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# Accuracy of the Polar M52 heart rate monitor for estimating energy expenditure, substrate utilization, and maximal oxygen uptake

Cory Matthew Alwardt

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To the Graduate Council:

I am submitting herewith a thesis written by Cory Matthew Alwardt entitled "Accuracy of the Polar M52 heart rate monitor for estimating energy expenditure, substrate utilization, and maximal oxygen uptake." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Human Performance and Sport Studies.

David R. Bassett, Major Professor

We have read this thesis and recommend its acceptance:

Dixie Thompson, Edward T. Howley

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Associate Vice Chancellor and
Dean of The Graduate School

# ACCURACY OF THE POLAR M52 HEART RATE MONITOR FOR ESTIMATING ENERGY EXPENDITURE, SUBSTRATE UTILIZATION, AND MAXIMAL OXYGEN UPTAKE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Cory Matthew Alwardt
August, 2000

# Dedication

To my mother, for love and support throughout the years, and for allowing me to have the opportunities to achieve my goals. Thank you.

To my late father, for love and support throughout the years. I wish you could be here to see it.

I love you both very much, and I'll never forget how I became the person that I am!

## Acknowledgements

I would like to thank all the subjects who participated in the study. I couldn't have done it without you, and your help is certainly appreciated. I would also like to thank Scott Strath and Ann Swartz for providing guidance and a helping hand. I would especially like to thank Scott Conger for his help in the laboratory and for his commitment to this project, and Cary Springer for statistical counseling.

Lastly, and most importantly, I would like to thank Dr. David Bassett, Jr. for his guidance and interest in this project. Thanks also to Dr. Edward Howley and Dr. Dixie Thompson for their time and commitment, and for serving on my graduate committee. Each of you has been a mentor and a role model to me, and I will never forget the enjoyment I have experienced working with each of you

Thank you all very much...you have all made a positive impact on my life!

## Abstract

This study investigated the accuracy of the Polar M52 heart rate monitor for estimating energy expenditure, substrate utilization, and $\mathrm{VO}_{2\,\mathrm{max}}$. Eight subjects (4 males, 4 females) between the ages of 22 and 41 participated in this study To be eligible, participants completed a health history form and an informed consent form. Each participant completed four exercise tests (including one maximal) on separate days. $\dot{\mathrm{V}}\mathrm{O}_{2\,\mathrm{max}}$ was measured by indirect calorimetry during a Bruce protocol treadmill exercise test, and was estimated using the Polar monitor Submaximal exercise tests consisted of three 8-minutes stages on a treadmill (3, 4.5, and 5 mph), cycle ergometer (50, 100, and 150 W), and a rowing ergometer (50, 100, and 150 W). Energy expenditure and substrate utilization were measured via indirect calorimetry and estimated by the Polar monitor. Repeated measures ANOVA demonstrated that there was no difference between methods and no stage/method interaction when comparing measures of energy expenditure except on the treadmill. For the treadmill submaximal test, no overall significant differences were found in methods, but there was a significant stage/method interaction. A post-hoc paired t-test (using Bonferoni adjusted alpha) indicated that there was a significant difference ($p = 0.005$) between methods during stage 1, but not during stages 2 and 3. The ANOVA analysis of substrate utilization showed significant differences between methods for each exercise mode. There was significant stage/method interaction on the treadmill, but not the rower or cycle. The monitor consistently overestimated the percentage of total calories derived from fat. A paired t-test indicated that there was a significant difference ($p = 0.015$) between predicted (45.9 $\mathrm{ml \cdot kg \cdot min^{-1}}$, SD 4.8) and measured (49.7 $\mathrm{ml \cdot kg \cdot min^{-1}}$, SD 5.1) values of $\dot{\mathrm{V}}\mathrm{O}_{2\,\mathrm{max}}$. A significant correlation ($r=$

0.772) was found between these measures. The conclusions of this study are that the Polar M52 heart rate monitor is accurate when estimating energy expenditure, particularly at higher exercise intensities. However, the monitor is not accurate for determining substrate utilization. Even though the monitor's estimates of $VO_{2\,max}$ were significantly different from measured values, the predictions were reasonably accurate, underestimating actual values by an average of 3 8 $ml \cdot kg^{-1} \cdot min^{-1}$. Due to this accuracy, this method may be preferred to those provided by many non-exercise fitness equations or submaximal exercise testing.

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# CHAPTER I

# INTRODUCTION

Heart rate measurement can be a valuable tool in exercise and fitness programs. Exercise prescription often relies on the heart rate response to determine the appropriate intensity of exercise. An individual's fitness level can be estimated either through incorporation of resting heart rate into non-exercise prediction models (55), or by extrapolation of the heart rate response to submaximal exercise testing (44, 71, 95, 103). Because heart rate is linearly related to oxygen uptake for most activities (24, 69, 96, 112), heart rate is an excellent indicator of energy expenditure (22, 35, 36, 57) . For these reasons, heart rate monitors have many practical applications in exercise testing and training.

Polar Electro, Inc is a major manufacturer of heart rate monitors. The company introduced its first wireless monitor in 1983. The validity of these monitors for accurately monitoring heart rate has been demonstrated by comparing them to electrocardiographic recordings (59, 66, 68). The newest heart rate monitors by Polar Electro, Inc use these heart rate measurements to provide other information related to exercise and fitness. The Polar M52 heart rate monitor uses an individual's heart rate to provide the user's target heart rate zone (OwnZone), estimate the aerobic fitness level (OwnIndex), and estimate the total number of calories expended as well as the percentage of those calories derived from fat

Maximal oxygen uptake ($\dot{V}O_{2\,max}$) is considered the "gold standard" of aerobic fitness (7, 91). There are a number of non-exercise fitness equations used to estimate the aerobic fitness level of an individual (55, 48, 109). These equations usually take into account gender, age, height and weight, activity level, and body composition. The Polar M52 heart rate monitor uses a non-exercise equation based on heart rate, heart rate variability at rest, body structure (based on height and weight), and self-assessed physical activity Theoretically, this estimate would be comparable to the $VO_{2\,max}$ value as determined by use of a maximal graded exercise test (GXT). The Bruce protocol is a maximal GXT consisting of treadmill walking and running with a progression in speed and percent grade (17). A subject walks/runs on the treadmill according to the protocol until volitional exhaustion, and the maximal oxygen uptake can be measured

Energy expenditure is another important variable concerning aerobic fitness Most of the energy used during exercise is derived from carbohydrate and fat (34, 37, 106). Since heart rate is linearly related to oxygen uptake over a wide range of intensities it could theoretically be used to estimate energy expenditure. The Polar M52 heart rate monitor uses this assumption to estimate energy expenditure during an exercise bout. In contrast, energy expenditure can be measured precisely using indirect calorimetry (34, 63, 106). This process involves expiratory ventilation measurements during steady state exercise The respiratory exchange ratio (RER) is the ratio of the amount of carbon dioxide and oxygen in expired air, and its values range from 0.70 to 1.0 during steady state exercise Experiment has determined that when burning an equal amount of carbohydrate and fat, the consumption of l liter of oxygen is associated with an energy expenditure of 4 85 kcals (75, 83)

Another important variable when discussing aerobic fitness is substrate utilization, which is determined from the RER. An RER of 0.85 implies equal use of carbohydrate and fat, and RER increases with the intensity of exercise. Higher RER values imply a higher relative rate of carbohydrate oxidation compared with that of fat. The opposite is true at low intensities. An RER of 1.0 would imply that virtually all energy is derived from carbohydrate, and an RER of 0.7 would imply the same regarding fat (75, 83). It is important to note that these measurements are only valuable when measured during steady state exercise (37)

The Polar M52 heart rate monitor uses resting heart rate measures to predict an individual's fitness level and provide information on caloric expenditure and substrate utilization during an exercise bout. The focus of the present study is to test the accuracy of this instrument against indirect calorimetry measurements during a maximal graded exercise test and submaximal graded exercise tests on various devices. We hypothesize that the estimated values of $VO_{2\,\max}$ provided by the Polar M52 heart rate monitor will be accurate compared to direct measurements of $\dot{V}O_{2\,\max}$ using the Bruce protocol. We also hypothesize that the values of energy expenditure and substrate utilization provided by the monitor will be accurate compared to those measured during submaximal exercise bouts on a treadmill, cycle ergometer, and rower

# CHAPTER II

# REVIEW OF LITERATURE

The purpose of this study was to test the accuracy of the Polar M52 heart rate monitor. Based on heart rate measurements, this monitor estimates variables such as maximal oxygen uptake, energy expenditure, and substrate utilization. The data measured by the monitor were compared to data obtained through indirect calorimetry. This review of literature will focus on various methods of measuring heart rate (including Polar monitors) and the importance of these measurements, other objective measures of energy expenditure, maximal oxygen uptake and related issues, and the laboratory measurements used in this study.

## Methods of Measuring Heart Rate

Accurate heart rate measurement is important in exercise testing and prescription, and consequently, much research has focused on the validation of different methods of measuring heart rate. Heart rate can be measured by several techniques including palpation, auscultation, electrocardiography, and heart rate monitors such as those manufactured by Polar Electro, Inc.

### Palpation of pulse

The classical and traditional method of heart rate measurement is by palpating the pulse of a blood vessel such as the carotid, radial, or brachial artery. While this method is commonly viewed as an accurate technique, there have been reports to the contrary. Clapp and Little (25) recognized that self-reported heart rate measurements may underestimate actual heart rate by as much as 10-30 bpm. Other studies have reported similar results concerning the inaccuracy of this method (9, 82, 95). However, this method may be improved with development of methods to teach proper pulse counting. Additionally it has been shown that palpation of the carotid artery may elicit a baroreceptor reflex, resulting in a lower heart rate (78, 108)

Electrocardiography

Because it may not always be practical to use palpation of the pulse to measure heart rate, more sophisticated methods have been developed. Since the heart has its own electrical activity, it would seem logical that one could measure heart rate by measuring the electrical activity. Electrocardiographic (ECG) techniques have long been regarded as the "gold standard" of heart rate measurement against which other devices are validated (59, 66, 68). Electrocardiographs use various electrodes placed on the chest to detect electrical signals which are then transmitted to a computer via hardwire or telemetry. Hardwire electrocardiographs consist of a direct link between the electrodes and the display unit. These devices are convenient for most uses in the exercise physiology realm. However, in such cases as cardiac rehabilitation, telemetry units may be preferred. These units use radio waves to transmit the signals from the electrodes to the display unit over a distance of up to 100 meters (19). Many times these units are preferred because individuals using a telemetry electrocardiograph are not constrained to a small area. The most common method of determining heart rate from the electrocardiogram is to count the frequency of ventricular depolarizations, or R waves.

Heart rate monitors

Though ECG's are excellent devices for measuring heart rate, they are many times too costly and inconvenient in field settings (68). Throughout the years, numerous devices have been manufactured to provide quality heart rate measurements in a field setting. These small and portable devices are convenient for use during exercise. Many of these monitors use conventional chest electrodes to measure electrical activity of the heart. Polar Electro, Inc. has been a leader in the manufacturing of these devices, and released its first wireless heart rate monitor (Sport Tester PE 2000) in 1983 Numerous studies have reported on the validity of heart rate monitors utilizing conventional chest electrodes Karvonen et al. (59) determined that the mean heart rate measurements recorded using this type of system were within 5 bpm of ECG recordings, and any single measurement showed a difference of 0-10 bpm when compared to ECG's. In another study by Leger and Thivierge (68), it was determined that heart rate monitors using conventional chest electrodes, such as Polar devices, are stable and reliable (r = 0.93-0.98) when validated against ECG measurements Clearly Polar monitors using conventional chest electrodes can accurately measure heart rate in both laboratory and field settings. However, other types of monitors may not be as accurate as those manufactured by Polar (20, 68).

## Objective Measures of Physical Activity and Energy Expenditure

Physical activity plays an important role in the health and longevity of individuals and populations (14, 67, 79) The effects of physical activity on the health of humans is discussed by Paffenbarger et al who stated, "When we are sedentary – not physically active – we deteriorate If we are active, our physical activity alters the effects of other influences on our health" (80). This statement validates the necessity of quantitative assessment of physical activity. In this discussion of physical activity assessment I will use the definition of physical activity provided by Caspersen et al. (21). Casperson defined physical activity as "any bodily movement produced by skeletal muscles that results in energy expenditure". Over the years there have been various attempts to estimate physical activity and energy expenditure objectively. In fact, over 30 different methods have been used to assess physical activity (65). Since physical activity results in energy expenditure, discussion of the measurement of physical activity is appropriate. The following section is concerned with objective measures estimating energy expenditure, including physical activity questionnaires, motion sensors, and heart rate analysis.

### Physical activity questionnaires

Physical activity questionnaires have long been used to determine the physical activity level and energy expenditure of large populations. Their primary application is for larger studies because they are very low in cost when compared with other methods for estimating energy expenditure These questionnaires can be self-administered, use an interview process, or a combination of both. It is important that these questionnaires include leisure-time, occupational, and household energy expenditure so that energy expenditure is not underestimated in certain populations (77). Consideration should also be given to temporal variation (seasonal and yearly) in energy expenditure since individuals may demonstrate different patterns over time (45) Also, care should be taken in choosing populations to be studied since different subpopulations may have vastly different physical activity routines and habits

There are many advantages of using questionnaires to assess physical activity. Administration of questionnaires is cost effective in large populations, and the assessment can cover an extended period of time Also, recall questionnaires do not alter the behavior of those being surveyed. However, recollection of previous activity is best assessed when the time frame is short, such as the previous week (56). Many times questionnaires use the information regarding physical activity routines to estimate caloric expenditure using tables of energy expenditure for given activities (1). However, the precision of this method is poor, and these tables are generally based on a population of only adult males (77).

Another disadvantage to using questionnaires to assess energy expenditure is that their accuracy for measuring mild- to moderate-intensity exercise such as walking is poor (12). Most importantly, the reliability and validity of questionnaires is uncertain. Many researchers have found that questionnaires are both reliable and valid (64, 80, 90), but other investigators disagree due to the lack of appropriate validation schemes. The most convincing evidence of this was shown by Jacobs et al. (56) who evaluated the reliability and validity of 10 commonly used questionnaires. The investigators studied test-retest reliability and also attempted to validate the questionnaires against a number of direct and indirect variables including treadmill times, body fatness, accelerometer readings, and dietary caloric intake They concluded that while some questionnaires may be useful, "there are multiple, nonoverlapping dimensions of physical activity, reflected in multiple nonoverlapping validation realms." Therefore, it is difficult to precisely measure energy expenditure through the use of physical activity questionnaires.

Despite the limitations of questionnaires, they are the tool of choice for epidemiologists who study trends throughout large populations. For these types of studies, stratification of a population is often more important than precision of measurement. In this manner, questionnaires have shown that increased physical activity can decrease all-cause mortality and improve longevity (14, 67, 79).

### Motion sensors

Using Caspersen's (21) definition of physical activity as, "any bodily movement produced by skeletal muscles that results in energy expenditure", it seems reasonable that one could obtain a measure of physical activity by assessing body movements. This has been the goal of many devices that attempt to measure the movement of the body by measuring the acceleration of an area of the body. These devices include pedometers and accelerometers which will be discussed in the following section.

#### Pedometers

Pedometers are small devices, worn on the belt, that measure very small units of acceleration. If the acceleration reaches a certain threshold, the unit will register a "count", or a step. These accumulated counts can be used to estimate distance walked. For many individuals, distance walked may account for a large amount of caloric expenditure. Additionally, Bassett et al. (10) cites that the Japanese recommend 10,000 steps per day for "optimum health benefits". Not only do these devices provide a measurement of physical activity, they may also be used as a motivational tool by providing a quantitative measure of daily physical activity.

The first research done regarding the accuracy of pedometers demonstrated poor results (43), but these devices have become more advanced and have recently been convincingly validated. Possibly the most significant contribution to the testing of pedometers was done by Bassett et al. (10) who studied 5 different commercially available electronic pedometers. The study concluded that these pedometers provide "a reasonably accurate estimate of the distance walked and number of steps taken". In particular, the Yamax pedometer demonstrated the most accurate results, recording 100.6% and 100.7% of all steps taken for pedometers worn on the right and left hip, respectively. Other significant findings of the study were that the pedometers were not affected by the walking surface or the side of the body on which the pedometer was placed. However, the authors did note that variability can exist between two units of the same model, and that this is likely due to manufacturing flaws. Also, pedometers tended to underestimate steps at slower speeds. However, the overall conclusion of the study that pedometers provide a reasonable estimate of walking parameters is unquestioned. Eston et al. (36) even noticed a significant linear relationship ($r= 0.806$) of hip pedometers (in combination with heart rate) vs. a scaled $\dot{V}O_2$ value. This relationship did not seem to improve after the addition of a wrist and ankle pedometer.

There are obvious advantages of the use of pedometers in measuring physical activity, but they also have their limitations. Even though pedometers are generally most useful when worn on the belt, when used in this manner they neglect the work of other parts of the body, such as the arms (40). Also, pedometers may not account for an increase in energy expenditure due to incline walking or resistance encountered while walking Finally, none of the commercially available pedometers provide minute-by-minute measures which are needed to capture any temporal patterns of body movement.

### Accelerometers

Accelerometers are similar to pedometers in that they respond to the acceleration of the body, but they also record the intensity of each acceleration. Some accelerometers include an internal clock allowing them to record data over a certain time interval and estimate energy expenditure based on age, gender, and body mass. Many of these accelerometers can even download information into a personal computer for analysis.

The simplest of the accelerometers are uniaxial, meaning that they measure acceleration in a single plane, usually vertical. A common uniaxial accelerometer is the Caltrac (Hemokinetics, Inc., Madison, WI) activity monitor. This microcomputer uses an individual's characteristics and acceleration measurements to express energy expenditure in kilocalories (kcals). The validity of these instruments has been demonstrated by other researchers (58, 89). Haymes and Byrnes (47) found significant correlations between the Caltrac and indirect calorimetry during walking (r= 0.91, S.E.E.= 0.88), but the monitor overestimated energy expenditure especially at higher speeds. In addition to the validity of these monitors, they have shown excellent inter-instrument reliability (81).

Another popular uniaxial accelerometer is the Computer and Science Applications (CSA) activity monitor. This monitor estimates energy expenditure in terms of kcals similarly to the Caltrac monitor. Trost et al. (104) found the CSA to be strongly correlated to energy expenditure as measured by indirect calorimetry. In the same study, it was demonstrated that the monitors were sensitive to changes in treadmill speed. However, these results are not consistent with those found in a previous study (47). These instruments also exhibit high inter-instrument reliability (104). While it is obvious that these instruments can be a valuable tool for quantifying physical activity in certain situations, they do have limitations. The accuracy of these instruments can vary, depending on the type of activity being done. For example, rowing or cycling may not be accurately reflected since the vertical acceleration in such activities is minimal (40).

In order to account for the multiple planes of acceleration in physical activity, triaxial accelerometers have been developed to measure acceleration in three planes. Early studies suggested that uniaxial accelerometers may be just as effective as triaxial ones (105). In a more recent study, Bouton et al. (16) compared uniaxial accelerometry and triaxial accelerometry during sedentary activities and walking. It was determined that energy expenditure during sedentary activities and walking using three axes of measurement could be estimated with an accuracy of about 85% and that this information was more accurate than measurement using only one plane of acceleration.

Motion sensors are useful to researchers because they are small, relatively inexpensive, and appropriate for a variety of activities. However, it is important that individuals using these devices understand their value as well as their limitations.

### Heart rate analysis

Since an individual's heart rate increases with exercise intensity, researchers have investigated numerous methods of assessing energy expenditure based on heart rate. Such methods of predicting energy expenditure may be preferred over other methods because heart rate is a *physiological* parameter related to exercise. The use of heart rate to predict energy expenditure is based on the concept of the linearity between heart rate and oxygen uptake (35, 96, 100, 101) However, heart rate and oxygen uptake are not always highly correlated, especially during low intensity exercise (24). This relationship can also be affected by factors unrelated to exercise such as emotional stress, body position, environmental factors, and fitness level (39, 88). It has been shown that endurance training results in a lower heart rate at a given intensity of exercise (50). The correlation of heart rate and oxygen uptake is also affected by the amount of muscle mass used during exercise (102). Also, during exercise, changes in heart rate tend to "lag" behind measures of oxygen uptake (94), meaning that heart rate increases and decreases to match the intensity of exercise.

Based on the concept that heart rate will be elevated during exercise, energy expenditure has been predicted using 24-hour average heart rate measurements (24). Janz et al. (57) used mean heart rate monitoring to predict physical activity and found that whole-day heart rate averages were correlated with questionnaire recall (r= 0.50) and self-rating (r = 0 35). However, this method has been criticized because it does not account for confounding factors such as emotional stress or environmental factors.

A common method of heart rate analysis is based on heart rate reserve. The percent heart rate reserve (%HRR) is defined as the percentage of the difference in heart rate between resting and maximal exercise. Swain and Leutholtz (100) found that %HRR is strongly correlated with percent $\dot{V}O_{2\,max}$ (% $\dot{V}O_{2\,max}$), and this finding is in agreement with other studies (99, 101). However, previous researchers accounted only for heart rate above rest and did not consider oxygen uptake in the same manner. Since an individual consumes oxygen even at rest, it is logical that %HRR would be equivalent to % $VO_2$ reserve (% $VO_{2\,r}$) and not simply the percent of maximal oxygen uptake (% $VO_{2\,max}$). In the previously mentioned study by Swain and Leutholtz (100), the findings suggested that % $\dot{V}O_{2\,r}$ was more highly correlated to %HRR than % $\dot{V}O_{2\,max}$ These findings were confirmed by Strath et al. (99) Using the regression curves from these studies, it is possible to accurately predict energy expenditure using heart rate analysis

The most accurate way to predict energy expenditure from heart rate analysis is to use individual heart rate vs $\dot{V}O_2$ calibration curves and the FLEX heart rate (FLEX HR) method. An individual's FLEX HR is determined by measuring heart rate in various body positions and while performing light exercise. The FLEX HR is defined as the average of the highest resting heart rate and the lowest heart rate during light exercise (99). During heart rate monitoring, any heart rate below the FLEX HR is considered resting, and any heart rate above the FLEX HR uses an individual's calibration curve to predict energy expenditure (99). Individual HR/$VO_2$ calibration curves are then used for each subject that reflect various types of exercise, and the respective curve should be used to determine energy expenditure. Numerous studies have demonstrated the validity of the FLEX HR method (23, 69, 96). Spurr et al. (96) compared minute-by-minute FLEX HR measurements to whole-body indirect calorimetry over a 22-hour period which included four exercise bouts. The investigators found no significant differences between the FLEX HR method and indirect calorimetry in calculating energy expenditure. Livingstone et al. (69) compared energy expenditure as measured by the FLEX HR method to that measured by the doubly labeled water method which is considered the "gold standard" measure of energy expenditure (77). The researchers concluded that this type of heart rate monitoring provides a close estimation of total energy expenditure, with most values lying within 10% of the respective doubly labeled water measure. However, it has been shown that the FLEX HR method of determining energy expenditure may overestimate actual energy expenditure by about 10% (35) Still the FLEX HR method is considered the most accurate method to predict energy expenditure based on heart rate measures (23, 69, 96). Despite the accuracy of this method, it may not be applicable for larger populations since individual calibration curves may be time consuming and expensive

No matter which method is used to analyze heart rate measurements, each method is based on the relationship between heart rate and oxygen uptake which is imperfect and can be confounded by many factors. While some techniques are certainly more accurate than others, it should be noted that each method of heart rate analysis may be appropriate in certain situations.

## Maximal Oxygen Uptake

Maximal oxygen uptake ( $\dot{V}O_{2\,max}$) is considered the best measurement cardiorespiratory fitness, or aerobic capacity (7, 92). It is defined by Powers and Howley (85) as "the greatest rate of oxygen uptake by the body measured during severe dynamic exercise, usually on a cycle ergometer or treadmill; dependent on maximal cardiac output and the maximal arteriovenous oxygen difference". It is one of the major factors affecting performance in any aerobic endurance activity, and it is commonly measured in exercise and performance laboratories. However, the importance of cardiorespiratory fitness is not limited to athletes. High levels of cardiovascular fitness are associated with lower rates of cardiovascular disease and all-cause mortality (14, 67, 79). Typical values of $\dot{V}O_{2\,max}$ vary from <20 $ml{\cdot}kg^{-1}\ min^{-1}$ for sedentary healthy individuals to >80 $ml\ kg^{-1}{\cdot}min^{-1}$ for elite endurance athletes. The following section will explain $VO_{2\,max}$ and its physiological determinants, and ways to measure $VO_{2\,max}$ both directly and indirectly.

## Physiological determinants of maximal oxygen uptake

VO2max equals the product of maximal cardiac output (Q) and maximal arteriovenous oxygen (a-$vO_2$) difference. When determining whole body $VO_{2\,max}$, it is important to consider metabolic capacity of the skeletal muscles, illustrated by the a-$vO_2$ difference. These are physiological variables that can adapt and improve with endurance training The next section will discuss maximal oxygen uptake, its physiological determinants, and factors limiting VO2max

### Cardiac output

Cardiac output is a measure of the heart's ability to supply oxygen enriched blood to the periphery of the body. Cardiac output is typically ~5 L/min at rest, and can increase fivefold during exercise (93, 98). Stroke volume and heart rate are direct determinants of cardiac output, and therefore indirect determinants of $\dot{V}O_{2\,max}$ Stroke volume is linearly related to the intensity of exercise until the intensity reaches 40-60% of maximum work rates, where it plateaus (93). Since both the size and the contractility of the heart increase with training, so too does stroke volume Blood volume can also contribute to a higher stroke volume. With an increase in stroke volume, an individual's heart rate at a given work rate after training is lower because of the improved efficiency of the heart (50). Cardiac output can be greatly improved with training, as evidenced by the range of values between individuals.

It has been determined that cardiac output is a limiting factor in whole body $VO_{2\,max}$ This is shown by the fact that during maximal effort, nearly all of the oxygen supplied via arterial blood is consumed by the active muscles (84). Further proof of cardiac output as a limiting factor is the fact that beta-blockers, which decrease maximal heart rate, cause a decline in $VO_{2\,max}$ (11)

### Arteriovenous oxygen difference

The arteriovenous oxygen difference is a measure of oxygen extraction by the working muscles. It is widely accepted that even during maximal effort, arterial blood is sufficiently saturated with oxygen as it passes through the lungs. However, this may not be true in all cases. In a study consisting of elite athletes, Dempsey et al. (31) showed that arterial desaturation may occur due to the decreased transit time through the pulmonary capillaries This is evidence that the arteriovenous oxygen difference can be a limiting factor for $\dot{V}O_{2\,max}$ in some circumstances. It should be noted that in most cases, an increase in $VO_{2\,max}$ results from an increase in cardiac output rather than the arteriovenous oxygen difference. Ekblom et al. (33) studied the effects of a 16-week training program to increase $\dot{V}O_{2\,max}$. He found that the increase in $\dot{V}O_{2\,max}$ corresponded with an 8% increase in cardiac output and only a 3.6% increase in arteriovenous oxygen difference, indicating that cardiac output has a greater impact on $VO_{2\,max}$.

### Skeletal muscle respiratory capacity

With endurance training there is a significant increase in the number of mitochondria and also in the level of mitochondrial enzymes in the muscles (91). The effects of these variables on $VO_{2\,max}$ is discussed in a classic paper by Saltin and Gollnick (91) These researchers claim that skeletal muscle adaptation plays only a minor role in the improvement of $VO_{2\,max}$. They point to the fact that low-intensity training may cause an increase in mitochondria and mitochondrial enzymes without a corresponding change in $\dot{V}O_{2\,max}$ They conclude that the skeletal muscle mitochondrial adaptations occur in order to allow the system to operate more efficiently and effectively. This is explained using the concept of Michaelis-Menten kinetics, that high levels of enzymes in the system allow for greater activation of the system with a smaller disturbance (a lower work rate). The result is less lactate and a greater utilization of fat at a given work rate. An improvement in capillary density is also seen following training (91). However, the researchers note that the increase in capillary density is to increase the amount of time the blood spends in the capillaries, and therefore plays only a minor role in the increase of $\dot{V}O_{2\,max}$. This is in agreement with suggestions made by other researchers (88).

In conclusion, it is apparent that both cardiac output and the arteriovenous oxygen difference are the primary factors limiting $\dot{V}O_{2\,max}$. It seems that the work by Saltin (91) in 1983 provides the most convincing evidence of the factors limiting $\dot{V}O_{2\,max}$. Saltin studied the effects of maximal effort in an isolated quadricep group. The results showed that the isolated muscle demonstrated a $\dot{V}O_{2\,max}$ 2-3 times higher than the same muscle group during whole body exercise. Thus, the skeletal muscle has an extremely high capacity for aerobic work, and the cardiovascular system, in particular cardiac output, must be the primary factor limiting $\dot{V}O_{2\,max}$. More recently, it has been estimated that 70-85% of the limitation in $\dot{V}O_{2\,max}$ is due to cardiac output (11).

### Protocols for the measurement of maximal oxygen uptake

Over the years there has been considerable discussion concerning factors that may effect the measurement of maximal oxygen uptake. It has been suggested the exercise protocol (continuous vs. discontinuous), exercise device, and even environmental temperature can affect the measurement of $VO_{2\,max}$ (95). The following section is devoted to the discussion of such factors.

### Discontinuous vs. Continuous protocols

A maximal exercise testing protocol can be classified as a continuous exercise test or a discontinuous exercise test. A discontinuous test would allow a person to rest from exercise for a given period of time, from a few minutes to hours. A continuous protocol consists of a sequential progression of the test with no rest periods. It was hypothesized that previous submaximal exercise may affect the outcomes of a maximal exercise test, and therefore a discontinuous protocol should be used to allow a subject to adequately recover before progressing. However, studies have shown that measures of $\dot{V}O_{2\,max}$ show no differences in measurements between a continuous and discontinuous protocol (72, 73, 97). Therefore it can be concluded that $\dot{V}O_{2\,max}$ is unaffected by "cumulative submaximal work", unless the submaximal work is extremely prolonged (97). Given the validity of a continuous protocol, it is generally the preferred protocol because it takes less time compared to a discontinuous protocol.

### Various modes of exercise

Research has shown that maximal oxygen uptake is influenced by the mass of muscle used during exercise (102). It seems logical then that various modes of exercise would yield different measures of maximal oxygen uptake since they require the use of different amounts of muscle mass

Graded exercise tests (GXT) are typically performed using a cycle ergometer or treadmill. McArdle et al. (73) determined that maximal oxygen uptake values measured on a cycle ergometer are 10-11% lower than those measured using a running treadmill protocol. This is because the cycle ergometer uses primarily the quadricep muscles. This finding has also been illustrated by other researchers (18, 42, 49). Although less common, arm crank ergometers have been used to measure $VO_{2\,max}$. As expected, these values have been shown to be 30% lower than treadmill values (7). Again this is due to the smaller muscle mass being utilized during exercise.

When choosing an appropriate GXT, it is important to consider the population being tested. Frail individuals, or individuals with orthopedic problems should be tested on a cycle ergometer since it puts less stress on the skeletal system. Also, although values of $\dot{V}O_{2\,max}$ tend to vary with the amount of muscle mass used (102), often it is most appropriate to use a protocol that is specific to the type of exercise performed by the athlete (95).

### Special considerations for treadmill testing

Treadmill exercise testing is unique to other types of tests because two variables, speed and percent grade, can be adjusted to modify the work rate. Treadmill GXT's may consist of a constant speed with a progressive increase in percent grade, while others incorporate a constant grade with an increase in speed. Several studies indicate that maximal exercise tests using an increase in grade result in higher values of $\dot{V}O_{2\,max}$ (3, 7, 102). This agrees with the notion that $\dot{V}O_{2\,max}$ is dependent on the amount of muscle mass involved. However, a specific training program can affect performance on these types of tests (3, 41)

Treadmill exercise tests consisting of a constant speed must select a speed which optimizes measurements while minimizing risks. A walking test such as the Balke protocol consists of a 3.3 mph walk with a progression of percent grade. This test is valuable for those with a low fitness level or for those at a higher risk of a cardiac event However, the Balke protocol tends to underestimate $\dot{V}O_{2\,max}$ when compared to running protocols (42).

### Bruce protocol

The $VO_{2\,max}$ test used in this study, the Bruce protocol, consists of a progression of both speed and grade with each 3-minute stage (17). This protocol is commonly used for young, healthy individuals without any apparent contraindications to high impact exercise. During the initial stage of this protocol, subjects walk at a speed of 1.7 mph at a grade of 10%. Each stage incorporates an increase of speed and a 2% grade increase It has been demonstrated that the Bruce protocol provides an accurate measure of aerobic capacity (42), and that these measures are reproducible (38). As seen with other running protocols, the Bruce protocol yields slightly higher values of $VO_{2\,max}$ than walking protocols

## Criteria for achieving maximal oxygen uptake

Maximal oxygen uptake was first studied in detail by A.V Hill in the early 1900's. While few of the theories and findings provided by Hill have been disproven, the vast majority of his ideas have held true. In 1923 Hill and Lupton (51) claimed that "actual oxygen intake...reaches a maximum beyond which no effort can drive it...The oxygen intake may attain its maximum and remain constant merely because it cannot go any higher" Hill's statements suggest that there may be a plateau in oxygen uptake at very high workloads, and it is this plateau that defines maximal oxygen uptake. A plateau in oxygen uptake has been considered the best determinant of $VO_{2\,max}$ (8). However, not all people demonstrate a plateau in oxygen uptake. In a review by Howley et al. (52) it is noted that studies investigating this plateau have shown contrasting results, and reports of the percent of individuals achieving this plateau has varied from 50-100%  These discrepancies may be due to different definitions of a plateau. In the same review Howley suggests that factors affecting the achievement of a plateau include the population being studied, the protocol being used, and subject motivation. Since not all individuals can achieve a plateau in oxygen uptake, secondary criteria have been developed to validate a $\dot{V}O_{2\,max}$ value. If a sufficient number of these criteria are not met, the value should be termed a $\dot{V}O_2$ peak and not a true max.

### Plateau in oxygen uptake

Defining a plateau in oxygen uptake has proven to be a difficult task. When defining this plateau, care should be taken so that the definition is not too liberal or conservative Measurement error should also be considered in the definition of a plateau  For example, Howley et al. (52) suggests that “cut-off values of approximately 50-60 ml/min approach the limits of one’s ability to measure $VO_{2\,max}$”. Most definitions for the plateau in oxygen uptake depend on the predicted change in oxygen uptake for sequential stages. For example, in a test protocol used by Mitchell et al. (76), a plateau was defined as an increase in oxygen uptake of less than 54 ml$\cdot$kg$^{-1}\cdot$min$^{-1}$ from one stage to the next. While many investigators have used this type of definition, they are not applicable to studies using different protocols. Issekutz et al  (54) suggested that the plateau would be evident if an increase in the workload of 150 $kpm\cdot min^{-1}$ does not increase oxygen uptake by more than 100 $ml\cdot min^{-1}$, or if the measured oxygen uptake at a given work rate is below the expected value by 150 $ml\cdot min^{-1}$ or more.

### Blood lactate

Blood lactate is an indicator of the intensity of effort because levels of lactate are associated with muscle fiber recruitment, plasma epinephrine levels, and the reduction in liver blood flow that occurs with exercise (52). In a classic study by Åstrand (4), those individuals achieving a plateau in $\dot{V}O_2$ had average blood lactate values of 7.9-8.4 mM. These values were then applied to those not achieving a plateau to validate their efforts. Even though there has been variation in the values of blood lactate indicative of a maximal effort, Åstrand's suggestion of 7.9-8.4 mM seems to be the most widely accepted.

### Respiratory exchange ratio

Blood lactate levels are theoretically related to RER because a rise in RER is due to the need to remove lactic acid from the body. Given this assumption, it logical that if one of these criteria is met, so should the other. This has been shown to be true (53). Cumming and Borysyk (29), however, have shown that lactic acid accumulation and RER are unrelated at maximal levels. Nevertheless, both blood lactate and RER are used as criteria for the achievement of $VO_{2\,max}$. In a classic paper by Issekutz et al. (53), the authors mention that RER at heavy work loads is always above 1.0, and that values as high as 2.1 have been reported. In the study by Issekutz et al, 32 untrained subjects exercised on a cycle ergometer until maximal oxygen uptake was achieved. Measurements during these maximal tests showed that "each subject, regardless of sex and age, reached the maximal $O_2$ uptake at about the same value of $\Delta RQ = 0\ 4$ (RQ 1.15)". According to Howley et al (52), "an $R \geq 1\ 15$ is not a universal finding, even in those who demonstrate a plateau in VO2". However, this value is commonly used value to validate a maximal effort.

Maximal heart rate

Using maximal heart rate as a criterion for achievement of a maximal effort has long been criticized because of the error of estimation. An individual's maximal heart rate can be estimated using the formula 220-age. However, the standard deviation associated with this formula is 11 $b \cdot min^{-1}$ (52). Therefore, an individual whose maximal heart rate lies below the predicted value cannot reach the age-adjusted predicted value during an exercise test. Because of the error involved, maximal heart rate cannot be considered accurate in validating a maximal effort (70) Nevertheless it is often used along with other criteria to assist in the validation of a measure of $\dot{V}O_{2\,max}$. Researchers have used different guidelines to determine whether or not an achieved heart rate is suggestive of a maximal effort These guidelines have included a heart rate at or above age-predicted maximal heart rate, 95% of the age-predicted value, or within 5 or 10 beats of the age-predicted value (52). No matter which guideline is used, there is considerable error involved with the use of heart rate as a criterion for $\dot{V}O_{2\,max}$.

Summary

It is important to note that the most widely used criteria for achieving $\dot{V}O_{2\,max}$ is the plateau in oxygen uptake (8) However not all subjects, regardless of effort, can achieve this plateau (52) The aforementioned criterion are often used to distinguish a $VO_{2\,max}$

from a $VO_2$ peak. However, these criteria were developed using a discontinuous protocol for measurement of $\dot{V}O_{2\,max}$ (32). Because most $\dot{V}O_{2\,max}$ tests currently used are continuous protocols, Duncan et al (32) studied the applicability of these criteria to a continuous protocol. The researchers found that these criteria are useful as secondary criteria for a continuous protocol, and specifically that the use of "RER and lactate in combination, increases the likelihood that the highest $VO_2$ value achieved was $VO_{2\,max}$".

Submaximal exercise tests to predict maximal oxygen uptake

Over the years there has been an increasing interest in the use of submaximal exercise tests to predict aerobic fitness due to the risks involved with maximal GXT's It has been reported that there is a 3-fold increase in health risks associated with a maximal GXT when compared to a submaximal test (95).

Historically, the most common submaximal tests to predict $\dot{V}O_{2\,max}$ were based on the relationship of heart rate and $VO_2$ at one or more submaximal work rates, and extrapolation of the plotted line to maximal heart rate This type of protocol was used by Åstrand and Rhyming in 1954 (5) and by other researchers to follow (44, 71) Using this protocol, the difference between estimated and determined values of half-maximum oxygen uptake was 0.023 ± 0 059 l/min. However, these results have been criticized because they do not represent a wide range of estimated values. Åstrand has since reported that when maximal treadmill test values are low, $\dot{V}O_{2\,max}$ is underestimated using submaximal tests and vice-versa (8) Other protocols have since been designed that incorporate two to four separate measures of heart rate vs. workload to reduce error associated with the extrapolation of the curve. Wyndham et al. (111) used four submaximal work rates to predict $VO_{2\,max}$ and compared the results to $VO_{2\,max}$ as measured during a maximal treadmill test. The predicted $\dot{V}O_{2\,max}$ of the subjects was 3 18 ± 0.75 l/min. The measured mean value was 3.21 ± .40 l/min, illustrating an insignificant difference In a more recent study by Loudon et al (71), $\dot{V}O_{2\,max}$ was predicted based on two submaximal heart rate measurements and was compared to a maximal exercise test. No significant differences were found between the predicted and measured values of $\dot{V}O_{2\,max}$. The investigators reported that the standard error of estimation of 10% is "clinically insignificant, and therefore the maximal exercise test can be a valid measurement of maximal oxygen consumption". This 7-10% error has been reported by additional researchers (44, 95). Wyndham notes that the error of estimation can be reduced by 2% if a true maximal heart rate is used instead of estimated for extrapolation (111).

Regarding submaximal exercise tests, "the present consensus is that prediction procedures give a useful indication of fitness levels in larger populations" (95) However, due to such variability in the heart rate response to exercise, and the error associated with the formula to predict maximal heart rate, "if applied to an individual, they provide a simple index of week-to-week variations in aerobic power, but on any one occasion, the range of possible error is too large to provide more than a very crude index of aerobic fitness" (95).

Non-exercise equations to predict fitness

$\dot{V}O_{2\,max}$ can be estimated without exercise testing using non-exercise prediction equations. Non-exercise prediction equations may take into account variables such as age, height, weight, body composition, physical activity levels, resting heart rate, and resting metabolic rate. Jackson and associates (55) studied the accuracy of these equations by comparing them with a submaximal exercise test and a Bruce protocol maximal exercise test. Gender, age, self-reported physical activity, and resting heart rate were used to develop two equations. One of these equations also included percent body fat (from skinfolds) to account for body composition, and the other used body mass index (BMI). The equation including percent body fat was the most accurate when compared with maximal exercise testing ($r= 0.821$, S.E.= 5.23 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) Inclusion of BMI instead of percent body fat resulted in a reduction in the multiple correlation from 0.821 to 0.794, and the S E. increased to 5.55 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$. Additionally, the researchers found that these equations were more accurate at predicting $VO_2$ peak than the submaximal exercise test proposed by Åstrand. Other studies that have investigated non-exercise regression models to estimate fitness have demonstrated similar results. Heil et al (48) developed a regression model including gender, age, percent body fat, and physical activity This equation yielded even more promising results ($r= 88$, S.E = 4 90 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) regarding the use of these equations.

Scientists at Polar Electro Oy, Inc. attempted to improve upon these non-exercise equations by incorporating heart rate variability (HRV) into a non-exercise fitness equation (61). HRV was measured using a Polar R-R recorder which recorded at least 250 R-R measurements. Results indicated that this prediction was more accurate (within 6.5% on average) than previously mentioned predictions for estimating fitness. The fact that HRV may be related to aerobic power has been shown be previous studies (30, 113).

Despite the accuracy of the predictions obtained using non-exercise equations, their use has been questioned. Whaley et al (107) suggests that due to extreme variability in predicted scores using these equations, “such models fail to provide the accuracy for categorizing cardiorespiratory fitness within large epidemiological cohorts”. However, the use of non-exercise equations to predict fitness are an invaluable tool in many settings, especially when considering those individuals for which exercise testing is contraindicated

## Indirect Calorimetry

Calorimetry is used to measure the amount of energy (heat) generated by the body Direct calorimetry measures the total amount of heat loss from the body using a thermically isolated chamber to measure the amount of heat dissipated by evaporation, radiation, and conduction/convection (37). The amount of heat dissipated provides valuable information regarding energy expenditure. Indirect calorimetry measures multiple variables of metabolism using oxygen consumption as well as carbon dioxide production. Indirect calorimetry has been a valuable tool for physiologists since the 19th century (83) Although direct calorimetry is less common than the indirect method, direct calorimetry has been important in the validation of indirect calorimetry (34) The following section is dedicated to discussion of the principles, applications, and limitations of indirect calorimetry in measuring energy expenditure and substrate utilization in humans.

### Principles of indirect calorimetry

When any substrate is oxidized, there is a concurrent consumption of oxygen and release of carbon dioxide and water. While either of these outcomes can be used alone to determine substrate utilization, it seems that measurement of oxygen consumption accompanied by measurement of carbon dioxide release is the most accurate when dealing with indirect calorimetry (34, 37). The result of these measurements is the respiratory quotient (RQ). This ratio, sometimes referred to as the respiratory exchange ratio can vary from 70 to >1.30 (75, 83) and is used to determine relative substrate utilization It has been shown that the respiratory quotient is accurately measured using indirect calorimetry up to 85% of $VO_{2\,max}$ (86). In addition to the respiratory quotient, the energy equivalents of oxygen and carbon dioxide are also important in indirect calorimetry, and will be discussed later.

### Respiratory quotient

As previously mentioned, the respiratory quotient is the ratio of the amount of carbon dioxide released and the amount of oxygen consumed. Since each substrate demands a given amount of oxygen and produces a given amount of carbon dioxide for oxidation, each of the substrates has its own quotient (FQ) The FQ of foodstuffs is determined using stoichiometric calculations using the appropriate calorimetric coefficients and heats of combustion (34).

Heats of combustion can be measured directly using a bomb calorimeter or can be predicted from the chemical composition of the molecule (34). Experiments using a bomb calorimeter can provide the appropriate information regarding oxygen consumption and carbon dioxide release from a particular foodstuff. However, the FQ for both carbohydrate and fat varies only slightly (34) Protein should be taken into consideration when dealing with these measurements, but its discussion will be presented later. It has been determined that oxidation of fat alone would yield an RQ of approximately .70 and the oxidation of carbohydrate alone would yield a value of 1.0 or higher (75, 83).

The respiratory exchange ratio (RER) is the equivalent of the RQ as measured at the mouth. RER is used to determine substrate utilization both at rest and during exercise. There are several factors that can alter RER at a given work rate. Costill studied the effects of exercise duration on RER and found that RER decreased after 2 hours of continuous exercise at a given intensity (27). This is related to substrate availability. After long periods of exercise, carbohydrate stores may be depleted and therefore the body oxidizes more fat as a fuel source, resulting in a lower RER value. RER is also dependent upon fitness level. Highly trained subjects will oxidize more fat (and have a lower RER) at a given absolute exercise intensity than untrained individuals (26). Also, the amount of fat and carbohydrate in a persons diet may alter RER because of the availability of substrates (23).

### Energy equivalents of oxygen and carbon dioxide

Also determined through the use of bomb calorimetry and stochiometry are the energy equivalents of oxygen and carbon dioxide. Similarly to RQ values, the energy equivalents of oxygen and carbon dioxide vary only slightly for both fat and carbohydrate (34). Indirect calorimetry only requires a knowledge of the energy equivalent of oxygen (along with the RQ) to determine overall energy expenditure. The energy equivalent of oxygen for fat is 4.686 kcals/$LO_2$, and for carbohydrate is 5.047 kcals/$LO_2$ (34). Theoretically then, if a researcher measures an RQ of 1.0 on a subject, that subject is utilizing only carbohydrate as a fuel and is expending 5.047 kcals of energy for each liter of oxygen consumed.

### Oxidation of a multiple-substrate mixture

So far, this review of indirect calorimetry has discussed the appropriate values and measurements associated with lone substrates. In reality, the human body oxidizes a mixture of a number of substrates including carbohydrate, fat, protein, and alcohol. When only two substrates are oxidized simultaneously, their relative utilization can be determined using the RQ (34). Using this method, any RQ between 0 70 (the RQ of fat) and 1.0 (the RQ of carbohydrate) illustrates a mixture of substrate contribution. The relative contributions of carbohydrate and fat for each RQ from 0.70 to 1.30 have been determined experimentally and have been published and revised for many decades (75, 83), with the most recent revisions done by Peronnet (83). It has also been determined that the RQ of a subject in the resting state is approximately 0.82 (63).

For each additional substrate being utilized, an additional measurement is necessary to determine its contribution to energy expenditure. Alcohol and protein are substrates of importance when performing indirect calorimetry in humans. Alcohol presents less of a problem than protein when measuring substrate utilization This is because virtually all alcohol is absorbed and oxidized by the body, therefore the amount ingested provides a good indication of the amount oxidized (34) Protein presents a larger problem, thus will be confined to the next section.

### Protein oxidation

There are many complications involved with protein metabolism, and its inclusion in indirect calorimetry measurements is very cumbersome. First, unlike each of the other substrates, protein is not completely oxidized in the body (34, 37) Secondly, different types of protein vary dramatically, therefore it is difficult to obtain an accurate RQ or energy equivalents (62). In fact, the FQ values of protein have ranged from 707 to 95 (62) Given these facts, it is not advantageous to measure protein oxidation via indirect calorimetry. The most common method of determining protein metabolism is by measuring urinary nitrogen, a byproduct of protein metabolism (34, 74). For every 6.25 grams of protein metabolized, 1 gram of nitrogen is excreted in the urine (74) Also, each gram of nitrogen excreted in the urine represents a $CO_2$ production of 4.8 L and an $O_2$ of 6.0 L (74). Using these conversions, one can calculate a *nonprotein* RQ, which is applies only to the oxidation of carbohydrate and fat. Due to the complicated nature of measuring protein metabolism, it is often ignored or estimated when measuring substrate utilization This is often preferred since it results in only an additional 1% error in substrate utilization measurements (63, 106).

### Assumptions and errors

Application of indirect calorimetry to measure energy expenditure and substrate utilization requires that assumptions be made, resulting in minor errors Since indirect calorimetry actually measures gas exchange and not metabolism, it must be assumed that all oxygen consumed is used to oxidize fuels (37). Additionally, it must be assumed that all of the carbon dioxide produced is recovered (37). Along the same lines, it is assumed that other metabolic processes such as lipogenesis are negligible (37).

It is important to note that indirect calorimetry is most useful when the subject is in steady state, meaning that all of the energy requirements are being met by aerobic metabolism During steady state exercise, oxygen uptake and carbon dioxide production are stable, and excess carbon dioxide production from blood bicarbonate stores (buffering of lactic acid) is not a factor. Research has shown that 1-3 minutes of constant load exercise is required to achieve steady state (76, 102). At very high work rates, the time required to achieve steady state may be even higher (6)

The term respiratory quotient, or RQ, refers to gas exchange in the tissues of the body. However, indirect calorimetry measures gas exchange at the mouth, and RQ is therefore not exactly the same as respiratory exchange ratio (RER). Since there is virtually no oxygen reserve in the body, oxygen consumption measured at the mouth quickly follows that measured at the tissues (37). Therefore, the terms RQ and RER are often used interchangeably.

Although the concepts and principles involved with indirect calorimetry are quite complex, there are few technical requirements. Still indirect calorimetry requires expertise regarding the instrumentation used and the principles involved. Ferrannini et al. (37) discusses some of the technical requirements which include: (1) sensitive and stable gas analyzers; (2) an appropriate calibration routine; (3) a system to remove moisture from expired air; and (4) software to store and manipulate data.

Even after consideration of the limitations and errors of indirect calorimetry, at present there is no simpler method of obtaining such accurate and precise measurements Given the appropriate stochiometric values and trained personnel, the error of presented using this method to estimate energy expenditure is 1.5-3% when both oxygen consumption and carbon dioxide production are measured (34, 65).

# CHAPTER III

# METHODS

Eight subjects (4 male, 4 female) under age 45 were recruited from the Knoxville, Tennessee community to participate in this study. Subjects were eligible for this study only if they had no apparent contraindications to exercise testing. Prior to participating in the study, each subject signed an informed consent form approved by the University of Tennessee-Knoxville institutional review board.

Each subject completed four separate exercise tests, including three submaximal tests and one maximal test. Each test was performed on a separate day. Each test lasted approximately one hour, and was done at the Applied Physiology Laboratory at the University of Tennessee-Knoxville.

## Baseline Data

On the first day of testing each subject was asked to complete a health history form (Appendix A) and an informed consent form (Appendix B). Next, the subjects weight was measured (without shoes and in exercise clothing) using a physician's scale Height was measured (without shoes) using a stadiometer. A Tanita TBF-305 (Skokie, IL) bioelectrical impedance machine was used to estimate each subject's body composition.

## Maximal testing

On the day of maximal testing, subjects were asked to avoid eating a heavy meal and smoking for 2-3 hours prior to testing. Subjects were also advised to avoid heavy physical effort, alcoholic beverages, and pharmacological stimulants on the test day and the day before.

### Polar fitness test

Subjects were asked to define their level of physical activity according to the categories provided in the literature supplied with the Polar M52 monitor (low, middle, or high). The heart rate watch was programmed with the appropriate information regarding the user, and the subject was asked to relax in a supine position while wearing the heart rate monitor. After 3-4 minutes of rest, the researchers started the fitness test to be performed by the monitor. Subjects were instructed to be relaxed and refrain from talking during the test, as instructed by the Polar literature After 5 minutes, the monitor displayed the fitness index, and the subject stood up.

### Maximal exercise test

After completing the Polar fitness test, the subject was instructed to stretch appropriate muscle groups and warm-up on the treadmill while wearing the Polar M52 heart rate monitor The warm-up lasted 5 minutes. During the warm-up the speed of the treadmill was controlled by the subjects who were instructed to reach 70% of age-predicted maximal heart rate. After the warm-up, subjects were provided a brief rest (approximately 2 minutes) while the researchers adjusted equipment. Subjects were equipped with a noseclip and a mouthpiece used for data collection. A Hans Rudolph (Kansas City, MO) two-way, non-breathing valve (2700 Series, large) was attached to the mouthpiece and also to two tubes, one for inspired and the other for expired air

Expired gases were collected and analyzed to calculate ventilation, oxygen consumption, and carbon dioxide production using a ParvoMedics TrueMax 2400

(Sandy, UT) metabolic cart. The Hans-Rudolph (Kansas City, MO) pneumotachometer was calibrated before each use with a 3 00 L syringe, and the gas analyzers were calibrated against concentrations of known gases previously analyzed using the Scholander technique The metabolic cart provided a hard copy of $VO_2$ and RER measurements every minute The subject was instructed to use appropriate hand gestures to signal volitional exhaustion, or to terminate the test for any other reason. The subject then performed the Bruce protocol (17) consisting of an increase in percent grade and speed every three minutes until volitional exhaustion. Subjects were encourage verbally to continue throughout the test At the end of each stage, heart rate and rating of percieved exertion were recorded. These variables were recorded more frequently as the subject approached volitional exhaustion so that maximal values were obtained. Maximal RER was also recorded using results provided by the metabolic system After volitional exhaustion was signaled, the subject remained walking on the treadmill for 3 minutes at a comfortable pace. After three minutes a 100 microliter blood sample was obtained from the subject's fingertip, using a sterile lancet to break the skin. This sample was then prepared for lactate analysis using the flourometric method described elsewhere (46). $VO_{2\,max}$ was defined as the highest oxygen uptake attained, and was further validated using additional criteria. Universal precautions were followed according to OSHA guidelines.

### Submaximal exercise testing

Three submaximal exercise tests were performed including a single test on a Monark 818E (Varberg, Sweden) cycle ergometer, a Quinton Q65 (Series 90) treadmill (Seattle, WA), and a Concept II rowing ergometer (Morrisville, VT). For each protocol, the subject exercised for three 8-minute stages, for a total of 24 minutes with a progressive increase in intensity at each stage. The rowing and cycle ergometer stages represented work rates of 50 watts (W), 100 W, and 150 W. The treadmill protocol included speeds of 3 mph, 4 5 mph, and 5 mph. During the cycle test, subjects were instructed to pedal to the beat of a metronome in order to maintain the work rates. While completing the rowing test, subjects controlled the work rate by watching the data output screen on the rower and self-maintaining the work rate. During testing, the researchers monitored the data output screen to be sure that work rates were maintained

Subjects were equipped with a noseclip and a mouthpiece used for data collection. A Hans Rudolph two-way, non-breathing valve (2700 Series, large) was attached to the mouthpiece and also to two tubes, one for inspired and the other for expired air. Expired gases were collected and analyzed to calculate ventilation, oxygen consumption, and carbon dioxide production using a ParvoMedics metabolic cart. The Hans-Rudolph pneumotachometer was calibrated before each use with a 3.00 L syringe, and the gas analyzers were calibrated against concentrations of known gases previously analyzed using the Scholander technique. The metabolic cart provided a hard copy of $\dot{V}O_2$ and RER measurements every minute. For the rowing ergometer test headgear was worn to hold the mouthpiece in place, and therefore the inspiratory tube was not needed. During each test, the subject also wore the Polar M52 heart rate chest strap and wristwatch. The watch was programmed with the user's information and was set to record OwnCal (energy expenditure and substrate utilization) The subject was allowed three minutes of exercise at each stage to reach steady state before measurements were recorded RER and $VO_2$ were recorded each minute and were averaged for minutes 3-8 of each stage

Energy expenditure and substrate utilization (OwnCal) were recorded from the heart rate monitor after the entire five minutes of steady state exercise, after which the watch was reset for the next recording

In order to determine *net* caloric expenditure, resting metabolic rate was estimated based on body surface area (15) and resting energy expenditure was subtracted from the measured *gross* caloric expenditure.

## Statistical analysis

Repeated measures ANOVA was used to compare the predicted and measured values of energy expenditure and substrate utilization over the three exercise intensities on each device. Using this analysis, both method differences and stage/method interaction were analyzed When appropriate, post-hoc paired samples t-tests (2-tailed) were done to determine differences at specific intensities This was done using a Bonferoni adjusted alpha to control for type I error

To examine differences between predicted and measured values of $VO_{2\,max}$, a paired samples t-test (2-tailed) was done. A correlation was also performed to determine the related trends

# CHAPTER IV

# RESULTS

This study was designed to investigate the accuracy of the Polar M52 heart rate monitor for estimating energy expenditure, substrate utilization, and maximal oxygen uptake Table 1 shows the physical characteristics of the subjects

**Table 1 – Subject characteristics**

| | N | Mean | Std Error |
|---|---|---|---|
| Age (years) | 8 | 25 8 | 2 2 |
| Height (in ) | 8 | 68 8 | 1 4 |
| Weight (lbs ) | 8 | 154 4 | 8 0 |
| Body Mass Index (kg/m$^2$) | 8 | 22.9 | 0 7 |
| Body fat (%) | 8 | 20 6 | 3 1 |
| RMR (kcals/hour) | 8 | 70 3 | 3 6 |

## Energy expenditure

Figure 1 shows bar graphs of mean energy expenditure for both Polar and indirect calorimetry measures for each exercise mode. Also, Bland-Altman plots are shown to the right of each respective bar graph to illustrate the individuals error scores (I C -Polar) over the range of exercise intensities.

For the treadmill submaximal exercise test there was a significant stage/method interaction (p= 0.049), meaning that the Polar estimates of energy expenditure were not consistent at each intensity. Post-hoc paired samples t-tests (using Bonferoni adjusted

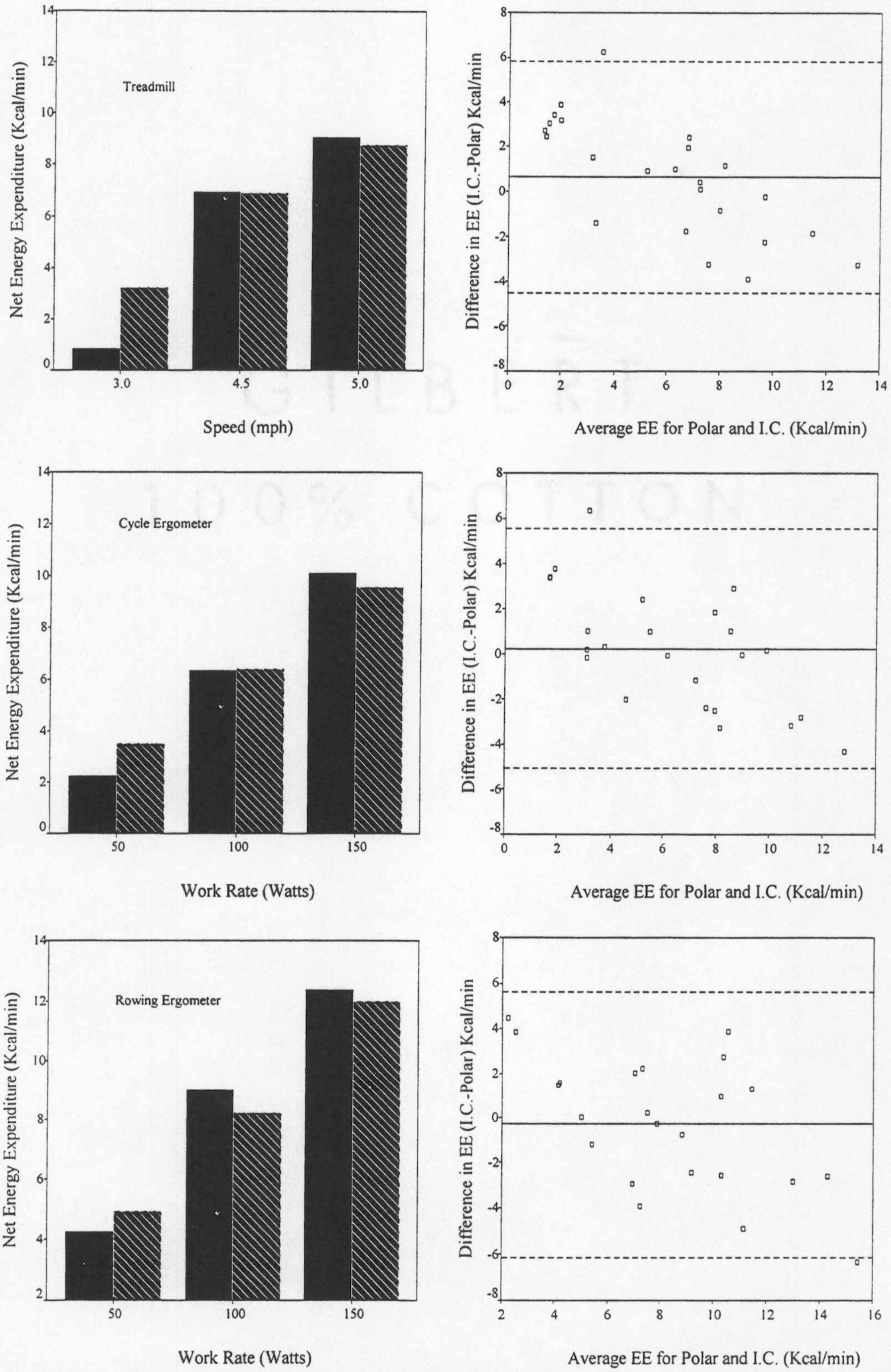

**Figure 1** – The bar graphs (left) contain mean data from all subjects for energy expenditure for each device (dark=Polar, light= Calorimetry). To the right of each bar graph is the respective Bland-Altman plot showing individual error scores over the entire range of intensities.

alpha of 0 016) indicated that there was a significant difference (p= 0.005) between the methods during stage 1, but not at stages 2 and 3 (p= 0.953 and 0.671). However, there was no overall significant difference between methods for determining energy expenditure (p= 0 367)

Both the cycle and treadmill exercise tests indicated that there was no significant stage/method interaction for either the cycle (p= 0 206) or the treadmill (p= 0.283) tests Also, there was no significant difference between indirect calorimetry and the Polar monitor for measuring energy expenditure (p= 0.778 and 0 862) It is worth noting that stage 3 of the rowing protocol had a single missing value because the subject did not complete the stage.

The Polar M52 heart rate monitor underestimated net energy expenditure by 0.22 kcal/min (6 76 vs. 6.98 kcals/min) for the entire pool of submaximal measurements

### Substrate utilization

Figure 2 shows bar graphs representing each exercise device and the mean values of the percent kcals from fat for both the Polar monitor and indirect calorimetry. Bland-Altman plots are shown to the right of each respective bar graph to illustrate the error associated with such measurements

The initial ANOVA performed for the treadmill showed no stage/method interaction (p= 0 057) and no significant differences between the two methods of measurement (p= 0 137) However, for the first stage there were 4 missing values, and for the second stage there was one missing value These values were missing because if the individual's heart

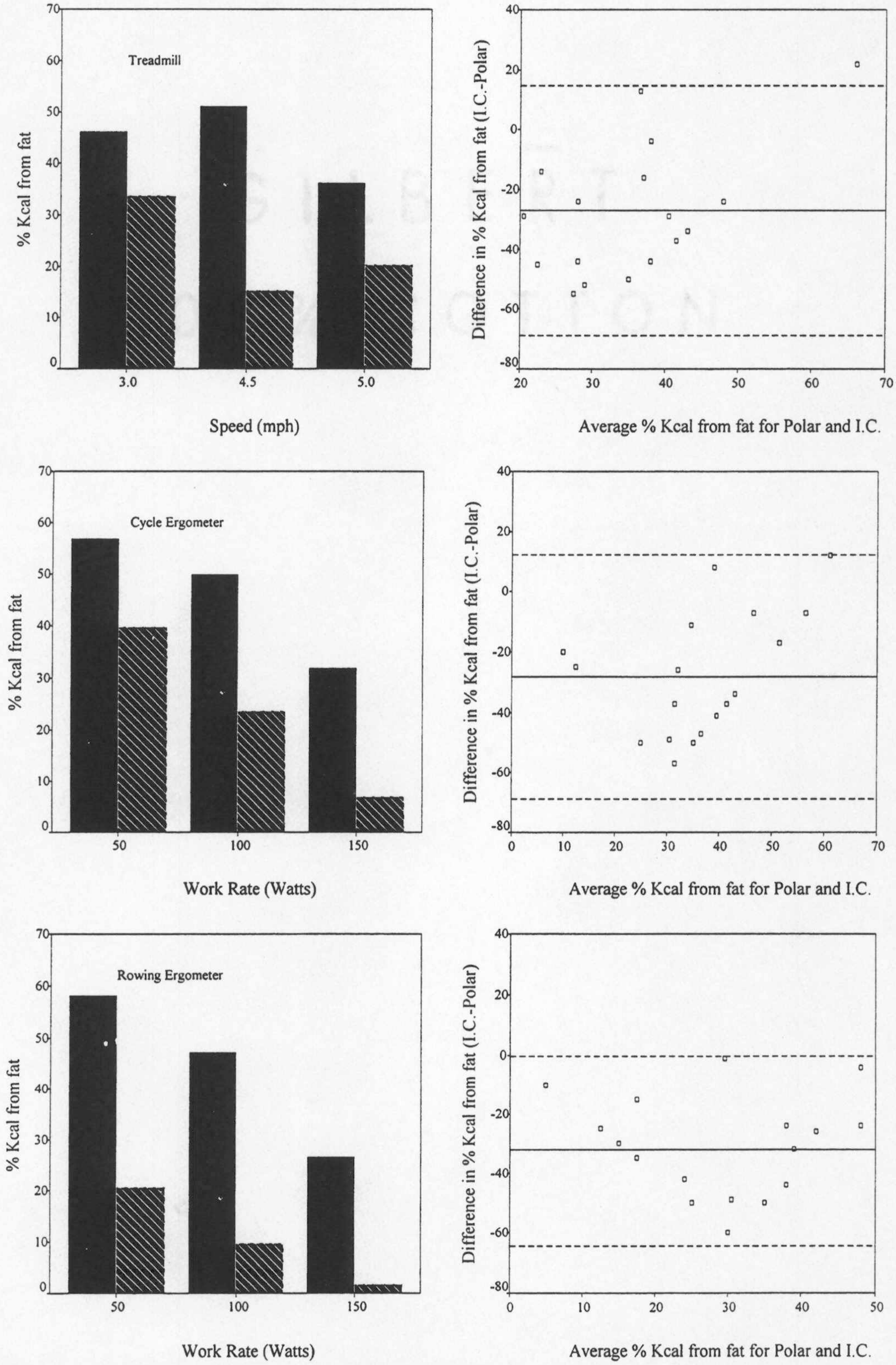

**Figure 2** – The bar graphs (left) contain mean data from all subjects for the percent kcals from fat for each device (dark=Polar, light= Calorimetry). To the right of each bar graph is the respective Bland-Altman plot showing individual error scores over the entire range of intensities.

rate did not reach 100 bpm for the stage, no values for carbohydrate or fat contribution to the total energy expenditure were displayed by the monitor. Since stage one (N= 4) lacked statistical power, ANOVA was repeated for only stages two and three This reanalysis demonstrated a significant stage/method interaction (p= 0.037) and a significant difference between methods (p= 0.004) It is obvious that the heart rate monitor grossly overestimated the percent of kilocalories from fat on the treadmill, but this overestimation was not consistent across all intensities

The results from the cycle ergometer ANOVA also suggested that there was no stage/method interaction (p= 0.205) for substrate utilization and no significant difference between methods (p= 0.059). However, again there were missing values in stage one (N= 5) resulting in a loss of statistical power. When ANOVA was repeated using only stages two (N=7) and three (N=8), there was no significant stage/method interaction (p= 0.965), but there was a significant difference between methods (p= 0.002) This suggests that even though the percentage of kcals from fat was underestimated, this underestimation was consistent throughout the exercise intensities.

Since there was only one missing value for the first stage of the rowing protocol, ANOVA was only performed for all three stages. There was also a missing value for stage three because one subject was unable to complete the stage. Using these results, there was no significant stage/method interaction (p= 0.068), but there was a highly significant difference (p= <0.001) between the methods of measurement. Again, the overestimation of fat utilization is at least reasonably consistent in this case

The Polar M52 heart rate monitor overestimated fat oxidation by 29.15 % kcals from fat (47.13 vs 17.98 % kcal from fat) for the entire pool of submaximal measurements

Since both energy expenditure and substrate utilization are related to heart rate during exercise, Table 2 was included to show the mean heart rate for all subjects for each exercise intensity on each device

## Maximal oxygen uptake

Table 3 shows the mean values for the $VO_{2\,max}$ test, including secondary criteria to distinguish $VO_{2\,max}$ from a $VO_2$ peak. All eight subjects achieved at least two of the three criteria, suggesting that each subject reached a true $VO_{2\,max}$.

Figure 3 depicts the estimated and measured values for $VO_{2\,max}$ The bar graph shows the mean values for the estimated (Polar) and measured (I C ) values. The plotted line graph shows the correlation between the methods of measurements.

A paired t-test indicated that there was a significant difference (p= 0 015) between the predicted and measured values of maximal oxygen uptake. The measured mean was 49 7 ml•kg$^{-1}$•min$^{-1}$ (S.D. 4.8) compared with an estimated mean of 45 9 ml•kg$^{-1}$•min$^{-1}$ (S.D

**Table 2 – Mean steady state heart rate (bpm) for submaximal testing.**

| | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| Treadmill | 94 3 | 130 4 | 143 5 |
| Cycle ergometer | 99 8 | 126 2 | 153 4 |
| Rowing ergometer | 112 4 | 141 8 | 167 8 |

**Table 3 – Maximal oxygen uptake data**

| | N | Mean | Std Deviation |
|---|---|---|---|
| Measured Maximal oxygen uptake (ml•kg$^{-1}$•min$^{-1}$) | 8 | 49 7 | 4 8 |
| Estimated Maximal oxygen uptake (ml•kg$^{-1}$•min$^{-1}$) | 8 | 45 9 | 5 1 |
| Lactate (mM) | 8 | 12 4 | 2 8 |
| Heart rate (bpm) | 8 | 189 4 | 11 4 |
| RER | 8 | 1 24 | 0 08 |
| Rating of perceived exertion | 8 | 18 6 | 1 19 |

5 1) A significant correlation (r= 0.772) between estimated and measured values (p= 0.025) was also demonstrated.

The Polar M52 heart rate monitor overestimated values of $VO_{2\,max}$ by an average of 3 8 $ml \cdot kg^{-1} \cdot min^{-1}$, or ~1 MET.

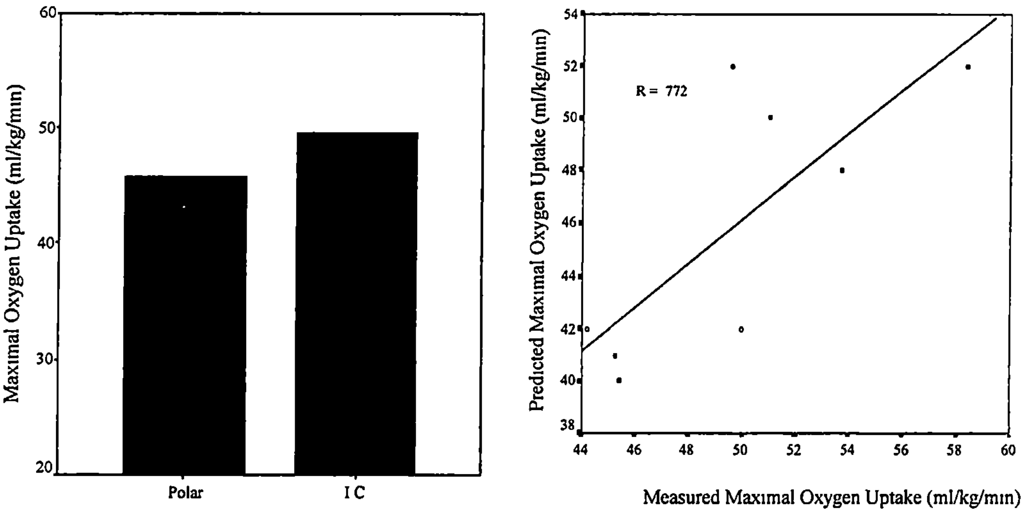

**Figure 3** – The left hand picture is bar graph comparing predicted (Polar) vs measured (I C ) maximal oxygen uptake On the right is an illustration of the paired samples correlation for the predicted and measured values

# CHAPTER V

# DISCUSSION

The purpose of this study was to determine the accuracy of the Polar M52 heart rate monitor for estimating energy expenditure, substrate utilization, and aerobic capacity. According to the measurements for the subjects in this study, the heart rate monitor was accurate when measuring energy expenditure at higher intensities However, the monitor was not accurate for measuring substrate utilization at any of the intensities used in this study The non-exercise prediction of maximal oxygen uptake performed by the monitor underestimated measured values of maximal oxygen uptake, but demonstrated a significant correlation (r= 0.77) with measured values.

## Estimates of energy expenditure

The conclusion that the Polar M52 heart rate monitor is accurate when estimating energy expenditure is not surprising since heart rate is linearly related to energy expenditure, especially at higher intensities (24, 69, 96, 112) While the heart rate response to exercise can vary dramatically among individuals, the monitor attempted to control for this by accounting for age, height and weight, gender, and activity level Even though these factors were accounted for, there is considerable scatter around the mean, indicating that some estimations were well above and below the mean

As mentioned previously, the Polar M52 heart rate monitor attempts to control for physiological differences in trained vs untrained individuals by accounting for physical activity level Those who have a high physical activity level are likely to have high values of $VO_{2\,max}$. However, only three categories were provided: low, middle, and high. Having only three categories that *estimate* physical activity and therefore, fitness, may result in large discrepancies when estimating caloric expenditure Since the heart rate response to exercise is dramatically different from person to person, the monitor would likely be more accurate (and show less scatter around the mean) if it employed a measured or more accurately predicted $VO_{2\,max}$. Because the monitor also estimates $VO_{2\,max}$, it could be suggested that this estimate be used instead of the estimation based on physical activity level since the monitor predicts $VO_{2\,max}$ with reasonable accuracy.

The Polar M52 demonstrated a stage/method interaction, mean that the accuracy of the monitor's accuracy is dependent on exercise intensity. In particular, the monitor was not accurate at the lowest intensities of exercise. This is explained by the fact that the monitor attempts to estimate *net* caloric expenditure In order to estimate the additional energy expended above resting metabolic rate, the monitor's calorie calculation begins only when the users heart rate exceeds 100 bpm. In contrast, many individuals (especially those who are fit) can exercise at low intensities while maintaining a heart rate under 100 bpm. This was the case in this study. In fact, in 1/3 of the 24 submaximal tests in this study, the subjects had not achieved a heart rate over 100 bpm during the first stage. One subject even maintained a heart rate below 100 bpm during the entire second stage on the cycle ergometer In these cases, the monitor estimated that the amount of calories expended was zero, resulting in underestimation of caloric expenditure for the group At exercise intensities demanding a heart rate above 100 bpm, the heart rate monitor was more accurate at estimating energy expenditure.

The FLEX heart rate (FLEX HR) method has been considered the most accurate way to predict energy expenditure from heart rate analysis (23, 69, 96). An individual's FLEX HR is determined by measuring heart rate in various body positions and during light exercise. FLEX HR is defined as the average of the highest resting heart rate and the lowest exercise heart rate When estimating energy expenditure based on heart rate, any heart rate below the FLEX HR is considered a resting heart rate, and any heart rate above FLEX HR is used to predict net energy expenditure. This method was designed to account for resting heart rate and any confounding factors such as stress or environmental factors. Livingstone et al (69) found no significant differences between energy expenditure measured by indirect calorimetry and estimation based on the FLEX HR method. The accuracy of the Polar M52 heart rate monitor for estimating energy expenditure may be improved if FLEX HR could be incorporated into its estimation of energy expenditure.

Since the Polar heart rate monitor calculates *net* energy expended, resting metabolic rate was subtracted from the measurements obtained by indirect calorimetry. Resting metabolic rate (RMR) was estimated based on body surface area, age, and gender according to an equation provided in a classic paper by Boothby (15) This estimation was chosen because body surface area bears a very good correlation with lean body mass, an indicator of RMR (37). Since normal variability in RMR associated with these estimations is 10-15%, this may be considered a limitation to the study However, since resting caloric expenditure represents a relatively small portion of total energy expenditure, the error associated with the estimation of resting metabolic rate would have a minimal effect on the calculation of net energy expenditure.

The Polar heart rate monitor estimated energy expenditure accurately for all three exercise devices. It seems the heart rate monitor is accurate during these types of exercise provided that the user's heart rate is above 100 bpm. There is an advantage to using the Polar monitor instead of motion sensors. Pedometers and accelerometers are not accurate in exercise modes that do not include a substantial amount of vertical acceleration (e.g. – cycling, rowing)

## Estimates of substrate utilization

The results of this study indicate that the Polar M52 heart rate monitor is not accurate at measuring substrate utilization at any exercise intensity, and the monitor consistently overestimated the relative contribution of fat However it worth noting that as exercise intensity increased, the estimated relative contribution of calories from fat decreased as one would expect.

The fact that the monitor overestimated the relative contribution of fat may result from the fact that substrate utilization is affected by fitness level. Those with higher levels of maximal aerobic power oxidize more fat at a given workload than their less-fit counterparts (26) It is possible that the subject pool used to determine the Polar algorithm consisted of highly fit individuals. These individuals would oxidize more fat than average individuals at a given workload, resulting in the monitor overestimating the relative contribution of fat in this study. The fact that the subjects in this study had average fitness levels suggests that, for this population, the validity with regard to substrate utilization is poor.

It has been shown that the relative contribution of carbohydrate to energy expenditure increases with intensity, and the opposite is true for fat (26). However, substrate utilization is also affected by carbohydrate availability This was shown in a study by Costill et al (27) who studied substrate utilization over long periods of exercise at a set intensity For example, during the first 10 minutes of exercise, the subjects burned an average of 90% carbohydrate, and this fell to <20% after 2 hours of exercise at this intensity. This suggests that as carbohydrate stores are depleted, individuals rely more on fat as a fuel source. Carbohydrate depletion was not controlled for in this study and therefore this is a potential limitation. However, if the subjects consumed a normal diet and did not exercise immediately before testing, these variables would not be a factor in the present study

Christensen and Hanson (23) studied the effects of a high carbohydrate, normal, and high fat diet on exercise performance. It was shown that individuals with a diet high in carbohydrates oxidize more carbohydrates at a given intensity than those on a normal diet Also, those taking a high fat diet oxidized even less carbohydrate at a given intensity. The effects of a long-term diet were not controlled for in this study, and therefore this is a potential limitation to this study. However, subjects were instructed to not eat for 2-3 hours prior to testing to minimize the effects of the diet immediately prior to testing

A possible limitation to the study is that protein oxidation was neglected when determining substrate utilization. Unlike each of the other substrates, protein is not completely oxidized in the body (34, 37), and the FQ for different types of protein vary dramatically (62) For these reasons it is difficult to obtain an accurate measure of protein oxidation using indirect calorimetry. The most common method of determining protein metabolism is by measurement of urinary nitrogen, a byproduct of protein metabolism (34, 74). Since protein oxidation was not measured, a table of non-protein respiratory quotients was used to determine substrate utilization and therefore a 1% error is introduced in the determination of substrate utilization (63, 106)

It has been suggested that indirect calorimetry may not be accurate at high intensities of exercise for measuring substrate utilization. However, a study by Romijn (86) suggests that indirect calorimetry is accurate for measuring substrate utilization up to 85% of $VO_{2\,max}$. It should be noted that the study by Romijn consisted of highly trained athletes who produce little lactate at this relative work rate. Nevertheless, an important finding of the study was the indirect calorimetry was accurate for measuring substrate utilization up to an RER of 0.90 The submaximal work rates chosen for this study represented less than 85% of $\dot{V}O_{2\,max}$ for all but one subject However, all subjects achieved a RER of at least 0.90. This could be considered a limitation of this study.

## Estimates of maximal oxygen uptake

Although significantly different, the Polar monitor was reasonably accurate at predicting $VO_{2\,max}$. The Polar monitor underestimated measured $\dot{V}O_{2\,max}$ by an average of 3 8 ml·kg$^{-1}$·min$^{-1}$, or about 1 MET There was also a significant correlation (r= 0 772 between the two methods.

In this study, $\dot{V}O_{2\,max}$ was distinguished from a $\dot{V}O_2$peak based on the following criteria (1) a maximal heart rate within 10 beats per minute of age-predicted maximal heart rate, (2) an RER value above 1.15, and (3) 3-minute post-exercise lactate of >8 0mM. If a subject achieved two of the three criteria, it was assumed that a $VO_{2\,max}$

was achieved All 8 subjects achieved a $VO_{2\,max}$ based on these criteria and therefore the mean for all 8 subjects was used

There has been much research in the area of non-exercise predictions of $VO_{2\,max}$. These equations have generally accounted for age, gender, physical activity level, body size, and resting heart rate (48, 55). The standard error of estimates (SEE) of values obtained using these equations have ranged from 4.64-5.35 $ml \cdot kg^{-1} \cdot min^{-1}$ (48, 55). Our results showed that the Polar heart rate monitor underestimated maximal oxygen uptake by 3.8 $ml \cdot kg^{-1} \cdot min^{-1}$ The non-exercise prediction provided by the Polar monitor includes the previous variables as well as heart rate variability (HRV). Scientists at Polar Electro found that the mean error of the $\dot{V}O_{2\,max}$ prediction provided by the Polar M52 heart rate monitor was 6.5%, which is reasonably consistent with the preliminary results from our study. The fact that Polar's estimation of fitness may be more accurate than those derived from previous non-exercise predictions could be due to the measurement of HRV The Polar heart rate monitor records at least 250 R-R intervals to determine a score for HRV, which was incorporated into the fitness prediction. HRV is an index of the heart's parasympathetic stimulation, and an increased HRV is related to high levels of aerobic fitness (30, 113). It is logical that the inclusion of yet another variable (HRV) results in an improvement in the prediction of fitness from previous non-exercise prediction equations

Scientists at Polar Electro have developed a regression to predict maximal aerobic power based on previously mentioned variables (61). The regression used to estimate aerobic power was based on actual measurements of $VO_{2\,max}$ obtained through maximal cycle ergometer and maximal treadmill tests (61). The fact that two-thirds of the measurements were obtained from maximal cycle ergometer tests may explain the underestimation of aerobic power in this study which used a Bruce treadmill protocol. Research has shown that $\dot{V}O_{2\,max}$ is dependent upon the amount of muscle mass used during exercise (102), and that $VO_{2\,max}$ values obtained on a cycle ergometer are lower than those obtained using a running treadmill protocol by ~10% (73). It is likely that if a cycle protocol were used in this study, the monitor would have demonstrated more accurate results in estimating $\dot{V}O_{2\,max}$.

## Directions for future research

Future studies regarding tools such as the Polar M52 heart rate monitor may include studies of different populations such as highly fit or sedentary individuals. This type of study could be used to determine which subpopulation could benefit most from this monitor. Also, studies may want to investigate the test-retest reliability of the estimates provided by the monitor Lastly, studies should be done to determine the sensitivity of the monitor to detect *changes* in aerobic fitness.

## Conclusions

Our findings suggest that the Polar M52 heart rate monitor is a useful tool for estimating energy expenditure at intensities of exercise demanding a heart rate above 100 bpm Below this threshold, the monitor does not record values. The monitor was not accurate when estimating substrate utilization at any of the exercise intensities studied, and consistently overestimated relative fat oxidation. The $VO_{2\,max}$ prediction provided by the monitor was significantly different from $\dot{V}O_{2\,max}$ measured using indirect calorimetry However, the estimates of $\dot{V}O_{2\,max}$ were, on average, within 8% of measured values This suggests that this particular fitness prediction may be more accurate than many commonly used non-exercise prediction equations

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# Appendices

# Appendix A

## (Health History Questionnaire)

# HEALTH HISTORY QUESTIONNAIRE

NAME: ____________________ AGE: ________ DATE OF BIRTH ____________
First MI Last

ADDRESS: ____________________________________________________________
Street City State Zip

TELEPHONE (home): ____________________

OCCUPATION: ________________________

Person to contact in case of emergency ____________ Phone #: _________ Relation: _______

**PLEASE CHECK YES or NO**

PAST HISTORY

| Have you ever had? | Yes | No |
|---|---|---|
| 1. High blood pressure | ☐ | ☐ |
| 2. Any heart trouble | ☐ | ☐ |
| 3 Artery disease | ☐ | ☐ |
| 4. Lung disease | ☐ | ☐ |
| 5 Asthma | ☐ | ☐ |
| 6 Diabetes | ☐ | ☐ |
| 7 Heart murmur | ☐ | ☐ |
| 8 Irregular heart beat | ☐ | ☐ |
| 9 Arthritis | ☐ | ☐ |
| 10 Seizures | ☐ | ☐ |

Additional comments ________________

________________________________

RECENT HISTORY

| Any of the following? | Yes | No |
|---|---|---|
| 1. Chest pain | ☐ | ☐ |
| 2. Shortness of breath | ☐ | ☐ |
| 3. Weakness in arm | ☐ | ☐ |
| 4. Feeling faint or dizzy | ☐ | ☐ |
| 5 Heart palpitations | ☐ | ☐ |
| 6 Blurred vision | ☐ | ☐ |
| 7 Severe headaches | ☐ | ☐ |
| 8 Irregular heart beat | ☐ | ☐ |

Other illness or symptoms that may affect your participation ______________

________________________________

Are you taking any prescription or over-the-counter medications? Yes______ No______

Name of medication? Reason for taking? For how long?

________________________________________________________________

________________________________________________________________

________________________________________________________________

Do you currently smoke? Yes______No_____ If so, what? Cigarettes / Cigars / Pipe

How much per day? < 5 pack____ 0.5 to 1 pack____ 1.5 to 2 packs____ >2 packs____

Have you ever quit smoking? Yes____No____When?____________________________

How many years and how much did you smoke?_________________________________

## ACTIVITY LEVEL EVALUATION

What is you occupational activity level? Sedentary___Light___Moderate___Heavy___

Do you engage in vigorous physical activity on a regular basis? Yes_____ No______

If so, what type?_______________ How many days per week?______________

How much time per day? <15 min___ 15-30 min___ 30-45 min___ >60 min___

How long have you been vigorously active? <1 mo.__1-6 mos.__6-12 mos.__>1 yr__

Do you ever have an uncomfortable shortness of breath during exercise? Yes___ No___

Do you ever have chest discomfort during exercise? Yes___ No___

If so, does it go away with rest? Yes___ No___

Do you engage in any recreational or leisure-time physical activities on a regular basis?

Yes_____ No_____ If so, what activities?

__________________________________________

On average: How often?_______times/week, For how long?_________time/session

FOR EXERCISE TESTING STAFF USE.

# Appendix B

## (Informed Consent Form)

## INFORMED CONSENT FORM

Title ACCURACY OF THE POLAR M52 HEART RATE MONITOR

Investigators Cory M Alwardt
David R Bassett, Jr

Address
Exercise Science and Sport Management
College of Education
University of Tennessee, Knoxville
1914 Andy Holt Ave Knoxville, TN 37996

Phone. (865) 974-1271

### INTRODUCTION

You are invited to participate in a research study. This purpose of the study is to determine the accuracy of the new Polar M52 heart rate monitor This monitor consists of a wrist band and a band to be worn around the chest The manufacturers of the monitor claim that it can estimate an individual's fitness level, and also provide information on calorie expenditure during exercise

### PROCEDURES

As a participant, you will be asked to undergo four different exercise tests The first of these is a maximal treadmill test to determine your level of physical fitness On three other occasions, you will participate in three different submaximal exercise tests. These tests will be done on a cycle ergometer, a treadmill, and a rowing ergometer While exercising, you will breath through a mouthpiece and wear a noseclip. The mouthpiece allows researchers to collect expired air and the noseclip will prevent nasal breathing The expired air will be analyzed using electronic equipment You will also be wearing the Polar M52 heart rate monitor that will estimate your fitness level and your caloric (energy) expenditure This monitor will also allow researchers to monitor your heart rate during testing. As a participant you are free to stop any test for any reason The time commitment for the maximal exercise testing will be approximately one hour and for the submaximal testing approximately 3 hours, for a total of 4 hours over the course of four separate days

### RISKS

There are certain health risks associated with this type of testing, but these risks are minimal in individuals who are physically active and fit Some of the noteworthy risks are abnormal heart conditions, musculo-skeletal injuries, blood pressure responses, and in extremely rare cases, death These risks are further reduced as a result of medical screening, and by having investigators trained in cardiopulmonary resuscitation administer the exercise tests

### BENEFITS

The benefit of the study to you as a participant is a quantitative and precise measure of your personal physical fitness level Also, if the Polar M52 heart rate monitor is found to be reasonably accurate, it could prove to be a useful tool for any individual in a fitness or weight loss program

## CONFIDENTIALITY

The information gathered by the investigators in the study will be confidential and will be kept in a locked file cabinet in the possession of the primary investigator. Only those individuals directly involved with this study will have access to these records The information will eventually be used in a research report, but no reference of any kind will be made which could link you as a participant to the study

## CONTACT INFORMATION

If you have questions or concerns regarding the procedures or the study, you may contact David Bassett at (865) 974-8766 If you have questions concerning your rights as a participant, contact the Compliance Section of the Office of Research at (865) 974-3466.

## PARTICIPATION

You are free to make a decision to participate in the study, and if you should choose to participate, you may withdraw from the study at any time without penalty. If you withdraw from the study, your data will be given to you or destroyed.

Before signing this form, please ask any questions about any aspects of the study which may be unclear

---

## CONSENT

I have read the above information and have decided to participate in the study described above I have also received a copy of this form

Participant's name________________________________

Participant's signature________________________________ Date______________

Witness's signature________________________________ Date______________

# Appendix C

## (Raw subject data for maximal oxygen uptake)

Table 2. Raw subject data for maximal oxygen uptake tests

| Subject | $VO_{2\,max}$ (I C ) | $VO_{2\,max}$ (Polar) | Lactate | HR | RER | RPE |
|---|---|---|---|---|---|---|
| 1 | 50 0 | 42 | 16 2 | 194 | 1 25 | 20 |
| 2 | 58 4 | 52 | 12 6 | 202 | 1 16 | 20 |
| 3 | 45 4 | 40 | 7 7 | 195 | 1 17 | 18 |
| 4 | 49 6 | 52 | 10 9 | 191 | 1 25 | 17 |
| 5 | 45 3 | 41 | 10.5 | 197 | 1 25 | 17 |
| 6 | 44 2 | 42 | 15 8 | 190 | 1 35 | 19 |
| 7 | 53 7 | 48 | 12 6 | 180 | 1 16 | 19 |
| 8 | 51 0 | 50 | 12 8 | 166 | 1 35 | 19 |

Note: All values shown are the maximal values attained.
$VO_{2\,max}$ values are expressed in $ml \cdot kg^{-1} \cdot min^{-1}$.
$VO_{2\,max}$ (Polar) is a prediction of $VO_{2\,max}$ based on resting variables
Heart rate is expressed in beats per minute.
Lactate values are expressed in mM

# Appendix D

## (Raw subject data for submaximal exercise tests)

Table 6 Raw subject data for submaximal rowing ergometer testing.

| Subject | 50 Watts | | | | 100 Watts | | | | 150 Watts | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Net Kcals (Polar) | Net Kcals (I C ) | % Kcals from fat (Polar) | % Kcals from fat (I C ) | Net Kcals (Polar) | Net Kcals (I C ) | % Kcals from fat (Polar) | % Kcals from fat (I C ) | Net Kcals (Polar) | Net Kcals (I C ) | % Kcals from fat (Polar) | % Kcals from fat (I C ) |
| 1 | 9 20 | 5 28 | 60 | 0 | 13 60 | 8 70 | 45 | 3 | 18 60 | 12 24 | 25 | 0 |
| 2 | 8 40 | 5 46 | 60 | 36 | 11 60 | 9 02 | 50 | 26 | 15 60 | 13 00 | 25 | 10 |
| 3 | 6 00 | 4 82 | 50 | 46 | 9 20 | 8 44 | 30 | 29 | X | X | X | X |
| 4 | 3 40 | 5 00 | 55 | 29 | 6 00 | 8 04 | 55 | 23 | 9 00 | 11 74 | 35 | 0 |
| 5 | 5.00 | 5 02 | 55 | 16 | 8 00 | 7 74 | 30 | 0 | 9 80 | 10 76 | 10 | 0 |
| 6 | 0 60 | 4 44 | 60 | 16 | 10 40 | 7 96 | 50 | 0 | 14 40 | 11 56 | 30 | 0 |
| 7 | 3 40 | 4 90 | 60 | 36 | 6 20 | 8 44 | 55 | 6 | 8 60 | 12 48 | 35 | 0 |
| 8 | 0 00 | 4 46 | X | X | 7 40 | 7 64 | 60 | 10 | 10 80 | 12 08 | 50 | 0 |

Note. Values are expressed in kcal/min.
X represents a missing value.

Table 4 Raw subject data for submaximal treadmill testing.

| Subject | 3 mph | | | | 4 5 mph | | | | 5 mph | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Net Kcals (Polar) | Net Kcals (I C ) | % Kcals from fat (Polar) | % Kcals from fat (I C ) | Net Kcals (Polar) | Net Kcals (I C ) | % Kcals from fat (Polar) | % Kcals from fat (I C ) | Net Kcals (Polar) | Net Kcals (I C ) | % Kcals from fat (Polar) | % Kcals from fat (I C ) |
| 1 | 2 40 | 3 92 | 60 | 26 | 11 00 | 7 10 | 60 | 16 | 14 80 | 11 54 | 40 | 16 |
| 2 | 0 40 | 3 56 | 30 | 16 | 9 80 | 9 56 | 55 | 3 | 12 40 | 10 54 | 40 | 16 |
| 3 | 4 00 | 2 60 | 55 | 77 | 7 60 | 5 84 | 40 | 36 | 8 40 | 7 58 | 30 | 43 |
| 4 | 0 00 | 2.72 | X | X | 4 80 | 5 72 | 60 | 23 | 5 80 | 7 76 | 60 | 36 |
| 5 | 0 20 | 2 64 | 40 | 16 | 5 80 | 6 80 | 50 | 6 | 7 20 | 7 30 | 35 | 6 |
| 6 | 0 00 | 3 04 | X | X | 9 20 | 5 96 | 55 | 0 | 10 80 | 8 54 | 45 | 0 |
| 7 | 0 00 | 3 88 | X | X | 7 00 | 7 44 | 45 | 29 | 5 60 | 8.00 | 55 | 26 |
| 8 | 0 00 | 3 40 | X | X | 0 40 | 6 64 | X | X | 7.60 | 8 74 | 60 | 10 |

Note· Values are expressed in kcal/min.
X represents a missing value.

Table 5. Raw subject data for submaximal cycle ergometer testing.

| Subject | 50 Watts | | | | 100 Watts | | | | 150 Watts | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Net Kcals (Polar) | Net Kcals (I C ) | % Kcals from fat (Polar) | % Kcals from fat (I C ) | Net Kcals (Polar) | Net Kcals (I C ) | % Kcals from fat (Polar) | % Kcals from fat (I C.) | Net Kcals (Polar) | Net Kcals (I C ) | % Kcals from fat (Polar) | % Kcals from fat (I C ) |
| 1 | 2 60 | 3 64 | 60 | 10 | 8 80 | 6 42 | 60 | 13 | 12 40 | 9 22 | 55 | 6 |
| 2 | 3 60 | 3 92 | 60 | 53 | 9 20 | 6 70 | 60 | 43 | 12.60 | 9 78 | 40 | 29 |
| 3 | 5 60 | 3.58 | 55 | 67 | 7 80 | 6 64 | 35 | 43 | 9 80 | 9 98 | 20 | 0 |
| 4 | 0 00 | 3 40 | X | X | 5 00 | 5 98 | 60 | 19 | 7 00 | 8 86 | 50 | 13 |
| 5 | 3 20 | 3 02 | 50 | 43 | 6 20 | 6 12 | 45 | 19 | 9 00 | 8 96 | 20 | 0 |
| 6 | 3 00 | 3 20 | 60 | 26 | 9.80 | 6 52 | 50 | 0 | 15 00 | 10 66 | 25 | 0 |
| 7 | 0 00 | 3 36 | X | X | 4 00 | 6 40 | 60 | 23 | 7 20 | 10 10 | 50 | 0 |
| 8 | 0 00 | 3 78 | X | X | 0 00 | 6 34 | X | X | 8 00 | 9 04 | 60 | 3 |

Note: Values are expressed in kcal/min.
X represents a missing value.

# VITA

Cory Matthew Alwardt was born in St. Louis, Missouri on September 13, 1976. He lived in the city of Collinsville, Illinois (a suburb of St. Louis, Missouri) until he graduated from Metro-East Lutheran High School in 1994. After high school he attended Illinois State University where he received his Bachelor of Science in 1998. He decided to pursue a Master of Science in Exercise Physiology at Illinois State University where he worked as a Graduate Teaching Assistant. After one semester he decided he needed a change of scenery and transferred into the graduate program at the University of Tennessee-Knoxville to finish his graduate degree. Upon completion of his Master of Science degree, he will attend the University of Arizona in Tucson to pursue a Doctor of Philosophy degree in Physiology. Mr Alwardt hopes to eventually reside in the St. Louis area where he grew up.