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We sought to identify whether the accumulation of metabolites in exercising muscle was associated with the ventilatory (VT) and heart rate thresholds (HRT). Subjects performed two incremental workload cycling exercise tests to maximal effort: 1) without intervention (CON) and 2) with leg venous occlusion cuffs inflated to 90 mmHg (CUF). Breath-by-breath measures of ventilation, expired respiratory gases and beat-to-beat heart rate were collected. VT and HRT were identified using mathematical techniques for the detection of thresholds. The VO_2 of the VT and HRT were not significantly different at $p<0.05$ and were strongly correlated in both CON ($r= 0.84$) and CUF ($r=0.83$). These data suggest that the accumulation of intramuscular metabolites provides a stimulus to increase ventilation and heart rate.

VENTILATORY AND HEART RATE RESPONSES

TO INCREMENTAL EXERCISE WITH AND

WITHOUT VENOUS OCCLUSION

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THESIS

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
ABP	Arterial Blood Pressure
CON	Control
CUFF	Cuff
ECG	Electrocardiogram
ET	Exercise-Trained
HR	Heart Rate
HRT	Heart Rate Threshold
LT	Lactate Threshold
MAP	Mean Arterial Pressure
min	Minutes
mmHg	Millimeters of Mercury
NET	Non-Exercise-Trained
RPE	Rate of Perceived Exertion
Sec	seconds
VT	Ventilatory Threshold

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CHAPTER I

INTRODUCTION

For many years the use of threshold detection of ventilation and blood lactate during exercise has been used to identify intracellular imbalances between metabolic energy production and the clearance of metabolites. At the blood lactate threshold (3) there appears to be an imbalance between intracellular lactate production and clearance mechanisms, such that an efflux into the blood of the excess intracellular lactate occurs (11, 5). Subsequently, bicarbonate buffering of blood lactate produces carbonic acid and excess carbon dioxide, which results in a hyperventilatory response to rid the body of excess acid. This response is identified as the ventilatory threshold (VT). Recently, Smith et al. (10) has demonstrated that an intramuscular stimulus for ventilation exists and appears to be linked to the VT. At the time of the efflux of lactate into the blood, identified as the lactate threshold (LT), intracellular metabolic acidosis with increasing workloads is present. This LT has been used as a marker of the onset of muscular fatigue, a concept which has recently been challenged (3). The close association between the LT and the VT was identified by Wasserman et al. (13) using serial blood sampling for the LT and a mathematical detection of acute changes in breath-by-breath ventilatory variables for the identification of the VT. Numerous verifications of the VT being

associated with metabolic acidosis of exercise have been made using a number of differing mathematical detection techniques for the detection of a threshold of associated respiratory variables (13).

However, it is well established that within the working muscle both mechano- and metabo- receptors function to provide neural feedback to the cardiovascular control center (ventro-lateral medulla) as to the adequacy of the oxygen delivered by the circulation to meet the metabolic demand of the muscle (8,9,12). Indeed, increases in metabolic acidosis within the exercising muscle have been directly associated with sympathetic activation (6, 7). Hence, it would be expected that intracellular acidosis would produce a disproportionate increase (threshold) in heart rate and blood pressure. However, the search for a mathematical technique to identify a heart rate threshold (HRT) has been inconclusive. Recently, investigators identified that the accumulation of metabolites within the working muscle and the subsequent activation of the metaboreceptors appeared to selectively activate the ventilatory response without affecting the cardiovascular responses (10, 14). However, a mathematical examination of the heart rate response rates prior to and following the VT was not used (4, 10). Furthermore, a beat-by-beat examination of the arterial blood pressure response to progressive exercise workloads with and without 90mmHG leg cuff occlusion was unable to consistently identify a threshold of mean arterial pressure (4). In contrast, when producing a severe muscle ischemia in the hind limb of exercising dogs, using terminal aortic occlusion, a marked hypertension was observed (9). Hence, the presence of a HRT or a mean arterial pressure (MAP) threshold occurring at the same time as the VT remains a question to be addressed.

Based upon the association between intramuscular acidosis, VT, LT and sympathetic activation, we hypothesized the presence of a HRT. In preliminary work Wyatt (15), using meta-analysis of a number of investigations reported an association between the HRT and the VT using a logarithmic regression analysis technique for HRT detection. Therefore, the goal of the present investigation was to determine the association between the HRT and VT using mathematical detection techniques and to demonstrate the close association between the two thresholds using a cuff inflation technique to produce a discrete onset of the VT and HRT linked to the accumulation of intramuscular metabolites in direct relation to oxygen uptake (VO_2) (1, 2, 4, 8, 10). By using the cuff inflation technique of Smith et al. (12) we propose to trap intramuscular metabolites during progressive load bicycle exercise to a maximal effort and thereby produce a physiological relocation of the HRT and VT to occur at a lower oxygen uptake.

Statement of the Problem

The problem of the study was to determine whether the accumulation of metabolites in exercising muscle is associated with the ventilatory and heart rate thresholds.

Purpose and Objective of the Study

The purpose of this investigation was to further elucidate mechanism of the heart rate threshold. To accomplish this, the following objectives were proposed: (i) To identify the occurrence of a heart rate threshold. (ii) To determine the association between the heart rate threshold and the ventilatory threshold.

Hypotheses

The following two-part hypothesis was proposed: (i) The presence of the heart rate threshold will be consistently identifiable. (ii) This heart rate threshold will be directly related to the ventilatory threshold.

Definition of Terms

1. Heart Rate Threshold- Initially, during a progressive workload exercise test, the heart rate will increase linearly with increments in work rate. Eventually, however, there will occur a workload rate which HR abruptly increases. This is termed the heart rate threshold (4).
2. Ventilatory Threshold- Initially, during a progressive workload exercise test, the rate of pulmonary minute ventilation (VE) will increase linearly with increments in work rate. Eventually, however, there will occur a workload rate which VE abruptly increases. This is termed the ventilatory threshold (4).

Delimitations

Factors were incorporated into the experimental protocol to reduce the number of uncontrolled variables in attempt to maintain feasibility and reliability of the data collected and thus obtain meaningful results:

1. Twenty-four subjects (21 men and 3 women) between the ages of 18-35 years were asked to volunteer for the study and were screened prior to being accepted.
2. The room temperature was held at approximately 24°C during all experimental trials.

3. The exercise testing occurred on the same piece of equipment for each trial in the same semi-recumbent position.
4. The test trials that were conducted on any given day were randomly assigned.
5. The subjects were asked to abstain from the consumption of any stimulants on the day of testing. The subjects were also asked to abstain from alcohol consumption or strenuous physical activity for 24hours prior to testing.

Limitations

1. It was possible that the subjects were not compliant to the suggestions made about substance consumption and physical activity prior to the experiment. This may have affected the reliability of the data collected.
2. The exercise tests were terminated when the subjects reached volitional fatigue. This may have been dependent on the subjects' desire to exercise under strenuous conditions and could have varied depending on psychological (i.e. mood, etc.) and physiological (i.e. nutrition, level of rest, etc.) factors.

CHAPTER II

REVIEW OF RELATED LITERATURE

To an athlete, training is everything. Therefore, making the most of every training session is a very high priority. With the help of exercise scientists, athletes can use measures of various physiological variables such as enzyme activity, lactate accumulation, ventilation volumes, heart rate, and blood pressure in order to maximize the efficiency of each workout.

Lactate is an important metabolite that accumulates at the site of the working muscle during exercise. It has been shown that during progressive exercise, muscle lactate accumulation is a linear function of the power output and oxygen consumption rate (VO_2). As workload increases, there will be a workload at which lactate will accumulate in a disproportionately high, non-linear manner. The workload at which this disproportionate increase occurs is called the lactate threshold (LT) (3). Similarly, during progressive exercise, pulmonary minute ventilation will increase linearly with increments in workload until it reaches a certain workload whereby it, too, will disproportionately increase. This workload is termed the ventilatory threshold (VT) (3). Wasserman et al., contend that the LT and VT occur at the same workload and are caused by an absence of oxygen in the muscle (12). Therefore, this threshold workload is also

referred to as the anaerobic threshold (13). However, this concept has been found to be associated with an imbalance between lactate production and the lactate clearance in the presence of adequate oxygen delivery (3). Thus, the use of the term anaerobic threshold has been discredited.

The presence of both the ventilatory and lactate thresholds is a valuable tool for endurance athletes in their training program in that it allows them to judge the workload at which they can perform optimally (2). However, these measurements are difficult to assess in the field. Therefore, elite endurance athletes have been trained to use their ventilation volume, or their self-rating of their breathing effort, to monitor their training status. Heart rate has become another non-invasive means by which athletes use to evaluate their training intensity. However, the presence of a heart rate threshold, and its relationship to the ventilatory threshold, remains to be validated.

During progressive exercise, heart rate, as with lactate and ventilation, increases linearly with workload. Therefore, the workload at which the heart rate begins to disproportionately increase is referred to as the heart rate threshold (HRT). Previous studies by Conconi et al. have established methods of detecting this heart rate deflection point (HDRP) mathematically by monitoring heart rate during progressive exercise and observing when it changes from a linear to curvilinear trend (4). Conconi et al. also hypothesized that the HDRP represented the HRT which could be used to assess LT or VT during exercise (4).

Previous investigations have demonstrated that the VT is triggered by an intramuscular stimulus (5, 10, 14). However, the accumulation of metabolites within the working muscle and the subsequent activation of the metaboreceptors appeared to

selectively activate the ventilatory response without affecting the cardiovascular responses (10, 15). Unfortunately, a mathematical examination of the heart rate response rates prior to and following the VT was not used in these studies (5, 10).

The mechanism behind the thresholds helps to elucidate why they are related. During exercise, lactic acid is produced and cleared within the working muscle. Eventually, there comes a point where lactate is not able to be cleared as fast as it is produced (the lactate threshold). The excess lactic acid within the muscle is effluxed into the blood where it is buffered by sodium bicarbonate. The products of this buffering are CO_2 and water, producing a chemoreceptor drive to the respiratory center stimulating a hyperventilation response (ventilatory threshold) to reduce blood pH and return PCO_2 levels to normal. Mechano- and metabo- receptors provide neural feedback to the cardiovascular control center regarding the adequacy of the oxygen delivered by the circulation to meet the metabolic demand of the muscle (8, 9, 11). Increases in metabolic acidosis within the exercising muscle have been directly associated with increased sympathetic activation (6, 7). Therefore, it would be expected that the onset of intracellular acidosis would increase heart rate and produce a disproportionate increase in the heart rate above the metabolic load (heart rate threshold). Hence, the ventilatory threshold should occur at the same workload as the heart rate threshold.

In order to confirm the effect of accumulating metabolites during exercise, a bilateral thigh cuff pressured at 90mmHG to retard venous outflow from the exercising muscle will be used in order to trap intramuscular metabolites during progressive load bicycle exercise to a maximal effort (1, 6). By using the cuffs, we expect to produce a physiological relocation of the HRT and VT to a lower oxygen uptake.

CHAPTER III

PROCEDURES AND METHODS

Subjects: Twenty-four subjects were recruited from the Dallas/Fort Worth area for participation in this study. The subjects were men and women, ages 18-35, normotensive nonsmokers who were asymptomatic for cardiovascular and respiratory disease and not currently taking any medication. Each subject was administered an informed consent as approved by the Institutional Review Board at the University of North Texas Health Science Center at Fort Worth. Each subject was screened for acceptance into the study using a physical examination, which included a resting 12-lead electrocardiogram (ECG) and ausculatory blood pressure to document a normal ECG and normotension and no vascular abnormality (i.e., stenosis or occlusion), respectively. Subjects were asked to abstain from caffeinated beverages, strenuous physical activity and alcohol for at least 12 hours before any scheduled test. Subject characteristics are summarized in Table 1.

Table 1. *Subject Information*

	Mean ± Standard Error
Age, yr	26.5 ± 0.8
Height, cm	179.4 ± 1.6
Weight, kg	78.1 ± 1.6
VO_{2max}, $mL*min^{-1}*kg^{-1}$	48.8 ± 2.0

Graded Exercise Testing: Each subject performed two graded exercise stress tests to volitional fatigue by cycling on a cycle ergometer. This test served to determine each subject's peak aerobic capacity and the heart rate and ventilatory thresholds. Differences between tests was determined by having the subjects randomly assigned to one of the following: i) test with no intervention (CON); ii) test with thigh cuff inflation (CUF). The second test (CON or CUF) was determined by the random assignment of the first testing procedure. The CUF protocol involved partial bilateral thigh cuff occlusion implemented as exercise begins and discontinued upon reaching the limit of exercise tolerance. The cuffs were 4.5 inches wide (Aspen Labs, Englewood, CO), placed as high on each thigh as possible and inflated to 90mmHg under solenoid control. It is at this pressure that metabolite "trapping" will occur (6, 12).

In order to account for individual amounts of exercise training between subjects, there were three different exercise test protocols: non-exercise-trained men (NET), exercise-trained men (ET), and all women regardless of training status. The NET men and women were allowed a five-minute warm-up ride at 50watts. Following the warm-up, the NET men began the exercise test at 100watts and increased by 50watts every 2mins while the women began the exercise test at 80watts and increased by 30watts every 2mins. The ET men were allowed a two minute warm-up ride at 50watts, began the test at 100watts, and increased by 25watts every 30sec., see Figure 1.

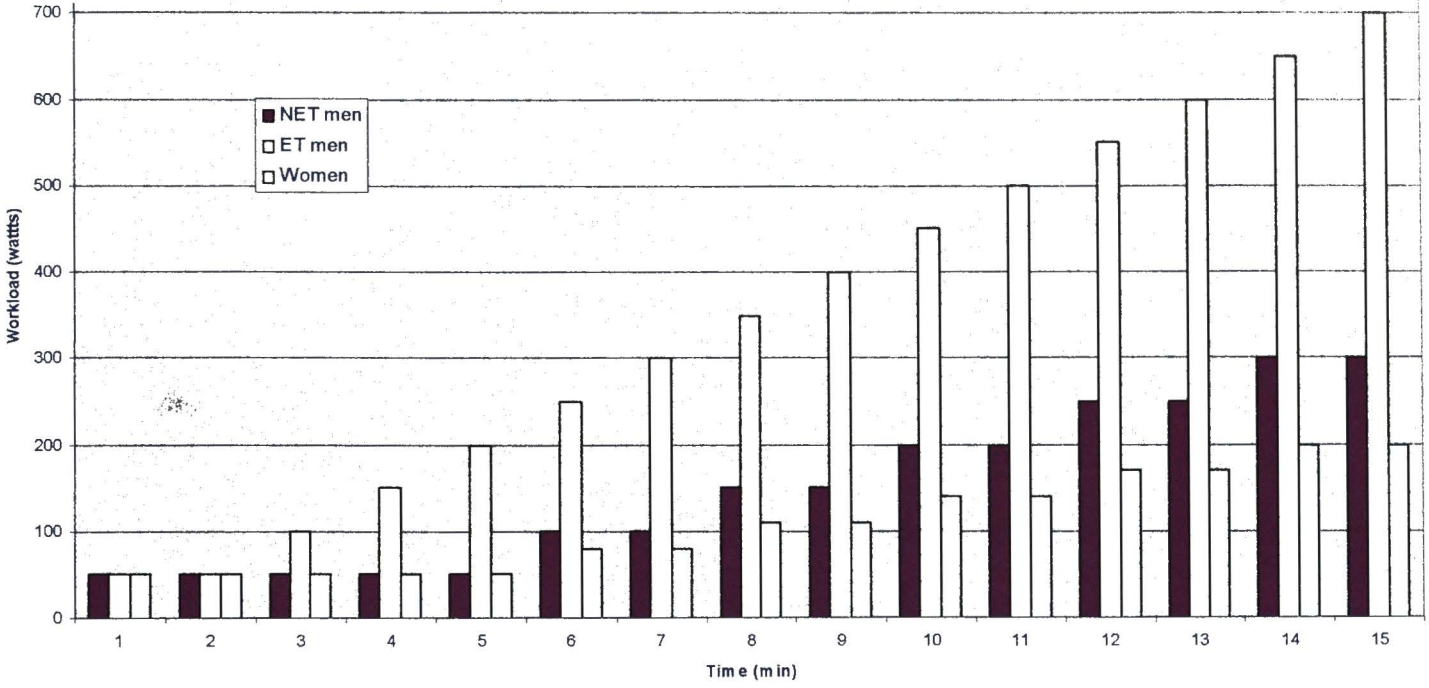

Figure 1.

Each subject was allowed to pedal at his or her desired cadence provided it is at least 60rpm, see Figure 2.

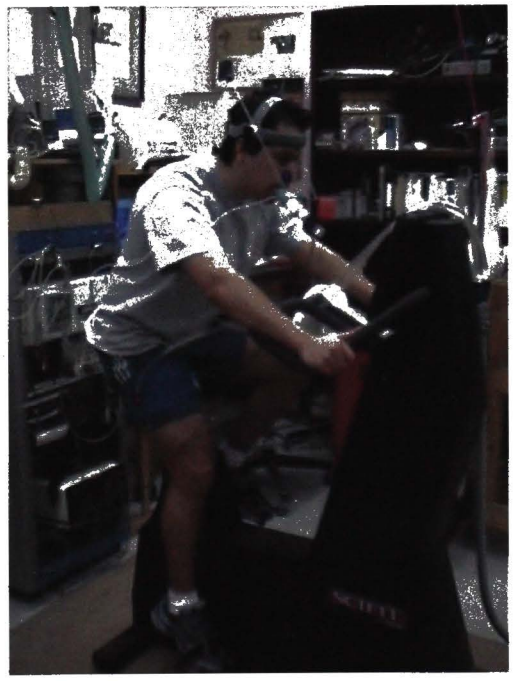

Figure 2.

The subject's workload continued to increase until he or she could no longer maintain a constant cadence despite strong verbal encouragement. In addition, the exercise test was terminated if: i) the subject expressed a desire to stop; ii) a systolic blood pressure reached 250 mmHg or diastolic pressure reached 110 mmHg; iii) his/her S-T segment depression equaled or was greater than 1 mm; iv) if there was a significant number of PAC's or PVC's; or v) multifoci PVC's were present. Upon reaching exhaustion, the resistance setting was reduced to facilitate active recovery. After the initial test, the subjects recovered in a seated position and were instructed to hydrate adequately for at east 60 minutes or until heart rate and blood pressure measurements had returned to baseline. Following this, the subjects completed the second test utilizing the alternative protocol as outlined above.

Measurements: Heart Rate (HR) was continuously measured using a 3-lead electrocardiogram. Ratings of Perceived Exertion (RPE) were assessed (Borg Scale 6-20) to quantify the sensation of leg discomfort. Blood Pressure (MAP) was measured by auscultation during rest prior to the test, regularly during exercise, and in the recovery period. The subjects breathed through a mouthpiece attached to a low-resistance turbine volume transducer (Sensor Medics, VMM series) for measurement of breath volumes while respiratory gases were continuously sampled from the mouthpiece for analysis of fractional concentrations of oxygen (O_2), carbon dioxide (CO_2), and nitrogen (N_2) via mass spectrometry (Perkin-Elmer MGA1100B). The mass spectrometer was calibrated prior to each test using known high-precision standard gases. The signals were analyzed using analog-to-digital conversion on a dedicated computer with a customized program

for on-line, breath-by-breath determination of VO_2, carbon dioxide output (VCO_2), minute ventilation (V_E), tidal volume (V_T), breathing frequency (B_f), and fraction of end-tidal PO_2 and PCO_2 (FET_{O2} and FET_{CO2}), respectively.

Statistical Analyses: Descriptive statistics include means (standard deviation) of demographic information (i.e., height, weight). Bivariate within group comparisons (CON vs. CUF) were determined through a randomized one-way analysis of variance (ANOVA). A Pearson Product R Correlation Coefficient was performed to determine associations between thresholds. Ventilatory threshold (VT) determination was accomplished utilizing the V-slope method, see Figure 3 (19).

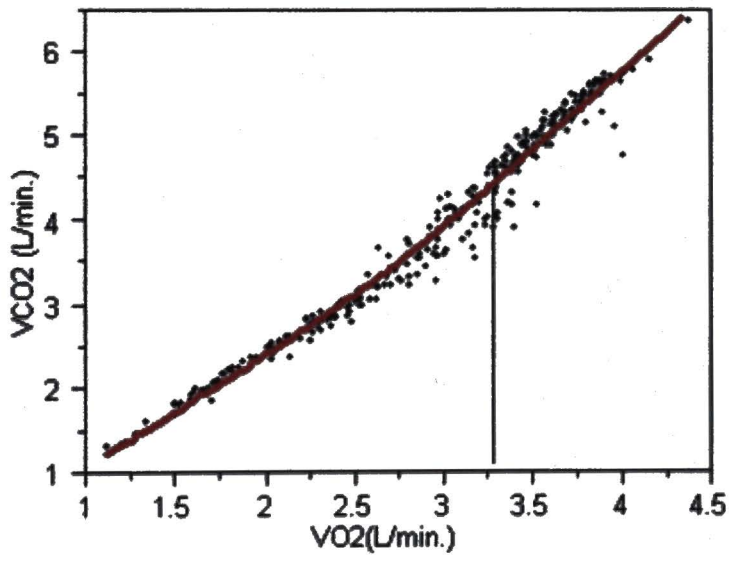

Figure 3. Example of Ventilatory Threshold Detection in One Subject

Heart rate threshold (HRT) was determined by the following: i) establishing a logarithmic line of best fit with time (min) matched to absolute VO_2 ($L*min^{-1}$) as the

independent variable (x-axis) and heart rate as the dependent variables (y-axis); ii) determining when y-axis variable separated from the line of best fit; iii) validated by the cross-over of a linear regression line of best fit to the logarithmic regression line of best fit. The time at which this threshold was achieved was then matched to determine the subjects VO_2 at the heart rate threshold, see Figure 4.

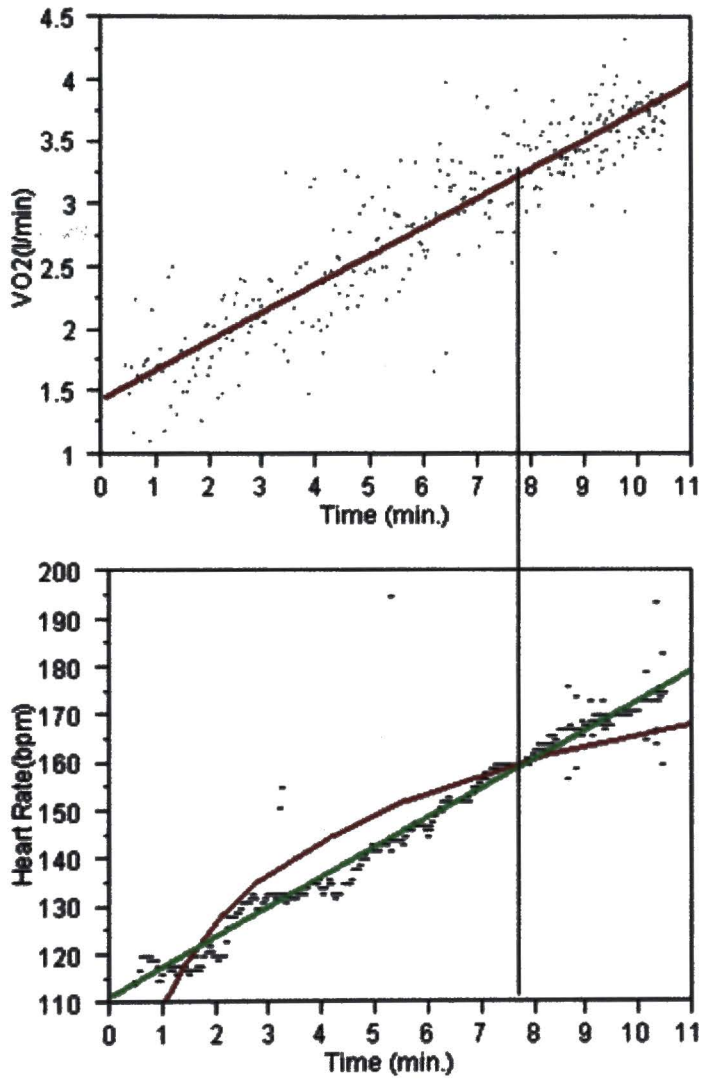

Figure 4. Example of Heart Rate Threshold Detection in One Subject

NOTE: Line indicates heart rate threshold: 1) data point moves above logarithmic line of best fit and, 2) linear regression line of best fit crosses over logarithmic line of best fit.

Power analysis for subject number indicated that an N of 16-21 would yield a power of 0.8 to 0.9 for a delta value of 0.8. Statistical significance was set a priori at $p \leq 0.05$.

CHAPTER IV

RESULTS

Maximum relative VO_{2max}, maximum heart rate, maximum workload, and time to exhaustion were all reduced during the cuff protocol compared with the control ($p<0.05$). See Table 2 and Figure 5.

Table 2. *Means ± SE for control and cuff protocols.*

	n	Control	Cuff	Significance
VO_{2max} (mL)	24	49.4±0.2	43.6±1.4	0.02*
Heart Rate max	24	189.9±1.4	181.9±1.9	0.001*
Workload max	24	346.5±117.8	274.2±87.6	0.02*
Time to exhaustion	24	13.7±5.4	10.0±0.6	0.004*
VO_2 @ VT	21	3.3±0.2	2.8±0.1	0.03*
VO_2 @ HRT	20	3.1±0.2	2.6±0.1	0.03*

Significance at $p<0.05$.

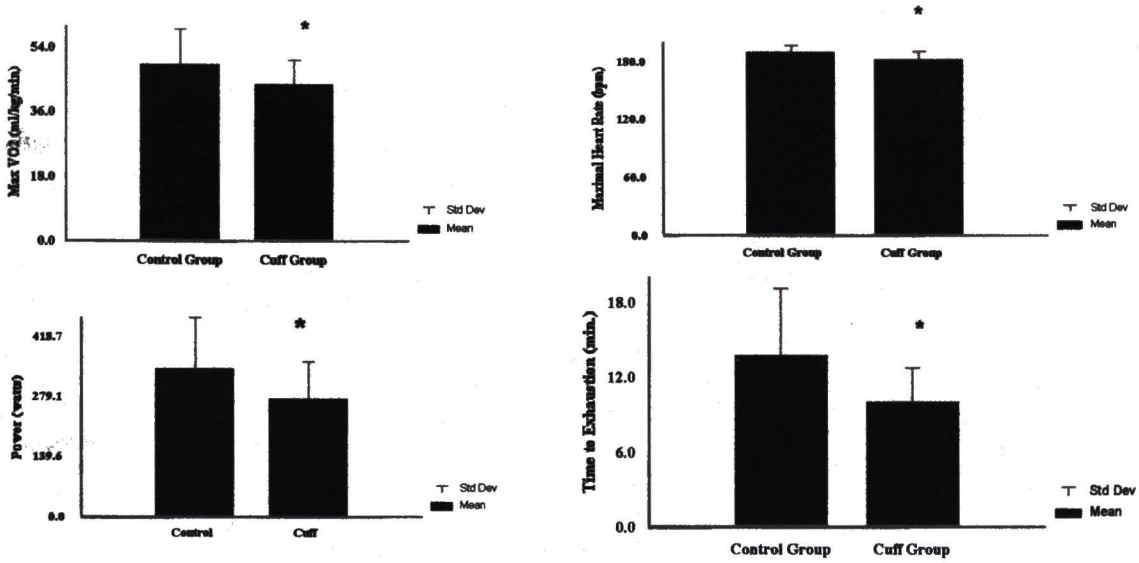

Figure 5. Comparison of maximum oxygen consumption, heart rate, power output, and time to exhaustion for CON and CUF protocols. *Indicates significance at $p<0.05$.

The ventilatory threshold occurred at a significantly lower VO_2 during the cuff protocol compared to the control ($p<0.05$). The heart rate threshold also occurred at a significantly lower VO_2 during the cuff protocol compared to the control ($p<0.05$). See Table 2, Figure 6, and Figure 7.

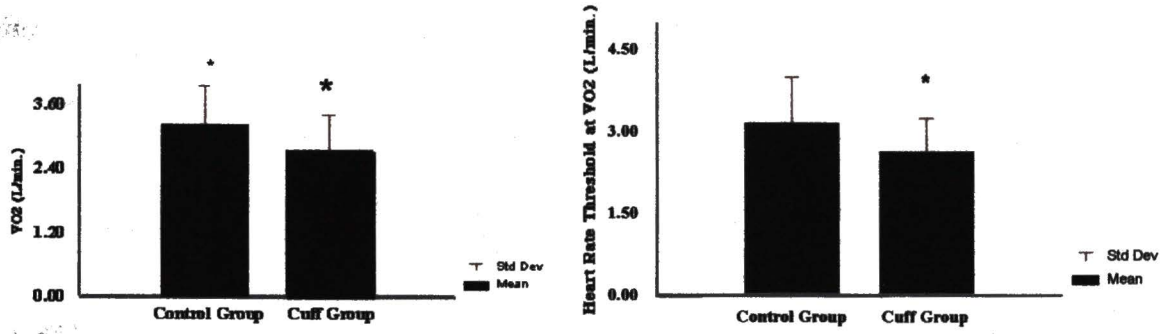

Figure 6. Comparison of ventilatory and heart rate thresholds for CON and CUF protocols. *Indicates significance at $p<0.05$.

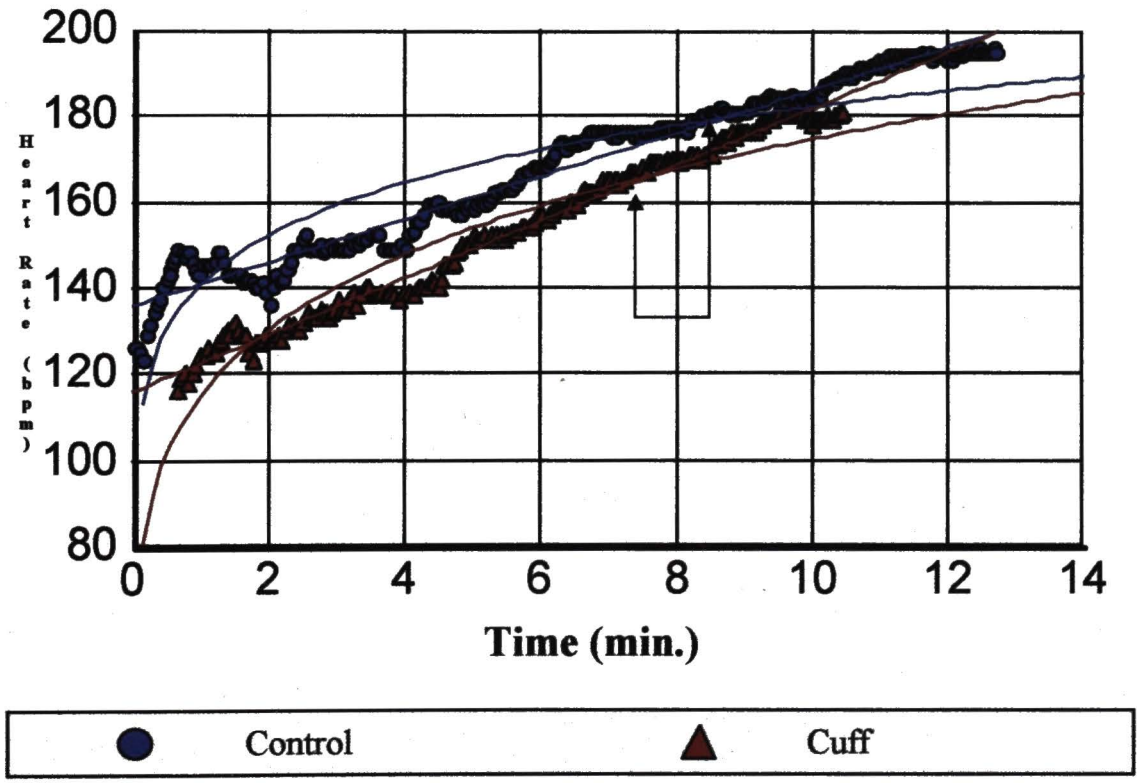

Figure 7. Comparison of heart rate responses with one individual during control and cuff tests. Arrows indicate thresholds defined as data points moving above the logarithmic regression line of best fit at the point of linear regression cross-over. As indicated, the threshold point shifts to the left at an earlier time during CUFF.

The ventilatory threshold and heart rate threshold occurred at the same VO_2 during the control protocol. The ventilatory threshold and heart rate threshold occurred at the same VO_2 during the cuff protocol. See Table 3. Furthermore, the VO_2 at the VT and HRT were both strongly correlated both during the control and during the cuff protocols, See Table 4.

Table 3. *VO_2 of VT and HRT during CON and CUF*

	P value
VO_2 @ VT Control vs. VO_2 @ HRT Control	0.69
VO_2 @ VT Cuff vs. VO_2 @ HRT Cuff	0.49

Table 4. *VO_2 of VT and HRT during CON and CUF*

	Correlation
VO_2 @ VT Control vs. VO_2 @ HRT Control	0.9381
VO_2 @ VT Cuff vs. VO_2 @ HRT Cuff	0.9613

CHAPTER V

DISCUSSION AND SUMMARY

The two main objectives of this study were to: 1) validate the presence of a heart rate threshold; and 2) identify the relationship between the ventilatory threshold and the heart rate threshold.

Using our mathematical method, a discernible heart rate threshold was obtained for 20 of the 24 (83%) subjects. This heart rate threshold was observed to be a point where the linear increase in heart rate intersected with the logarithmic line of best fit of the heart rate data early on in exercise. The four subjects without an obvious threshold had heart rate data that followed a strictly linear pattern rather than the curvilinear pattern established early in the exercise test. According to Conconi et al, in a large enough population, a deflection point is always detectable (5). While our method was not 100% effective, other studies were even less successful (20,21). Varying exercise protocols, subjective methods of heart rate detection, and diverse populations may account for the inconsistencies in identifying the threshold.

Bilateral thigh cuff occlusion was used in order to trap metabolites within the interstitium of the working muscle. Previous studies using this technique have shown that thigh cuff occlusion of 90 mmHg was sufficient to impede venous outflow and produce an increase in venous blood lactate concentration (6, 22).

Maximum oxygen uptake, maximum heart rate, maximum workload, and time to exhaustion were all significantly reduced during the cuff protocol compared with the control. These results are similar to those found by Smith, et al. (12) who also used cuff occlusion at 90 mmHg during dynamic leg exercise. Early termination of exercise and reduced values of maximum VO_2, heart rate and workload can be attributed to the increased accumulation of metabolites and an increase rating of perceived exertion (12).

Cuff occlusion also significantly reduced the VO_2 at which the ventilatory and heart rate thresholds occurred. During the control protocol, the ventilatory threshold and the heart rate threshold occurred at the same VO_2. Further, the application of cuff occlusion shifted both the ventilatory threshold and the heart rate threshold to a lower VO_2 value. Previous studies have presented conflicting results concerning the involvement (23, 24, 25) or uninvolvement (26, 27, 28) of the ventilatory threshold and the heart rate threshold. Being that the ventilatory threshold and the heart rate thresholds occur at the same VO_2, are stimulated by the same muscle metabolite perturbation, and respond to the perturbation identically, our data suggest that these thresholds are directly related.

During exercise, the working muscle produces and eliminates lactic acid efficiently. Lactic acid is buffered by sodium bicarbonate to produce carbonic acid. Carbonic acid further reacts with hydrogen atoms to produce carbon dioxide and water. Carbon dioxide and water are taken up by the circulation and cleared via the respiratory system and renal system (29). However, during progressive exercise where workload is constantly increasing, the amount of lactic acid produced begins to surpass the amount of lactic acid that is cleared and lactic acid accumulation occurs in the working muscle (5,

11). Excess amounts of CO_2 and H^+ elicit a hyperventilatory response to increase ventilation and thereby increase the removal of CO_2 (29). By trapping these metabolites within the muscle interstitium during exercise via venous cuff occlusion and preventing their disposal, we were able to exacerbate the activation of the exercise pressor reflex via the metaboreceptors located in the working muscle.

Previous research has shown that the ventilatory threshold is triggered from an intramuscular metaboreceptor stimulus (6, 12, 17). Using cuff occlusion, Smith, et al. activated the exercise pressor reflex and relocated the ventilatory threshold to a lower VO_2 (12). Our data supports this finding. Further, we were able to elicit the same relocation response for the heart rate via presumably the same muscle acidosis stimulation. Figure 7, pg. 18, represents one subject's heart rate response to cuff occlusion. This graph further illustrates the relocation of the heart rate threshold to an earlier time with the application of leg venous occlusion cuffs. In addition, although both CON and CUFF begin similarly, the linear trajectory is greater in the CUFF test. This is most likely due to the increased sympathetic activation elicited by the accumulation of metabolites in the exercising muscle. It has been shown that increases in metabolic acidosis within the exercising muscle were directly associated with increased sympathetic activation. Our data suggest that the metaboreceptors responsible for increases in ventilation are also responsible for increases in heart rate at the respective thresholds.

Summary

In summary, we have shown that during exercise, as workload continues to increase, eventually there will be a disproportiate increase in heart rate above the

curvilinear heart rate, a response established early in exercise, which is referred to as the heart rate threshold. This heart rate threshold is consistently present and identifiable using mathematical techniques. Also, by using cuff inflation to trap metabolites in the working muscle, we were able to relocate both the heart rate threshold and the ventilatory threshold to a lower workload. Since heart rate and ventilation both respond in the same manner both with and without muscle metabolite perturbation, we conclude that they are elicited by the same intramuscular stimulus.

Future Research

Future research for the current investigation should include gender differences in heart rate thresholds. Also, heart rate thresholds and fitness differences should be studied to account for the changes in stroke volume and cardiac wall dimensions elicited by exercise training. In addition, although it seems intuitive that if the exercise pressor reflex is responsible for heart rate thresholds a similar response would be expected for blood pressure, this hypothesis needs to be further explored.

REFERENCES

1) Alam, M. and Smirk, F.H. (1937) Observations in man upon a blood pressure raising reflex arising from the voluntary muscles. *J Physiol (Lond.)* **89**:372-383.

2) Asmussen, E. and Nielsen M. (1964) Experiments of nervous factors controlling respiration and circulation during exercise employing blocking of blood flow. *Acta Physiol Scand* **60**:103-111.

3) Billat, L.V. (1996) Use of blood lactate measurements for the prediction of exercise performance and control for training. *Sports Med.* **22**:157-175.

4) Brooks, G. (1985). Anaerobic threshold: review of the concept and directions for future research. *Med Sci Sports Exerc* **17**(1):22-31.

5) Conconi, F., M. Ferrari, P. G. Ziglio, P. Droghetti, and L. Codeca. (1982) Determination of the anaerobic threshold by a noninvasive field test in runners. *J Appl. Physiol.* **52**:869-873.

6) Gallagher K.M., Fadel, P.J., Smith, S.A., Norton, K.H., Querry, R.G., Olivencia-Yurvati, A., & Raven, P.B. (2001). Increases in intramuscular pressure raise arterial blood pressure during dynamic exercise. *J Appl Physiol* **91**: 2351-2358.

7) Hall, G.V., Jensen-Urstad, M., Rosdahl, H., Holmberg, H.-C., Saltin, B., & Calbet, J.A. (2003). Leg and Arm lactate and substrate kinetics during exercise. *Am J Physiol Endocrinol Metab* **284**: E193-E205.

8) McCloskey, D.I. & Mitchell, J.H. (1972) Reflex cardiovascular and respiratory responses originating in exercising muscle. *J Physiol (Lond)* **224**:173-186.

9) Mitchell, J.H. (1985) Cardiovascular contol during exercise: central and reflex neural mechanisms. *Am J Cardiol* **55**:34D-41D.

10) Rowell, L.B., Hermansen, L, & Blackmon, J.R. (1976) Human cardiovascular and respiratory responses to graded muscle ischemia. *J Appl Physiol* **41**:693-701.

11) Sheriff D.D., Wyss, C.R., Rowell, L.B., and Scher, A.M. (1987). Does inadequate oxygen delivery trigger pressor response to muscle hypoperfusion during exercise. *Am J Physiol Heart Circ Physiol* **253**:H1199-H1207.

12) Smith, S.A., Gallagher, K.M., Norton, K.H., Querry, R.G., Welch-O'Conner, R.M., & Raven, P.B. (1999). Ventilatory responses to dynamic exercise elicited by intramuscular sensors. *Med Sci Sports Exerc* **31(2):** 227-286.

13) Stanley, W.C., Gertz, E.W., Wisneski, J.A., Neese, R.A., Morris, D.L., & Brooks, G.A. (1986). Lactate extraction during net lactate release in legs of humans during exercise. *J Appl Physiol* **60(4)**: 1116-1120.

14) Stebbins, C.L. Brown B., Levin D., & Longhurst J.C. (1988) Reflex effect of skeletal muscle mechanoreceptor stimulation on the cardiovascular system. *J Appl Physiol* **65**:1539-1547.

15) Wassermann, K. and M. B. McIlroy. (1964) Detecting the threshold of anaerobic metabolism in cardiac patients during exercise. *Am J. Physiol.* **14**:844-852.

16) Wasserman, K., Whipp, B.J., Koyl, S.N., & Beaver, W.L. (1973) Anaerobic threshold and respiratory gas exchange during exercise. *J Appl Physiol* **35(2)**: 236-243.

17) Williamson J.W., Raven, P.B., Foresman, B.H., Whipp, B.J. (1993) Evidence for an intramuscular ventilatory stimulus during exercise in man. *Respiration Physiology*:1-15.

18) Wyatt, F.B. (1999) Comparision of lactate and ventilatory threshold to maximal oxygen consumption: a meta-analysis. *J Strength and Conditioning Res* **13(1)**: 67-71.

19) Beaver, W., K. Wassermann, and B.J. Whipp. (1985) Improved detection of lactate threshold during exercise using a log-log transformation. *J. Appl. Physiol.* **59**:1936-1940.

20) Ribierno, J.P., R.A. Fielding, V. Hughes, A. Balck, M.A. Bochese, and H.G. Knuttegen. (1985) Heart rate breakpoint may coincide with the anaerobic threshold and not the aerobic threshold. *Int. J. Sports Med.* **6**:220-224.

21) Droghetti, P., C. Borsetto, I. Casoni, M. Cellini, M. Ferrari, A.R. Paoline, P.G. Ziglio. (1985) Noninvasive determination of the anaerobic threshold in canoeing, cross-country skiing, cycling, roller and ice-skating, rowing and walking. *Eur. J. Appl. Physiol.* **53**:299-303.

22) Oelberg, D. A., A.B. Evans, M.I. Hrovat, P.P. Pappagianopoulos, S. Patz, and D.M. Systrom. (1998) Skeletal muscle chemoreflex and pH_i in exercise ventilatory control. *J. Appl. Physiol.* **84**:676-682.

23) Bunc, V.J. and J. Heller. (1992) Comparision of two methods of non-invasive anaerobic threshold determination in middle-aged men. *Sports Med. Training Rehab.* **3**:87-94.

24) Bunc, V.J., P. Hoffmann, H. Leitner, and G. Gaisl. (1995) Verification of the heart rate threshold. *Eur. J. Appl. Physiol.* **70**:263-269.

25) Hoffmann, P., R. Pokan, S.P. von Duvillard, F.J. Seibert, R. Zweiker, and P. Schmid. (1997) Heart rate performance curve during incremental cycle ergomentry exercise in healthy young male subjects. *Med. Sci. Sport Exerc.* **29**:762-768.

26) Jones, A.M. and J. H. Doust. (1997) The Conconi test is not valid for estimation of the lactate turnpoint in runners. *J. Sport Sci.* **15**:385-394.

27) Kuipers, H., H.A. Keizer, T. De Vries, P. Van Rijthoven, and M. Wijts. (1988) Comparison of heart rate as a non-invasive determination of anaerobic threshold with the lactate threshold when cycling. *Eur. J. Appl. Phyisol.* **58**:303-306.

28) Francis, K.T., P.R. McClatchey, J.R. Sumison, and D.E. Hansen. (1989) The relationship between anaerobic threshold and heart rate linearity during cycle ergometry. *Eur. J. Appl. Physiol.* **59**:273-277.

29) Wilmore, J.H. and Costill, D.L. (1988) *Training for Sport and Activity: The Physiological Basis of the Conditioning Process*. Dubuque: Wm. C. Brown Publishers, pp. 54-58.