slope \(b\) are as follows:

\[ H'_w = a' + b' w \]

where \(H'_w = \ln \left( \frac{1}{H_w} - \frac{1}{m} \right)\); \(a' = \ln a\); \(b' = \ln b\)

5. A linear regression solves for \(a'\) and \(b'\) which are used to estimate \(H'_w\). With a natural log estimate, \(H'_w\) and a known maximal heart rate \(m\), a value for the heart rate at a given power output (watts) can be calculated:

\[ H_w = \frac{1}{\text{exponent} (H'_w) + 1/m} \]
Appendix B

Transformation of the Heart Rate Logistic Curve to a Heart Rate Derivative Curve

The heart rate derivative curve is derived using the following function:

$$\frac{((H_x - H_{x-1}) / (H_o - H_f))}{((W_x - W_{x-1}) / (W_o - W_f))}$$

- \(W\) = power output (watts)
- \(H\) = heart rate
- \(x\) = the point on the curve of the current derivation
- \(o\) = the first point of derivation (130 Watts)
- \(f\) = final point of derivation (maximal power output in exercise test)

Point \(f\) corresponds to the subjects maximal power output achieved during incremental cycle ergometry. Pilot research using a ramped cycling protocol identified this initial point of derivation as 130 watts for well-trained cyclists. The first point of derivation, \(o\) remained constant between subjects for this study (Petit, Nelson and Rhodes, 1997).