VALIDATION OF THE POLAR S410 HEART RATE MONITOR FOR ESTIMATING ENERGY EXPENDITURE IN WOMEN

by

MIA KAY THOMAS

(Under the Direction of Kirk J. Cureton)

ABSTRACT

To determine the effect of ambient temperature on the validity of the Polar S410 heart rate (HR) monitor for estimating energy expenditure (EE), EE estimates obtained during cycling at 30%, 60%, and 80% of maximal oxygen uptake ($\dot{V}O_{2max}$) in 25˚C, 30˚C, and 35˚C ambient temperatures, were compared with indirect calorimetry (IC). Three different methods of estimating EE using the monitor were compared: (a) the AHR method used the actual values for HRmax and $\dot{V}O_{2max}$, (b) the PHR method used the HRmax and $\dot{V}O_{2max}$ predicted by the "OwnIndex" software, with resting HR measured in the ambient temperature for the test, (c) and the PHRTM method used the HRmax and $\dot{V}O_{2max}$ predicted by the "OwnIndex" software, with resting HR measured in thermoneutral (22˚C) conditions. The traditional method of using individualized heart rate-$\dot{V}O_2$ relationship to estimate EE was also compared to IC and the Polar S410 methods. In the 25˚C, 30˚C, and 35˚C conditions AHR overestimated [means (SD)] EE from IC by 4% (11), 7% (11), and 9% (8); PHR overestimated EE from IC by 17% (21), 18% (22), and 19% (19); PHRTM overestimated EE from IC by 20% (21), 22% (21), and 24% (19); and the HR-$\dot{V}O_2$ method underestimated EE from IC by 8% (12), 4% (12), and 1.4% (11). It is concluded that the Polar S410 using the actual values for HRmax and $\dot{V}O_{2max}$ programmed into the Polar S410 (AHR), provides estimates of EE for a group of young women that are within 10% of those from IC. These EE estimates are similar in accuracy (i.e. 4%-9% difference) to estimates from the traditional HR-$\dot{V}O_2$ relationship (i.e. 8%-1.4% difference). Estimates of EE from the Polar S410 based on estimates of $\dot{V}O_{2max}$ and HRmax (PHR and PHRTM) are unacceptably high (>10%), with errors ranging from 17%-24% difference in estimates of EE. Ambient temperatures above 25˚C slightly increase the error of EE estimates from the Polar S410 due to the dissociation of HR from $\dot{V}O_2$.

INDEX WORDS: Heart Rate Monitoring, Maximal Oxygen Uptake, EE, Heat, Cycling

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CHAPTER 1

INTRODUCTION

Heart rate (HR) and oxygen consumption ($\dot{V}O_2$) increase proportionately during continuous aerobic exercise. The linear relationship between HR and $\dot{V}O_2$ has been used to estimate energy expenditure (EE) from HR during periods of activity (12; 15; 27; 38; 44). HR monitoring has been shown to be a valid method of measuring EE when measurement of $\dot{V}O_2$ is not practical or possible, such as during activities performed outside of a laboratory or in the field. HR monitors are also appropriate for large-scale studies and can provide estimates of frequency, intensity and duration of habitual activity (16).

Recently, Polar Electro, Inc (Polar Electro Inc. Woodbury, NY), one of the leading manufacturers of HR monitors, developed software that utilizes the relationship between HR and $\dot{V}O_2$ to estimate EE during bouts of exercise. The Polar S410 HR monitor incorporates the individual user information into a non-exercise based estimate of maximal aerobic power ($\dot{V}O_{2max}$) and maximal HR. These predicted values along with HR during submaximal exercise are then used to estimate EE. Although the algorithms have not been disclosed, apparently the relationship between percentage of maximal HR and percentage $\dot{V}O_{2max}$ is used to estimate $\dot{V}O_2$ and EE from HRs recorded during a bout of exercise. The Polar S410 has recently been shown to provide a rough estimate of EE during several aerobic activities(11). The approach used for estimating EE from HR is different than the traditional method of using HR monitoring, which requires establishing each individual's HR-$\dot{V}O_2$ relation during an exercise test prior to the estimation of EE (9; 12; 28; 38; 44).

Although the use of HR monitoring and the HR-$\dot{V}O_2$ relationship has been shown to be an effective way to estimate EE, there are several non-exercise factors that influence HR, thereby dissociating it from $\dot{V}O_2$ (12; 23; 24; 44). One such factor is environmental temperature. As the temperature of the environment in which exercise is being performed increases, HR increases independently of $\dot{V}O_2$ (18; 23; 24; 34). For example, Kamon, et al. found an increase in HR of about 1 beat/min per rise of 1 ˚C in ambient temperature (dry heat) (23). The increase in HR with increased environmental temperature can be attributed primarily to autonomic influences (both vagal withdrawal and sympathetic activation) and partly to local temperature influences on pacemaker tissue (18). The dissociation between HR and $\dot{V}O_2$ is a source of error when using the HR-$\dot{V}O_2$ relationship to estimate EE.

Because, the dissociation between HR and $\dot{V}O_2$ is a source of error in the estimation of EE from the HR-$\dot{V}O_2$ relationship, it can be assumed that this would also be a source of error for the estimation derived from the Polar S410 HR monitor. However, it has not been determined how an increase in environmental temperature would affect the accuracy of the prediction of HRmax and $\dot{V}O_{2max}$, and subsequently the estimation of EE, derived from the Polar S410 HR monitor. Establishing the validity of this instrument in hot as well as thermoneutral environments is needed before it is accepted as an alternative to the traditional method of determining the individualized relationships between HR and $\dot{V}O_2$ to estimate the energy expended during exercise.

Crouter et al. (11) found estimates of EE from the Polar S410 HR monitor were more accurate in men than in women. However, the samples of women and men were small and sampling error may have produced results different than what might be obtained from a larger, more heterogeneous sample. Additional studies of the validity of the S410 in larger samples are needed.

Purpose

The specific aims of this study were: (1) To compare estimates of EE from the HR monitor with estimates of EE obtained by indirect calorimetry (IC) and with the traditional use of individualized HR-$\dot{V}$O2 relationship to estimate EE in women (2) To compare estimates of EE from the Polar S410 based on estimated $\dot{V}O_{2max}$ and HRmax with estimates based on measured $\dot{V}O_{2max}$ and HRmax, and (3) and to determine the effect of environmental temperature on estimates of EE obtained by the Polar S410 HR monitor. The first of these purposes was accomplished by comparing the estimates of EE from the Polar S410 with the estimates obtained by indirect calorimetry, as well as the traditional method of using individualized HR-$\dot{V}O_2$ relationship.The second purpose was accomplished by comparing estimates of EE obtained by the Polar S410 which used the actual values for $\dot{V}O_{2max}$ and HRmax for the estimation of EE (AHR), to estimates which used the $\dot{V}O_{2max}$ and HRmax predicted by the "OwnIndex" software, with resting HR measured in the specific ambient temperature for the test (PHR). Additionally, estimates of EE obtained by a third monitor which used the values for $\dot{V}O_{2max}$ and HRmax predicted by the "OwnIndex" software, with resting HR measured in thermoneutral temperature (PHRTM), were obtained to determine the effects of ambient temperature on the prediction of these variables. The third purpose was accomplished by comparing the estimates of EE obtained by the Polar S410 HR monitor during submaximal cycling in three different ambient temperature conditions. If estimates of EE from the Polar S410 HR monitor are similar to those derived from the traditional methods, it could be useful in settings where the measurement of $\dot{V}O_2$ is not practical or possible.

Hypotheses

Estimates from the Polar S410 based on measured $\dot{V}O_{2max}$ and HRmax were hypothesized to be more accurate (as compared to IC) than those based on estimates of $\dot{V}O_{2max}$ and HRmax under all temperature conditions. It was also hypothesized that the dissociation of HR and $\dot{V}O_2$, caused by the increased environmental temperature, would reduce the accuracy of the estimation of EE by the Polar S410 HR monitor. However, because the traditional method of using individualized HR-$\dot{V}O_2$ relationships to estimate EE is subject to the same dissociation with increased environmental temperatures, it was hypothesized that the estimates obtained by the Polar S410 would be comparable to those derived from the individualized HR-$\dot{V}O_2$ relationship.

Significance

Using traditional HR monitoring to estimate EE during physical activity requires establishing the relationship between HR and $\dot{V}O_2$ in a preliminary graded exercise test for each individual prior to the HR monitoring. If this laborious and time-consuming step could be avoided by obtaining estimates from a programmed heart watch, this would save time and effort. This study will provide new information whether this simpler approach is as accurate as the traditional, more-laborious approach.

The method for estimating EE employed by the Polar S410 HR monitor, which depends on estimations of $\dot{V}O_{2max}$ and HRmax from demographic data and resting HR, and then appropriately utilizing the known relation between the percentage HRmax and the percentage of $\dot{V}O_{2max}$ during exercise from HR, to estimate EE is fundamentally different from obtaining estimates of EE from a HR-$\dot{V}O_2$ calibration curve established during a graded exercise test prior to physical activity monitoring. Which method is more accurate is unknown. This study will provide new information on the relative accuracy of the two approaches and provide insight into the bases for any differences.

Finally, although it is well established that increased ambient temperature dissociates the relation of HR to $\dot{V}O_2$, the extent to which this affects estimates of EE from HR is unknown. This study will provide new information on the magnitude of the effect of increasing ambient temperature on estimates of EE from the Polar S410 HR monitor as well as from traditional HR monitoring. If the estimates of EE obtained by the Polar S410 are comparable to IC and the HR-$\dot{V}O_2$ method, the Polar S410 could be a convenient alternative to these methods for the estimation of EE during exercise outside of a lab setting.

Limitations

The subjects who participated in this study were volunteers drawn from the University of Georgia. These subjects were all at least moderately active, and were all college-aged females. These characteristics make the results of this study difficult to generalize to other populations. Only one exercise mode was used in this study, therefore the results may not generalize to other modes. Also, although three different ambient temperatures were used, the humidity and wind speed remained the same for all trials. The results from these temperatures may or may not generalize to other environmental conditions.

CHAPTER 2

REVIEW OF LITERATURE

In this chapter, literature on the use of HR monitoring to estimate EE, on the effects of heat on HR, and on the validity of the Polar S410 HR monitor are reviewed.

Heart Rate Monitoring

HR monitoring is a valuable method for the assessment of total daily energy expended in situations where the direct measurement of $\dot{V}O_2$ is not practical or possible. Additionally, HR monitoring can provide a method by which the intensity, patterns of physical activity can be monitored. This is a limitation of other methods such as doubly labeled water, and pedometers.

Comparison with indirect calorimetry. Assessment of daily EE is a difficult process which requires the direct measurement of heat production via whole-body calorimetry, or the measurement of $\dot{V}O_2$. In many situations, these methods are not practical or possible. Therefore, alternate methods must be used to determine the EE. HR monitoring is one such method. Using HR monitoring for determining EE is based on the linear relationship between HR and $\dot{V}O_2$, and requires that this relationship be determined for each individual.

Bradfield et al. (8) first described the technique used to establish the HR-$\dot{V}O_2$ relationship. They simultaneously measured HR and oxygen consumption at rest and at several levels of stepping activity. Their measurements included points at various HR levels: 75-90 beats/min (rest), 120-130 beats/min, 140-150 beats/min and >160 beats/min. They used these HR points and the corresponding $\dot{V}O_2$ to construct a regression equation for each individual. Caloric values were obtained by the Weir formula. Using this regression equation and the mean 24-hour HR, estimates of 24-hour

EE were obtained. They found the internal validity of this method to be $\pm$ 5 to 15%, depending on the amount of sedentary activities included.

Dauncey et al. (12) compared the HR method of estimating EE to the heat production measured while subjects were in a whole-body calorimeter and found that this method was fairly unreliable. They proposed that the low mean 24-hour HR obtained in the calorimeter, due to the large amounts of time spent in sedentary behaviors, contributed to the unreliability.

Christensen et al. (10) tested the reproducibility and reliability of the method described by Bradfield in 5 healthy subjects, 5 subjects with obesity, 5 subjects with untreated thyrotoxicosis, and 2 subjects with anorexia nervosa. The regression equations for these subjects were determined during periods of lying rest, seated rest, three 10-minute bouts of cycling, and three 10-minute bouts of walking for two consecutive days. Using these regression equations and the mean 24 hour HR, the energy expended over two 24-hour periods was estimated and the estimations for each day were compared.

They found generally high correlation coefficients between HR and $\dot{V}O_2$. However, they observed fairly large differences between the slopes and intercepts of the duplicate regression lines obtained under the same conditions. These differences resulted in large discrepancies in the estimates of EE. From their results, the authors postulated that variations in HR independent of $\dot{V}O_2$ at low levels of activity were responsible for the discrepancies, and suggested that regression lines based on the specific HR-$\dot{V}O_2$ relationship for various activities may be more appropriate. However, this approach would be much more time consuming and the reliability of estimates of daily EE might not be improved (10).

The results from the previous studies suggested that the majority of the differences in estimates of EE obtained from the HR-$\dot{V}O_2$ method and either indirect or direct calorimetry are due to discrepancies between measured and estimated EE at low HRs. Development of the FLEX HR method allowed measured HRs to be separated into periods of rest and periods of activity in an attempt to decrease the error associated with the HR-$\dot{V}O_2$ method. The FLEX HR is determined by averaging the highest HR obtained at rest and the lowest HR obtained during exercise. To estimate EE, HR values above the FLEX HR are used in the equation of the HR-$\dot{V}O_2$ calibration curve, and HR below the FLEX HR utilize the resting metabolic rate (RMR) (38).

In one of the first studies to use the FLEX HR, Spurr et al. (38) compared estimates of EE from minute-by-minute HR monitoring, to the EE obtained through indirect calorimetry. Subjects spent 22 hours in a calorimeter, during which time subjects followed one of four activity protocols in addition to usual activities (eating, sleeping, etc). Prior to the calorimeter protocol, each subject was individually calibrated to establish the HR-$\dot{V}O_2$ relationship, and to determine the RMR. Estimates of EE obtained by the HR-$\dot{V}O_2$ method were reported as total daily EE (TDEE) and energy expended in activity (EAC). Their results indicated that there were no statistically significant differences between the two methods in TDEE and EAC in any of the sex or protocol groupings. They found a maximum error of TDEE for individuals of +20% and -15%. Their results suggested that when the FLEX HR was used, the HR-$\dot{V}O_2$ method produced estimates of EE that were quite good for groups of subjects, and although the variability was wider for individuals, the estimates of TDEE and EAC were still acceptable.

Bitar et al. (5) investigated to validity of the HR monitoring method compared to whole-body indirect calorimetry in 19 children. Individual relationships between HR and $\dot{V}O_2$ were calibrated for each subject during periods of rest and light exercise including lifting light weights, and pedaling on a cycle ergometer without added resistance. Data from this calibration period was used to determine the regression equation for the HR-$\dot{V}O_2$ relationship. The subjects then spent 36 hours in a calorimetric chamber during which they followed a specific activity program. Data for HR and EE measured over 24 hours in the calorimetric chamber were averaged every 5 minutes during exercise periods, and every 15 minutes during the rest of the time (including sleep). Several mathematical models were calculated using these data, and these models were all tested to determine the most accurate. The most accurate model overestimated the total EE by 7.6 $\pm$ 20.1% compared with the EE measured in the calorimetric chamber. However, the difference was not significant.

Comparison with doubly labeled water method. The doubly labeled water (DLW) technique has been used as a low-interference technique that accurately measures total daily EE. However, the complex nature and high cost of this method makes it difficult to apply to large-scale studies. Additionally, it does not allow researchers to distinguish between energy expended in activity, and total daily EE (15; 27; 28).

Livingstone et al. (28)compared estimates of EE obtained by the FLEX HR method to estimates obtained by the DLW technique. They measured total EE over 15 days by the DLW technique and for 2-4 separate days by HR monitoring. Initially, measurements of basal metabolic rate and individual HR-$\dot{V}O_2$ regression equations were calculated based on several resting and activity periods. HR was monitored in laboratory and free-living situations during the DLW measurement period. They found that the FLEX HR method produced group estimates of total EE that were very similar to estimates obtained by DLW (12.99 $\pm$ 3.83 MJ/day and 12.89 $\pm$ 3.8 MJ/day, respectively). Individual differences between HR estimates of EE and DLW estimates of EE ranged from -22.2% to +52.1%, with nine values lying within $\pm$ 10%. They suggested that the accuracy of the FLEX HR for estimating total EE would be increased if a greater number of sampling days were included.

Livingstone et al. (27) conducted another similar study using children as subjects. Thirty-six children participated, and the methods were similar to those mentioned in the previous study, with the total EE (TEE) measured over 10-15 days with the DLW method and 2-3 days of continuous HR monitoring. When calibrating the HR-$\dot{V}O_2$ relationship, however, the children performed bouts of treadmill exercise, whereas the adult subjects in the previous study determined the relationship based on stepping and cycling. Individual differences between estimates of EE obtained by the FLEX HR method and estimates obtained by DLW ranged from -16.7% to +18.8%, with 23 values lying within ± 10%. In addition to measuring TEE, the HR monitoring period was also used to determine the amount of time the children were active. They concluded that continuous HR monitoring provided a close estimation of the mean TEE for the group (-1.99 to +1.44 MJ/day, 95% confidence interval), as well as an objective assessment of associated patterns of physical activity, in this sample of children.

Ekelund et al. (13) compared the estimates of total EE obtained by DLW and the FLEX HR methods in young speed skaters (mean age 18.2 ± 1.3 years). They also determined the amount of energy expended as activity (AEE) based on the FLEX HR method. They hypothesized that the FLEX HR method would be affected by the type of training regimen the athletes followed and by the definition of the FLEX HR. Eight subjects were monitored for 10 days during the off-season, when their training regimen consisted of primarily running, and 10 days during pre-season training. The FLEX HR was defined the average of the mean HRs during all resting calibration activities and the lowest HR during exercise (FLEX HR1); and as the average of the highest HR during rest and the lowest HR during exercise (FLEX HR2). Although they found a significant difference between the values for FLEX HR1 and FLEX HR2, no significant difference was observed between the errors associated with each of these methods when compared to DLW. Therefore, the definition of the FLEX HR did not affect the estimate of TEE obtained by this method. The estimates of TEE obtained by the two FLEX HRs and the DLW technique were also similar for the two training periods, suggesting that the training regimen also did not affect the FLEX HR estimate of TEE. TEE values obtained by DLW were 16.8 ± 3.8 MJ/day and 16.9 ±2.9 MJ/day for the off-season and pre-season training periods, respectively. TEE values obtained by FLEX HR1 were 17.8 ± 3.6 and 17.4 ± 2.6 MJ/day, and those from FLEX HR2 were 17.1 ± 3.1 and 17.0 ± 2.7 MJ/day for the two periods, respectively (13).

In contrast, the definition of FLEX HR did affect the estimates of the amount of time spent in activity. The AEE was significantly larger when calculated from FLEX HR1 when compared to FLEX HR2. They suggested that if HR monitoring was being used to evaluate physical activity patterns, lower FLEX HRs (e.g. FLEX HR1) may be more appropriate for aerobically fit subjects, who tend to have lower resting HRs and lower HRs in light exercise.

In conclusion, HR monitoring has been found to be a valuable alternative to indirect calorimetry for estimating EE for various modes of exercise. Although mean estimates for a group are quite accurate, errors associated with individual estimates can be large. The definition of the FLEX HR point may be a source of variability and should be kept constant between trials. Additionally, the activities used to calibrate the individual HR-$\dot{V}O_2$ relationships may also influence the subsequent estimates of EE obtained by this method. Including several types of resting and exercise calibration activities may increase the accuracy of this method.

Polar S410 HR Monitor

Polar Electro, Inc. is a leading manufacturer of HR monitors. They have recently developed software that allows the estimation of EE (EE) during exercise ("OwnCal"). This software incorporates user information, including height, weight, gender, date of birth, and activity level, as well as either the predicted or tested values for HRmax and $\dot{V}O_{2max}$. The "OwnIndex" software uses a non-exercise equation which incorporates the user information and resting HR information to predict HRmax and $\dot{V}O_{2max}$ if these values are not known.

The Polar S410 HR monitor is one of the Polar models that include the "OwnIndex" and "OwnCal" software. It is a relatively new device, with very little research published concerning its validity and accuracy for estimating EE. Crouter et al. (11) investigated the accuracy of the Polar S410 during submaximal exercise at RPE's of 3, 5, and 7, on a treadmill, cycle, and rowing ergometer. Their subjects included 10 men and 10 women, all of whom performed a maximal exercise test in addition to the submaximal exercise bouts. HR and $\dot{V}O_2$ were monitored simultaneously while during all exercise bouts. During the submaximal bouts two of the Polar S410 watch receivers were used, one programmed with the participant's predicted HRmax and $\dot{V}O_{2max}$ (PHRM), and the other programmed with the actual HRmax and $\dot{V}O_{2max}$ (AHRM), to determine the effects of the predicted vs. the actual values on the estimation of EE obtained by the Polar S410 (11).

In men, they found no significant differences between the mean values for EE predicted for the AHRM, the PHRM, and indirect calorimetry for any of the exercise modes. In females, the PHRM significantly overestimated the mean EE by 2.4 $kcal \cdot min^{-1}$, 2.9 $kcal \cdot min^{-1}$, and 1.9 $kcal \cdot min^{-1}$ on the treadmill, cycle, and rower, respectively. The AHRM improved the estimation of EE for all modes, but EE was still overestimated by 0.6 $kcal \cdot min^{-1}$ and 1.2 $kcal \cdot min^{-1}$ on the treadmill and cycle, respectively. The mean error for the PHRM watch was 2% (SD + 18%) in males, and 33% (SD + 20.9) in females. The mean error was improved to 12% (SD $\pm$ 13%) in females when the actual values for HRmax and $\dot{V}O_{2max}$ were used. However, for males the use of the actual values resulted in a mean error of 4% (SD $\pm$ 10%) (11). They concluded that the Polar S410 provided rough estimates of EE during treadmill, cycle, and rowing exercise, and this estimate was improved when the actual values for HRmax and $\dot{V}O_{2max}$ were programmed into the watch receiver. The large error associated with the PHRM watch for the female subjects was due primarily to the inaccurate prediction of $\dot{V}O_{2max}$ by the Polar S410. For males, a significant correlation between the predicted and actual $\dot{V}O_{2max}$ was observed ($r = 0.87$, $p = 0.001$). However, the correlation between the predicted and actual $\dot{V}O_{2max}$ for the female subjects was not significant ($r = 0.48$, $p > 0.05$). The inaccurate prediction of $\dot{V}O_{2max}$ resulted in overestimated values for EE obtained from the PHRM watch. The error associated with the AHRM watch for the female subjects compared to the male subjects may be due to the small sample of each gender, and the differences between these samples. The female subjects had actual $\dot{V}O_{2max}$ values ranging from 35 to 45 $ml \cdot kg^{-1} \cdot min^{-1}$. However, the sample of male subjects had a much larger range of $\dot{V}O_{2max}$ values (30-75 $ml \cdot kg^{-1} \cdot min^{-1}$). The larger range of values for the male subjects may have contributed to the smaller mean error with this sample.

Crouter et al. (11) also investigated the relationship between HRmax and $\dot{V}O_{2max}$ in the estimation of EE, in an attempt to understand how the Polar S410 estimates EE. As expected, they found a strong linear relationship between HR and EE, however, this relationship was unique for each participant. Therefore, they investigated the relationship between the percentage of HRmax and the percentage of $\dot{V}O_{2max}$ and found this relationship to be nearly identical for all participants, regardless of fitness level, gender, age, etc. They postulated that the relationship between the percentage of HRmax and the percentage of $\dot{V}O_{2max}$ was the method by which the Polar S410 was estimating EE.

While the non-exercise based equation used by the Polar S410 to predict HRmax and $\dot{V}O_{2max}$ has not been released, several studies have developed equations that may provide insight into this method. Jackson et al. (19) conducted a study which included 2.009 subjects recruited from NASA, with the purpose of determining whether $\dot{V}O_2$ prediction models that did not involve exercise testing could be developed to validly estimate aerobic capacity. The accuracy of these models for the prediction of $\dot{V}$O2peak was compared to the Astrand single-stage submaximal prediction model.

Subject characteristics were measured followed by a measure of self-report activity level, continuous measurement of $\dot{V}O_2$ and HR, and analysis of submaximal and maximal data, to develop two different non-exercise prediction models. One model calculated $\dot{V}O_{2peak}$ as a product of self-report activity, age, gender and %fat, and their regression weights (N-Ex %fat). The second model calculated $\dot{V}O_{2peak}$ as a product of self-report activity, age, gender and body mass index (BMI), and their regression weights (N-Ex BMI). The multiple correlations for these models were R=0.81 (SE = 5.3 $ml \cdot kg^{-1} \cdot min^{-1}$) and R=0.78 (SE = 5.6 $ml \cdot kg^{-1} \cdot min^{-1}$) for the N-Ex %fat and the N-Ex BMI, respectively. With a sample of normal, healthy adults the N-Ex models provided a more accurate estimate of $\dot{V}O_{2peak}$ than the estimates obtained by the Astrand submaximal protocol (SE = 5.5-9.7 $ml \cdot kg^{-1} \cdot min^{-1}$). However, the N-Ex models were not accurate for those subjects who's $\dot{V}O_{2peak}$ exceeded 55 $ml \cdot kg^{-1} \cdot min^{-1}$. The N-Ex models were most accurate for the $\dot{V}O_2$ range of 36-55 $ml \cdot kg^{-1} \cdot min^{-1}$ (19).

Matthews et al. (29) conducted a study similar to the Jackson study. They developed another non-exercise based equation to predict $\dot{V}O_{2max}$. Variables used in the equation which produced the most accurate prediction included: age, age^2**,** gender, physical activity status, height, and body mass. The accuracy of this method for the classification of cardiorespiratory fitness was examined by cross-classification of measured and predicted $\dot{V}O_{2max}$ quintiles. Of the total sample, 83% of the subjects were classified correctly or within one fitness quintile. Unlike the Jackson study, however, slightly higher classification accuracy was observed in the upper as compared with the lower end of the cardiorespiratory fitness distribution (29). While it is not know if one of the equations developed in these studies, along with resting HR, is the equation used by the Polar S410 "OwnIndex" software, it can probably be assumed that they are representative of the type of equation that could provide estimates of $\dot{V}O_{2max}$ used by this instrument to estimate EE.

Interest in the assessment of EE expenditure in many fields of study is increasing. New user-friendly methods for monitoring EE would be desirable for recreational exercisers whose goal is to monitor their body weight, as well as more competitive athletes whose goal is to balance their nutritional needs to facilitate high levels of activity. The Polar S410 could provide such a method that could be an alternative to complex calculations, or cumbersome equipment. Currently, the small amount of literature reviewing the accuracy of this method prevents the widespread use of this instrument with any confidence. Investigation of the limitations and advantages of this instrument could provide insight into its usefulness. Additionally, investigation of the effects of heat on the accuracy of the Polar S410 will clarify limitations of this instrument in outdoor activities.

Effects of Increased Ambient Temperature

Effects of heat on resting HR. One source of error when using HR to estimate $\dot{V}O_2$, is the dissociation between these variables during exercise in increased environmental temperatures. Early studies that investigated the effects of heat on HR observed an increase in HR that was independent $\dot{V}O_2$ during rest, in conditions of high ambient temperatures (18; 23-25; 32-35). Koroxenidis et al. (25) measured HR, while subjects were wrapped in blankets and their legs immersed in water heated to 44˚C. HR was measured continuously while subjects lay comfortably (with the body heating) for 50-105 minutes. They saw a 49% increase in HR after 50 minutes of heating, with an increase of ~2˚F in oral temperature. Similar increases in HR were observed by Rowell et al (34), when subjects wore a water-perfused suit, which covered the entire body with the exception of the skin. The suit was perfused with water heated to 47.5˚C, and cardiac output, aortic blood pressure, T_c, $\overline{T}_{sk}$, blood temperature, and HR were measured. They saw an average increase in HR of 122% (from the control period to ~50 minutes) with a ~5˚C increase in $\overline{T}_{sk.}$ The increase in HR in these studies was postulated to contribute to an increase in cardiac output due to an increase in blood flow to the skin. However, the exact mechanisms responsible for the increase in HR were not discussed.

Gorman et al. (18) attempted to investigate those mechanisms in seven baboons. Using four different protocols, they isolated local mechanisms, sympathetic influences, parasympathetic influences, and autonomic mechanisms combined. They concluded that both autonomic and local mechanisms contributed to the rise in HR caused by heating. They determined that 40% of the increase in HR was due to local influences, corresponding with an 8.5 beats/min increase with every 1˚C increase in T_c. They concluded that the local influences were caused by the direct effect of temperature on the sinoatrial node. A similar study conducted on human subjects (21) , found a 7 beat/min per 1˚C increase in T_c, when autonomic influences were blocked during heating at rest.

Changes in autonomic activity with heating also contributed to the increase in HR in this study. Autonomic influences accounted for 60% of the increase in HR, with both sympathetic activation and parasympathetic withdrawal contributing to the increase. The relative contributions of the sympathetic and vagal influences were determined using the HR from the protocols that involved blockade of one branch of the autonomic nervous system, and the protocol that involved blockade of both branches. They determined that ~75% of the autonomic influence on HR was due to vagal withdrawal, with the remainder caused by sympathetic activation.

A contribution of autonomic influences was also observed by Rowell et al, (33) during exercise in increased ambient temperatures. They observed a rise in norepinephrine (NE), indicative of sympathetic activity, accompanying the rise in HR during exercise in the heat. The variables did not increase in a linear fashion, as the greatest increments in NE were observed when HR exceeded 110-120 beats/min, when nearly all vagal activity is thought to be withdrawn.

Effects of heat on exercise HR. As expected, effects similar to those observed at rest are observed during exercise in increased ambient temperatures. Williams et al. (47) examined the effects of heat on the relationship between work rate and several physiological variables. They saw significant and relatively large increases in HR at all levels of work up to near subjects' maximal work rate when subjects cycled in the heat (~98˚F) compared to the same work in comfortable temperatures (~70˚F). They also saw a trend for HR to reach maximum values at lower levels of $\dot{V}O_2$, in the heat.

Rowell et al. (32) measured HR and $\dot{V}O_2$ during 15-minute bouts of treadmill exercise in ambient temperatures of 78˚F and 110˚F. They found no statistically significant differences in either maximal or submaximal $\dot{V}O_2$ at 110˚F when compared to the same workloads at 78˚F. However, submaximal HRs were significantly different at

110˚F than at 78˚F and maximal HR was reached at lower levels of work at 110˚F than at 78˚F. They commented that tests which determine $\dot{V}O_2$ or work rate based on a given HR provide misleading results when conducted in conditions of increased ambient temperature.

Kamon et al. (24) investigated the relationship between HR and rectal temperature (T_{re}), during exercise in the heat. Subjects were acclimatized to the heat and then performed maximal and submaximal work in various temperature conditions. The results from this study suggested that a linear relationship existed between HR and T_{re}, and determined that T_{re} response to work and heat could be predicted from change in HR. In a similar study (23), the same authors investigated the HR-T_{re} relationship with continuous and intermittent exercise in various temperature conditions. They observed the same relationship between HR and T_{re} during cycling and load carrying in dry, neutral to hot temperatures that was seen during continuous treadmill walking in the previous study. They also observed that in the heat there is a shift in the relationship between HR and $\dot{V}O_2$ such that, for a given $\dot{V}O_2$, there is an estimated 1 beat/min increase in HR per 1˚C increase in ambient temperature. These studies are only a fraction of a large volume of literature which illustrates the shift in the HR-$\dot{V}O_2$ when exercise is performed in increased ambient temperatures.

Effects of the menstrual cycle. The use of female subjects for this study required that the menstrual cycle and the effects of heat relative to the menstrual cycle be considered. Wells et al. (46) investigated the responses to walking in the heat in different phases of the menstrual cycle. Their subjects included seven untrained, unacclimatized women, who were required to rest and walk (at an intensity corresponding to 50% $\dot{V}O_{2max}$) in an environment that was heated to 48 ˚C, within 36 hours of the onset of menstrual flow, again during the ovulatory phase, and again during the luteal phase. HR, $\dot{V}O_2$, rectal temperature, and skin temperature were monitored during each session. No significant differences attributable to the menstrual phase were found in rectal temperature, skin temperature, mean body temperature, HR, or $\dot{V}O_2$, during any of the three periods of the heat exposure. The responses of these variables to exercise in the heat were similar to those seen during rest in the heat, and these responses were not different between the three phases. Therefore, from this study it can be concluded that the various phases of the menstrual cycle would not have an effect on the estimation of EE based on HR.

Avellini et al.(3) observed the responses of men and women to exercise in the heat prior to, and after heat acclimation. The female subjects were tested during both preovulation (pre-OV) and postovulation (post-OV), to investigate the effects of the menstrual cycle. Subjects were required to walk on a treadmill for 3 hours at 5.6 km/hour up a 2% grade in a chamber at 36 ˚C, both before and after acclimation (women were test twice before and twice after acclimation). Prior to acclimation, HR responses to the protocol were similar for pre-OV and post-OV women at 30 minutes and 60 minutes. However, significant differences in HRs were observed at the 90-minute time point, with the post-OV women reaching higher HRs. Higher rectal temperatures were observed in the post-OV women, as compared to the pre-OV women. However, this difference did not appear to affect the HR response. Post-acclimation these differences were eliminated, and HR responses were identical in pre-OV and post-OV women.

Similar results were observed in other studies comparing the responses of HR during the luteal and follicular phases of the menstrual cycle during exercise in the heat in athletic and non-athletic, healthy females (22; 36; 39). Schoene et al. (36) also included several competitive athletes who were amenorrheic, in addition to regularly menstruating competitive athletes, and women who were never active in competitive athletics. The amenorrheic athletes were tested two weeks apart, and no changes were observed between the two test periods.

From the literature presented, it is clear that although some differences are observed in other cardiovascular and thermoregulatory responses, significant differences in HR were not observed. Therefore, when HR is the primary variable being investigated, controlling for the menstrual cycle is not necessary.

CHAPTER 3

VALIDATION OF THE POLAR S410 HEART RATE MONITOR FOR ESTIMATING ENERGY EXPENDITURE IN WOMEN[1]

[1] Thomas, M.K., Wingo, J.E., Ganio, M.S., Trilk, J.L., Cureton, K.J. Validation of the Polar S410 for estimating energy expenditure in women. To be submitted to Medicine and Science in Sports and Exercise.

Abstract

To determine the effect of ambient temperature on the validity of the Polar S410 heart rate (HR) monitor for estimating energy expenditure (EE), EE estimates obtained during cycling at 30%, 60%, and 80% of maximal oxygen uptake ($\dot{V}O_{2max}$) in 25˚C, 30˚C, and 35˚C ambient temperatures, were compared with indirect calorimetry (IC). Three different methods of estimating EE using the monitor were compared: (a) the AHR method used the actual values for HRmax and $\dot{V}O_{2max}$, (b) the PHR method used the HRmax and $\dot{V}O_{2max}$ predicted by the "OwnIndex" software, with resting HR measured in the ambient temperature for the test, (c) and the PHRTM method used the HRmax and $\dot{V}O_{2max}$ predicted by the "OwnIndex" software, with resting HR measured in thermoneutral (22˚C) conditions. The traditional method of using individualized heart rate-$\dot{V}O_2$ relationship to estimate EE was also compared to IC and the Polar S410 methods. In the 25˚C, 30˚C, and 35˚C conditions AHR overestimated [means (SD)] EE from IC by 4% (11), 7% (11), and 9% (8); PHR overestimated EE from IC by 17% (21), 18% (22), and 19% (19); PHRTM overestimated EE from IC by 20% (21), 22% (21), and 24% (19); and the HR-$\dot{V}O_2$ method underestimated EE from IC by 8% (12), 4% (12), and 1.4% (11). It is concluded that the Polar S410 using the actual values for HRmax and $\dot{V}O_{2max}$ programmed into the Polar S410 (AHR), provides estimates of EE for a group of young women that are within 10% of those from IC. These EE estimates are similar in accuracy (i.e. 4%-9% difference) to estimates from the traditional HR-$\dot{V}O_2$ relationship (i.e. 8%-1.4% difference). Estimates of EE from the Polar S410 based on estimates of $\dot{V}O_{2max}$ and HRmax (PHR and PHRTM) are unacceptably high (>10%), with errors ranging from 17%-24% difference in estimates of EE. Ambient temperatures above 25˚C slightly increase the error of EE estimates from the Polar S410 due to the dissociation of HR from $\dot{V}O_2$.

Introduction

HR and oxygen consumption ($\dot{V}O_2$) increase proportionately during continuous aerobic exercise. The linear relationship between HR and $\dot{V}O_2$ has been used to estimate energy expenditure (EE) from HR during periods of activity (12; 15; 15; 27; 38; 38; 44). HR monitoring has been shown to be a valid method of measuring EE when measurement of $\dot{V}O_2$ is not practical or possible, such as during activities performed outside of a laboratory or in the field (9; 13; 27; 28; 30; 43). HR monitors are also appropriate for large-scale studies and can provide estimates of frequency, intensity and duration of habitual activity (16).

Recently, Polar Electro, Inc (Woodbury, NY), one of the leading manufacturers of HR monitors, developed software that utilizes the relationship between HR and $\dot{V}O_2$ to estimate EE during bouts of exercise. The Polar S410 HR monitor incorporates the individual user information into a non-exercise based estimate of maximal aerobic power ($\dot{V}O_{2max}$) and maximal HR. These predicted values along with HR during submaximal exercise are then used to estimate EE. Although the algorithms have not been disclosed, apparently the relationship between percentage of maximal HR and percentage $\dot{V}O_{2max}$ is used to estimate $\dot{V}O_2$ and EE from HRs recorded during a bout of exercise. The Polar S410 has recently been shown to provide a rough estimate of EE during several aerobic activities (11). The approach used for estimating EE from HR is different than the traditional method of HR monitoring, which requires establishing each individual's HR-$\dot{V}O_2$ relation during an exercise test prior to the estimation of EE (9; 12; 28; 38; 44).

Although the use of HR monitoring and the HR-$\dot{V}O_2$ relationship has been shown to be an effective way to estimate EE, there are several non-exercise factors that influence HR, thereby dissociating it from $\dot{V}O_2$ (12; 23; 24; 44). One such factor is environmental temperature. As the temperature of the environment in which exercise is being performed increases, HR increases independently of $\dot{V}O_2$ (18; 23; 24; 34). For example, Kamon, et al. found an increase in HR of about 1 beat/min per rise of 1 ˚C in ambient temperature (dry heat) (23). The increase in HR with increased environmental temperature can be attributed primarily to autonomic influences (both vagal withdrawal and sympathetic activation) and partly to local temperature influences on pacemaker tissue (18). The dissociation between HR and $\dot{V}O_2$ is a source of error when using the HR-$\dot{V}O_2$ relationship to estimate EE.

Because, the dissociation between HR and $\dot{V}O_2$ is a source of error in the estimation of EE from the HR-$\dot{V}O_2$ relationship, it can be assumed that this would also be a source of error for the estimation derived from the Polar S410 HR monitor. However, it has not been determined how an increase in environmental temperature would affect the accuracy of the prediction of HRmax and $\dot{V}O_{2max}$, and subsequently the estimation of EE, derived from the Polar S410 HR monitor. Establishing the validity of this instrument in hot as well as thermoneutral environments is needed before it is accepted as an alternative to the traditional method of determining the individualized relationships between HR and $\dot{V}O_2$ to estimate the energy expended during exercise.

Crouter et al. (11) found estimates of EE from the Polar S410 HR monitor were more accurate in men than in women. However, the samples of women and men were small and sampling error may have produced results different than what might be obtained from a larger, more heterogeneous sample. Additional studies of the validity of the S410 in larger samples are needed.

The specific aims of this study were: (1) To compare estimates of EE from the HR monitor to estimates of EE obtained by indirect calorimetry (IC) and to estimates of EE obtained from the traditional use of individualized HR-$\dot{V}O2$ relationships to estimate EE in women (2) To compare estimates of EE from the Polar S410 based on estimated $\dot{V}O_{2max}$ and HRmax with estimates based on measured $\dot{V}O_{2max}$ and HRmax, and (3) and to determine the effect of environmental temperature on estimates of EE obtained by the Polar S410 HR monitor. The first of these purposes was accomplished by comparing the estimates of EE from the Polar S410 with the estimates obtained by indirect calorimetry, as well as the traditional method of using individualized HR-$\dot{V}O_2$ relationship. The second purpose was accomplished by comparing estimates of EE obtained by the Polar S410 which used the actual values for $\dot{V}O_{2max}$ and HRmax for the estimation of EE (AHR), to estimates which used the $\dot{V}O_{2max}$ and HRmax predicted by the "OwnIndex" software, with resting HR measured in the specific ambient temperature for the test (PHR). Additionally, estimates of EE obtained by a third monitor which used the values for $\dot{V}O_{2max}$ and HRmax predicted by the "OwnIndex" software, with resting HR measured in thermoneutral temperature (PHRTM), were obtained to determine the effects of ambient temperature on the prediction of these variables. The third purpose was accomplished by comparing the estimates of EE obtained by the Polar S410 HR monitor during submaximal cycling in three different ambient temperature conditions. If estimates of EE from the Polar S410 HR monitor are similar to those derived from the traditional methods, it could be useful in settings where the measurement of $\dot{V}O_2$ is not practical or possible.

Methods

Subjects

Eighteen women attending the University of Georgia, or residing in the local area, were recruited to participate in the study. Their mean (SD) age, height, mass, and percent body fat were 23 (3) yr, 166.1 (7.1) cm, 61.02 (8.12) kg, and 22% (5.6), respectively. The mean (SD) measured $\dot{V}O_{2max}$ obtained from the graded exercise test (GXT) was 42.8 (7.47) $ml \cdot kg^{-1} \cdot min^{-1}$ and the mean (SD) actual HRmax obtained from the GXT was 194 (7.68) bpm. This sample size was sufficient to detect a 5% difference (0.3 kcal/min) in the mean values for EE estimated using paired t-tests for each comparison alpha equal to 0.05 and a statistical power of 0.8 (26), assuming a correlation of 0.8 between repeated estimates of EE.

Women of various levels of cardiovascular fitness were included in the sample. No specific criteria for activity level or fitness was used, as a variety of activity levels was desired in order to have a more diverse group of subjects. Subjects rated their usual level of activity based on the criteria provided in the Polar S410 instruction manual as low, middle, high, or top (14). The group of subjects included primarily women who ranked their activity level as "middle" or "high". The distribution of activity levels was: middle = 7 subjects, high = 7, top = 4 subjects.

The Godin Leisure-Time Exercise Questionnaire was also used to assess the activity level of each subject. This questionnaire determines a score based on the average numbers of strenuous, moderate, and mild exercise sessions performed during an average week. The number of strenuous, moderate, and mild exercise sessions are multiplied by 9, 5, and 3, and then summed to produce an arbitrary score of physical activity (17). The mean (SD) number of strenuous, moderate and mild exercise sessions performed by subjects each week were: 4.1 (1.4), 2.9 (2.1), and 2.3 (2.7), respectively. The scores obtained by this questionnaire for each subject were compared with their ranking of physical activity level from the Polar S410 instruction manual. The correlation between these variables was not significant ($p>0.05$).

All subjects were free of any previous or current medical conditions that could potentially initiate any adverse responses to exercise in the heat. Subjects were required to complete medical history and physical activity history questionnaires to ensure that they met the specified criteria. Subjects also were required to complete a menstrual history questionnaire, which allowed determination of the phase of the menstrual cycle the subject was in throughout the time of participation in the study. During the luteal phase of the menstrual cycle mean core temperature has been shown to be higher than during the follicular phase. However, this increase is modest (0.5-0.6˚C), and occurs independent of any change in HR (22; 39; 46). Any effect should not have influenced the results. Approximately the same number of tests were conducted in each phase of the menstrual cycle. The distribution of these tests was: GXT 1 -10 subjects were in the follicular phase and 8 were in the luteal phase; GXT 2 - 11 subjects were in the luteal phase and 7 were in the luteal phase; 25˚C – 10 subjects were in the follicular phase and 8 were in the luteal phase; 30˚C – 8 subjects were in the follicular phase and 10 were in the luteal phase; 35˚C – 9 subjects were in the follicular phase and 9 were in the luteal phase. The even distribution of sessions between the phases of the menstrual cycle would have offset any effect of the menstrual cycle on the results obtained in this study.

Research Design

A repeated-measures experimental design in which the subjects serve as their own controls was used. The initial visit to the laboratory was used to familiarize subjects with the testing protocol and equipment used during the study. Subjects completed a discontinuous exercise test in which exercise intensity was progressively increased to establish the individual relationship between HR and $\dot{V}O_2$, and to determine $\dot{V}O_{2max}$. The second visit to the laboratory was identical to the first visit. The primary purpose of this session was to determine the reliability of the Polar S410 HR monitor for the estimation of EE. Following the graded exercise test (GXT) the subjects performed three trials, under three different environmental temperatures (25˚C, 30˚C, 35˚C), which consisted of three 10-minute bouts of cycling on an electronically-braked ergometer (Lode Excalibur Sport, Lode B.V., Groningen, NL) at intensities of 30%, 60%, and 80% $\dot{V}O_{2max}$, separated by 15 minutes of rest. The $\dot{V}O_{2max}$ test and each of the three submaximal trials were separated by a period of 3-7 days.

Protocols and Procedures

Subjects were asked to refrain from the use of alcohol, caffeine, or non-prescription drugs on the day prior to, and the day of testing. Subjects were instructed to remain hydrated, and to fast for at least 3 hours prior to testing. Upon arrival to the laboratory for all test sessions, subjects completed a 24 hour history questionnaire to ensure that pre-test instructions were followed. Additionally, urine specific gravity (USG) and tympanic temperature were measured to ensure subjects were not dehydrated (USG<1.030 g/ml), and did not have a fever (tympanic temperature<37.8˚C). All testing was conducted in an environmental chamber at temperatures of 25˚C, 30˚C, or 35˚C and 40% humidity. Each subject was tested at the same time of day to minimize the effects of circadian rhythms in HR and core temperature. Test sessions were separated by 4.6 (2.0) days.

VO2max test sessions. On the first day of testing, the procedure for all trials was described in detail. Subjects received paperwork which included the informed consent, physical activity history, Godin Leisure-Time Physical Activity Questionnaire, medical history, 24-hour history, and menstrual history questionnaires. Each subject who agreed to participate in the study and met the criteria described previously, was assigned a subject number. All results of testing that subject were associated with this subject number to ensure anonymity. After completion of the paperwork, skinfolds were measured to estimate body composition using the seven-site Jackson, Pollock and Ward equation (20) to estimate body density and the Siri equation (37) to determine the percent fat. The subjects' weight (kg) and height (in) in light clothing without shoes was measured using a platform digital scale and stadiometer, respectively. Each subject's weight, height, date of birth, and activity level rating was entered into the receiver of the Polar S410 watch while the subject sat quietly for 10 minutes Following this seated rest, the "FitTest" program in the Polar S410 was run according to the manufacturer's instructions (14). The "FitTest" requires the subject to sit quietly for 5 minutes while the monitor records resting HR and predicts HRmax and $\dot{V}O_{2max}$. The subjects then entered the chamber and were briefed on the equipment that would be used throughout the study. These pre-test procedures were repeated for the second $\dot{V}O_{2max}$ test session, with the exception of the paperwork. The subjects were required to complete the 24-hour history questionnaire only, prior to each of the remaining 4 sessions.

At the first and second sessions, subjects completed a cycle protocol designed to determine the HR-$\dot{V}O_2$ relationship, and to elicit $\dot{V}O_{2max}$. After the pre-test procedures were completed, subjects entered the environmental chamber and the cycle ergometer's seat and handlebar heights were adjusted to fit each subject comfortably. The various settings for the cycle ergometer were recorded to ensure that they were the same for every session. Subjects performed a brief warm-up for 10 minutes at a self-selected power output. Following a brief rest, subjects began the $\dot{V}O_{2max}$ test. The test was a discontinuous, load-incremental, progressive protocol with 5-minute bouts of exercise separated by 1 minute of rest. Subjects began cycling at 65 W for 5 minutes, with the power output increased 25 W at each successive stage. Subjects cycled until volitional fatigue. $\dot{V}O_2$ and related gas exchange measures taken during the test and taken one minute prior to the start of the test were determined by indirect calorimetry in 30-second intervals using a PARVO Medics TrueOne 2400 Metabolic Measurement System (Parvo Medics, Inc., Salt Lake City, UT). HR was measured using the Polar S410 HR monitor (Polar Electro Inc. Woodbury, NY). HR and $\dot{V}O2$ from the last two minutes of each stage were used to determine the HR-$\dot{V}O2$ relationship. Rating of perceived exertion (RPE) was measured at rest, halfway through every stage, the last 15 seconds of every stage, and at the end of the $\dot{V}O_{2max}$ test, using the 15-point Borg scale and standardized instructions (7). Three minutes after completion of the test, a finger-stick blood sample was obtained for determination of blood lactate concentration. Blood lactate concentration was measured using an YSI 2300 Stat Plus Analyzer (Yellow Springs Instruments, Inc., Yellow Springs, OH). After completion of the $\dot{V}O_{2max}$ test, subjects rested for 20 minutes and then re-entered the chamber and cycled to exhaustion at a power output equivalent to the last workload performed during the graded test (if less than 1 minute was completed during the last stage of the graded test) or at a power output 25 W higher than the last workload performed during the graded test (if more than 1 minute was completed during the last stage of the graded test).

Attainment of $\dot{V}O_{2max}$ (average of the two highest consecutive 30-sec values) was determined using a modification of the plateauing criterion described by Taylor et al. (42). The criterion for determining a plateau was an increase in $\dot{V}O_2$ (l/min) between the last two stages of less than half of the expected 0.135 l/min increase, based on the American College of Sports Medicine metabolic equation:

$$\dot{V}O_2 = (10.8 \times W/M) + 3.5$$

where $\dot{V}O_2$ is gross oxygen consumption in $ml \cdot kg^{-1} \cdot min^{-1}$; M is body mass in kg; and W is power in Watts (2).

Experimental test sessions. Three experimental test sessions were conducted using the same protocol and procedures, under the following ambient temperatures: 25˚C, 30˚C, 35˚C (order of temperatures randomized). The pretest measures, paperwork and procedures conducted before the $\dot{V}O_{2max}$ trials were also administered before the three experimental sessions. In addition to these procedures, the subjects were also required to insert a temperature probe (Ellab, Inc., Arvada, CO, model MOV-55044-A) 10 cm past the anal sphincter, for the measurement of rectal temperature (T_{re}). The subjects' individual information (variables) was input into three different Polar S410 watch receivers. Their $\dot{V}O_{2max}$ and HRmax determined from the $\dot{V}O_{2max}$ protocol was entered into one of the watch receivers. Upon entering the chamber, the subjects sat quietly for 15 minutes and then the "FitTest" program in the Polar S410 was performed while the subject was sitting in the environmental chamber. The watch receiver with the predicted values for HRmax and $\dot{V}O_{2max}$ (determined by the "FitTest" performed while the subject was in the chamber) was labeled the "predicted HR" (PHR) method. The watch receiver in which the previously measured values for $\dot{V}O_{2max}$ and HRmax were entered was labeled the "actual HR" (AHR) method. Using two watches, it was possible to determine whether inputting the actual, measured HRmax and $\dot{V}O_{2max}$ increased the accuracy of the estimation of EE by the Polar S410. A third HR watch receiver was also used to determine the effect of the environment in which the "FitTest" was conducted, on the prediction of HRmax and $\dot{V}O_{2max}$, and the subsequent estimation of EE. This watch also used the HRmax and $\dot{V}O_{2max}$ predicted by the Polar S410, but the "FitTest" procedures were conducted in the thermoneutral (~22˚C) environment of the lab, prior to the subject entering the environmental chamber. The third watch was labeled the "predicted HR-thermoneutral" (PHR-TM) method.

The reliability of the Polar S410 HR monitor was determined using the data obtained during the initial two sessions from 12 of the subjects. The intraclass correlation between the Polar S410 estimates of EE from stages 2 and 3 of the GXT the Polar S410 was r = .89. The mean (SD) estimates of EE during the first and second graded exercise tests were 108 (21.3) kcal and 106 (21.1) kcal. The standard deviation of the differences between the two trials was 6.4 kcal.

Following the period of rest, subjects mounted the cycle ergometer, which was adjusted according to the specifications determined during the initial session. The subject sat on the cycle while probes designed to measure skin temperature (Ellab, Inc., Arvada, CO, model MHF-18058-A) were attached on the lateral sub-deltoid, chest, thigh, and calf. Mean skin temperature ($\overline{T}_{sk}$) was calculated according to the formula of Ramanathan (31):

$$\overline{T}_{sk} = 0.3(T1 + T2) + 0.2(T3 + T4),$$

where T1, T2, T3, and T4, are chest, lateral sub-deltoid, thigh, and calf skin temperatures, respectively. Mean body temperature ($\overline{T}b$) was calculated from mean rectal temperature ($\overline{T}re$) and $\overline{T}sk$ with the formula of Baum et al.(4). The rectal and skin temperature probes were connected to a temperature data acquisition system (Ellab, Inc., model TM9608 with Eval 2.1 software), which collects and stores temperatures continuously.

Once the resting procedures were completed, subjects began cycling at the first of three submaximal intensities. Subjects cycled at power outputs that produced intensities corresponding to 30%, 60%, and 80% of $\dot{V}O_{2max}$ in order of increasing intensity. Throughout cycling, respiratory variables and HR were measured continuously. First, subjects cycled for 10 minutes at 30% $\dot{V}O_{2max}$. The first 5 minutes allowed HR and $\dot{V}O_2$ to reach a steady state at the specific intensity. Then, during the last 5 minutes of each cycling bout, measurements of EE from the Polar S410 receivers, HR, and $\dot{V}O_2$ were recorded. The "OwnCal" software for all three Polar S410 watches was started simultaneously at the start of the second 5 minutes of each bout. Immediately following the submaximal the 10 minute exercise bout, the subjects were asked to rate their thermal sensation and level of comfort associated with the environment in which they were exercising. Subjects then exited the environmental chamber immediately, and rested (seated) outside of the chamber for 5 minutes. Subjects returned to the chamber and completed 10 more minutes of seated rest inside the environmental chamber for a total of 15 minutes of seated rest. Following the completion of the rest period, subjects mounted the cycle ergometer and repeated the protocol at 60% $\dot{V}O_{2max}$. Again the subjects provided a rating of thermal and comfort sensation, were removed from the chamber for 5 minutes, and then re-entered the chamber and rested for 10 minutes for a total of 15 minutes of recovery. Finally, the subjects once again cycled for 10 minutes, this time at 80% of their $\dot{V}O_{2max}$. When the last 10-minute bout of exercise was completed, the skin temperature probes were detached, and the subject exited the chamber, removed the rectal probe, and weighed themselves. The procedures were identical for all three environmental temperatures (25˚C, 30˚C, 35˚C).

Determination of EE. The Polar S410 monitor uses a program called "OwnCal" to estimate EE based on the HRs that are recorded. This software was run during minutes 6-10 of each of the 10-minute exercise bouts. The estimate of EE in kcal displayed on the watch at the end of the 10 minutes was recorded. The number recorded from the watch was divided by 5 minutes to obtain the rate of EE in kcal/minute.

The $\dot{V}O_2$ and $\dot{V}CO_2$ were measured and recorded throughout the entire 10 minutes of each exercise bout. The $\dot{V}O_2$ and $\dot{V}CO_2$ for minutes 6-10 were used to determine the EE for the "indirect calorimetry" method. The $\dot{V}O_2$ and $\dot{V}CO_2$ were multiplied by factors of 3.9 and 1.1, respectively and summed to produce kcals (45). The values obtained were divided by 5 minutes to produce kcal·min^{-1}.

The graded exercise test performed during the second session was used to determine the relationship between HR and $\dot{V}O_2$ for each subject, which was described by a linear regression equation for predicting $\dot{V}O_2$ from HR for each subject. The HRs recorded for each of the bouts of exercise were input into the equation for each subject, and the $\dot{V}O_2$ for minutes 6-10 of each bout were determined. The resulting $\dot{V}O_2$ was multiplied by 5 to obtain EE in kcals for each bout, and the kcals were converted to kcal·min^{-1}by dividing by 5 (45).

Statistical analysis

Statistical analyses were performed using SPSS v. 13 for Windows (SPSS, Inc., Chicago, IL). Data were reported as means and standard deviations. For the submaximal sessions, a three-way (Temperature x Intensity x Method) repeated measures analysis of variance (ANOVA) was used to test the significance of mean differences between the three methods at the various intensities, and environmental temperatures. No three-way interaction existed; therefore, two-way ANOVAS collapsing over the third factor were performed followed by tests for simple effects and pair-wise comparisons determined with paired-sample t-tests and the Bonferroni alpha correction. Simple correlation and regression analysis was used to describe the relation between the EE estimated by indirect calorimetry and each of the other methods (Polar S410 and HR-VO2 relationship), as well as the interrelations between the variables.

Results

$\dot{V}O_{2max}$

The mean (SD) measured $\dot{V}O_{2max}$ obtained from the GXT was 42.8 (7.47) ml·kg^{-1}·min^{-1} and the mean (SD) actual HRmax obtained from the GXT was 194 (7.68) bpm. The mean (SD) lactate, RPE, and RER at max were 6.9 (1.3) mmol/L, 19 (0.8) and 1.15 (0.1), respectively. The mean (SD) $\dot{V}O_{2max}$ predicted from the Polar S410 prior to each GXT was 49 (9.6) ml·kg^{-1}·min^{-1} and the mean predicted max HR was 197 (3.9) bpm. There was a significant correlation between the $\dot{V}O_{2max}$ predicted by the Polar S410 in the thermoneutral condition, and the actual $\dot{V}O_{2max}$ obtained from the graded exercise test (r = 0.79, p = 0.01). The correlations between the HRmax predicted by the Polar S410 and the actual HRmax obtained from the graded exercise test was not significant (p>0.01). The correlation between the $\dot{V}O_{2max}$ and HRmax obtained from the graded exercise test and the $\dot{V}O_{2max}$ and HRmax predicted by the Polar S410 for each of the experimental conditions are presented in Table 1.

The mean (SD) values for $\dot{V}O_{2max}$ predicted by the Polar S410 "OwnIndex" software in each of the conditions are shown in Figure 1. The mean values for the predicted $\dot{V}O_{2max}$ in all conditions were significantly different from the mean value for the relative $\dot{V}O_{2max}$ obtained from the graded exercise test (p<0.01). The mean (SD) values for HRmax predicted by the Polar S410 "OwnIndex" software in each of the conditions are shown in Figure 2. The mean values for the predicted HRmax in all conditions were not significantly different from the mean value for the relative $\dot{V}O_{2max}$ obtained from the graded exercise test (p>0.01).

Table 1: Correlation between the actual $\dot{V}O_{2max}$ and HRmax, and the $\dot{V}O_{2max}$ and HRmax predicted from the Polar S410.

	Actual $\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	**Actual HRmax (bpm)**
Predicted 25˚C	r = .81	r = .63
Predicted 25˚C-TM	r = .80	r = .55
Predicted 30˚C	r = .79	r = .25
Predicted 30˚C-TM	r = .82	r = .40
Predicted 35˚C	r = .80	r = .34
Predicted 35˚C-TM	r = .82	r = .64

The individual variation in the predicted $\dot{V}O_{2max}$ and HRmax as compared to the actual values for $\dot{V}O_{2max}$ and HRmax are illustrated in Figure 3. The individual predicted $\dot{V}O_{2max}$ and HRmax obtained from each method are represented.

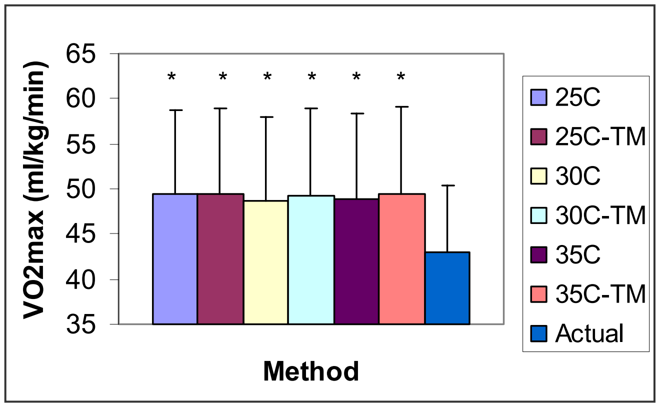

Figure 1: Mean (SD) values for $\dot{V}O_{2max}$ obtained by the PHR and PHRTM methods in each temperature condition, and the actual $\dot{V}O_{2max}$ obtained from the graded exercise test. *Significantly different from the actual $\dot{V}O_{2max}$ ($p < 0.008$).

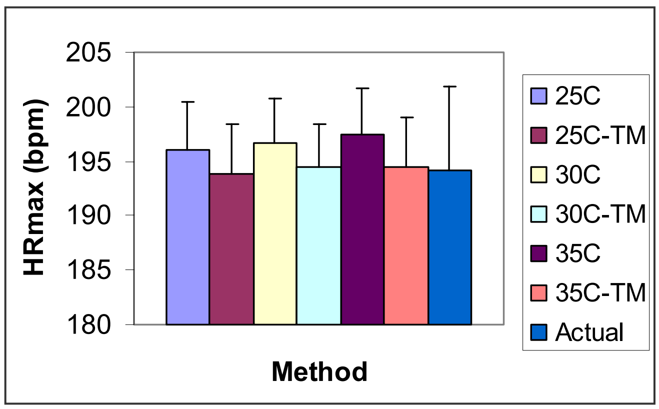

Figure 2:Mean (SD) values for HRmax obtained by the PHR and PHRTM methods in each temperature condition, and the actual HRmax obtained from the graded exercise test.

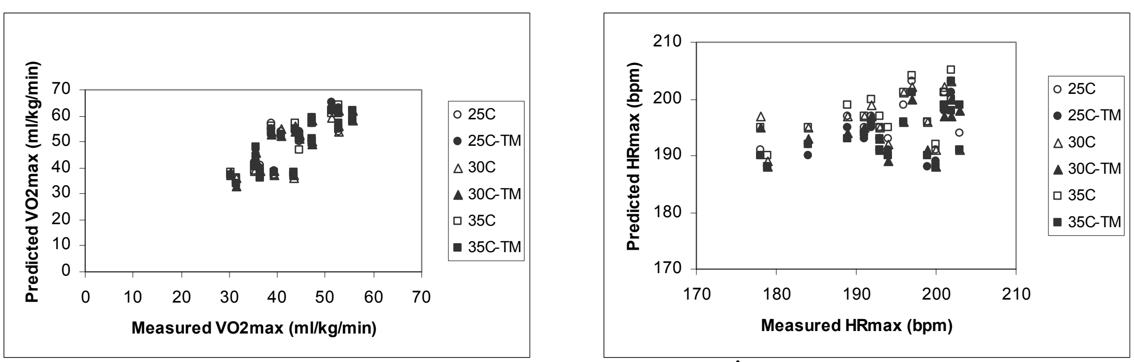

Figure 3: Relationship of individual values for measured $\dot{V}O_{2max}$ and HRmax with values for $\dot{V}O_{2max}$ and HRmax predicted from the Polar S410.

Mean (SD) HR and $\dot{V}O_2$ for each submaximal intensity under each temperature condition are presented in Table 2. Mean heart rates recorded at the three intensities were significantly different among each of the temperature conditions ($p<0.016$), except for the differences between the 30˚C and 35˚C conditions at the 30% intensity and the 25˚C and 30˚C conditions, at the 80% intensity. These differences were not significant ($p>0.017$). Mean values for $\dot{V}O_2$ recorded at the three $\dot{V}O_{2max}$ intensities were not significantly different at the 30% intensity between any of the temperature conditions. Mean values for $\dot{V}O_2$ recorded at the 60% intensity were not significantly different between the 25˚C and 30˚C conditions. Mean values for $\dot{V}O_2$ recorded at the 60% intensity were significantly different between the 25˚C and 35˚C conditions, and between the 30˚C and 35˚C conditions. Mean values for $\dot{V}O_2$ recorded at the 80% intensity were significantly different among all temperature conditions.

Table 2: HR and $\dot{V}O_2$ responses to submaximal cycling at different intensities for each ambient temperature condition. Values are means (SD).

Intensity	**HR, bpm**			**$\dot{V}O_2$, L·min^{-1}**		
(%$\dot{V}O_{2max}$)	**25˚C**	**30˚C**	**35˚C**	**25˚C**	**30˚C**	**35˚C**
30%	106 (21)	108 (12)	111 (14)	0.86 (0.1)	0.88 (0.2)	0.90 (0.2)
60%	148 (15)	151 (14)	156 (13)	1.58 (0.3)	1.60 (0.3)	1.64 (0.3)
80%	176 (11)	177 (11)	180 (10)	2.11 (0.3)	2.15 (0.4)	2.20 (0.3)

Complete temperature data were collected for 13 of the 18 subjects. The mean values for rectal temperature (T_{re}), mean skin temperature ($\overline{T}_{sk}$), and mean body temperature ($\overline{T}_b$) for these 13 subjects are presented in Table 3. Differences in T_{re} between temperature conditions were not significant for the 30% and 60% intensities. Significant differences in T_{re} were observed between the 30˚C and 35 ˚C for the 80%

intensity. Differences in $\overline{T}_{sk}$ between temperatures were significant within each of the intensities. Significant differences in $\overline{T}_b$, were also observed between ambient temperatures, within each intensity.

Table 3: Rectal ($\overline{T}_{re}$), skin ($\overline{T}_{sk}$), and total body ($\overline{T}_{bod}$) temperatures (˚C) during cycling at different intensities for each ambient temperature condition. Values are presented as means (SD).

	Mean $\overline{T}_{re}$			**Mean $\overline{T}_{sk}$**			**Mean $\overline{T}_{bod}$**		
	25˚C	**30˚C**	**35˚C**	**25˚C**	**30˚C**	**35˚C**	**25˚C**	**30˚C**	**35˚C**
30%	37.4 (0.3)	37.4 (0.1)	37.5 (0.2)	31.7 (0.7)	33.8 (0.4)	35.6 (0.4)	36.7 (0.3)	37.0 (0.1)	37.3 (0.2)
60%	37.6 (0.2)	37.6 (0.1)	37.8 (0.2)	32.1 (0.5)	34.3 (0.6)	36.0 (0.3)	36.9 (0.2)	37.1 (0.1)	37.5 (0.2)
80%	38.0 (0.3)	38.0 (0.2)	38.2 (0.2)	32.3 (0.8)	34.5 (0.7)	36.0 (0.4)	37.2 (0.3)	37.5 (0.2)	37.9 (0.2)

The average estimates of EE obtained from each of the methods, for each of the temperature conditions are presented in Figure 4. The initial three-way (Temperature x Intensity x Method) repeated measures ANOVA indicated that no significant three-way interaction existed. There were significant Temperature x Method and Intensity x Method interactions ($p<0.05$). One-way repeated measures ANOVA indicated that differences among methods were significant at each temperature ($P<0.017$), and means as temperature increased, the differences between the estimates of EE obtained by each method increased. Differences in EE also were significant among intensities ($p<0.017$), therefore as subjects worked at increasing intensities, differences between the estimates of EE obtained by each method increased. Therefore, paired sample t-tests were conducted for each comparison, and comparisons with $p<0.005$ were considered significant. The mean estimates of EE obtained from the Polar S410 methods (PHR and PHRTM) that utilized the predicted values for HRmax and $\dot{V}O_{2max}$ were significantly different from those obtained by indirect calorimetry (IC) ($p<0.005$). Additionally, the estimates from the PHRTM method (which utilized the HRmax and $\dot{V}O_{2max}$ predicted in the thermoneutral environment) also were significantly different from the estimates of EE obtained by the PHR method (which utilized the HRmax and $\dot{V}O_{2max}$ predicted in the temperature corresponding with the specific session condition) ($p<0.005$).

The prediction of EE using actual values for HRmax and $\dot{V}O_{2max}$ (AHR) provided the best estimates of EE by the Polar S410 monitor across all temperatures. These values were not significantly different than those obtained by IC ($p>0.005$). The method using the individualized HR-$\dot{V}O_2$ relationships (HR-$\dot{V}O_2$) produced estimates of EE that also were not significantly different than IC ($p>0.005$). Correlations between each of the methods and IC are presented in Table 4. Significant correlations existed between all methods and IC ($p< 0.01$), the strongest of which were observed between the AHR method and IC ($r = 0.88$-0.96).

The individual errors in estimating EE for each method and each temperature are depicted as Bland-Altman plots (1; 6) in Figure 5. The AHR method overestimated EE by 4% (11), 7% (11), and 9% (8) in the 25˚C, 30˚C, and 35˚C, respectively. The average error (AHR-IC) for the 25˚C condition was 0.3 $kcal{\cdot}min^{-1}$ (-1.4 to +2.0 $kcal{\cdot}min^{-1}$, 95% CI). The average error for the 30˚C condition was 0.5 $kcal{\cdot}min^{-1}$ (-1.3 to +2.3 $kcal{\cdot}min^{-1}$, 95% CI). The average error for the 35˚C condition was 0.7 $kcal{\cdot}min^{-1}$(-0.9 to +2.3 $kcal{\cdot}min^{-1}$, 95% CI).

The PHR method overestimated EE in the 25˚C, 30˚C, and 35˚C by 17% (21), 18% (22), and 19% (19), respectively. The average error (PHR-IC) for the 25˚C condition was 1.3 $kcal{\cdot}min^{-1}$ (-2.1 to + 4.6 $kcal{\cdot}min^{-1}$, 95% CI). The average error for the 30˚C condition was 1.3 $kcal{\cdot}min^{-1}$ (-2.2 to + 4.8 $kcal{\cdot}min^{-1}$, 95% CI). The average error for the 35˚C condition was 1.5 $kcal{\cdot}min^{-1}$ (-1.8 to + 4.8 $kcal{\cdot}min^{-1}$, 95% CI).

The PHRTM method overestimated the EE by 20% (21), 22% (21), and 24% (19) in the 25˚C, 30˚C, and 35˚C, respectively. The average error (PHRTM-IC) for the 25˚C condition was 1.5 $kcal{\cdot}min^{-1}$ (-1.9 to + 4.8 $kcal{\cdot}min^{-1}$, 95% CI). The average error for the

30˚C condition was 1.7 kcal·min^{-1} (-1.8 to + 5.1 kcal·min^{-1}, 95% CI). The average error for the 35˚C condition was 1.9 kcal·min^{-1} (-1.5 to + 5.3 kcal·min^{-1}, 95% CI).

The HR-$\dot{V}O_2$ method underestimated EE by 8% (12), 4% (12), and 1.4% (11), in the 25˚C, 30˚C, and 35˚C, respectively. The average error (HR-$\dot{V}O_2$-IC) for the 25˚C condition was -0.6 kcal·min^{-1} (-3.2 to + 2.0 kcal·min^{-1}, 95% CI). The average error for the 30˚C condition was -0.3 kcal·min^{-1} (-3.1 to + 2.5 kcal·min^{-1}, 95% CI). The average error for the 35˚C condition was -0.1 kcal·min^{-1} (-2.7 to + 2.5 kcal·min^{-1}, 95% CI).

Table 4: Correlations between methods for estimating EE and EE measured by Indirect Calorimetry at each temperature condition. Significant at $p<0.01$
.

Method	**Indirect Calorimetry 25˚C**	**Indirect Calorimetry 30˚C**	**Indirect Calorimetry 35˚C**
"Actual" HR Method (AHR)	r = .88	r = .83	r = .96
"Predicted" HR Method (PHR)	r = .71	r = .74	r = .80
"Predicted" HR Method-TM (PHRTM)	r = .75	r = .72	r = .81
HR - $\dot{V}O_2$ Method (HR- $\dot{V}O_2$)	r = .78	r = .72	r = .82

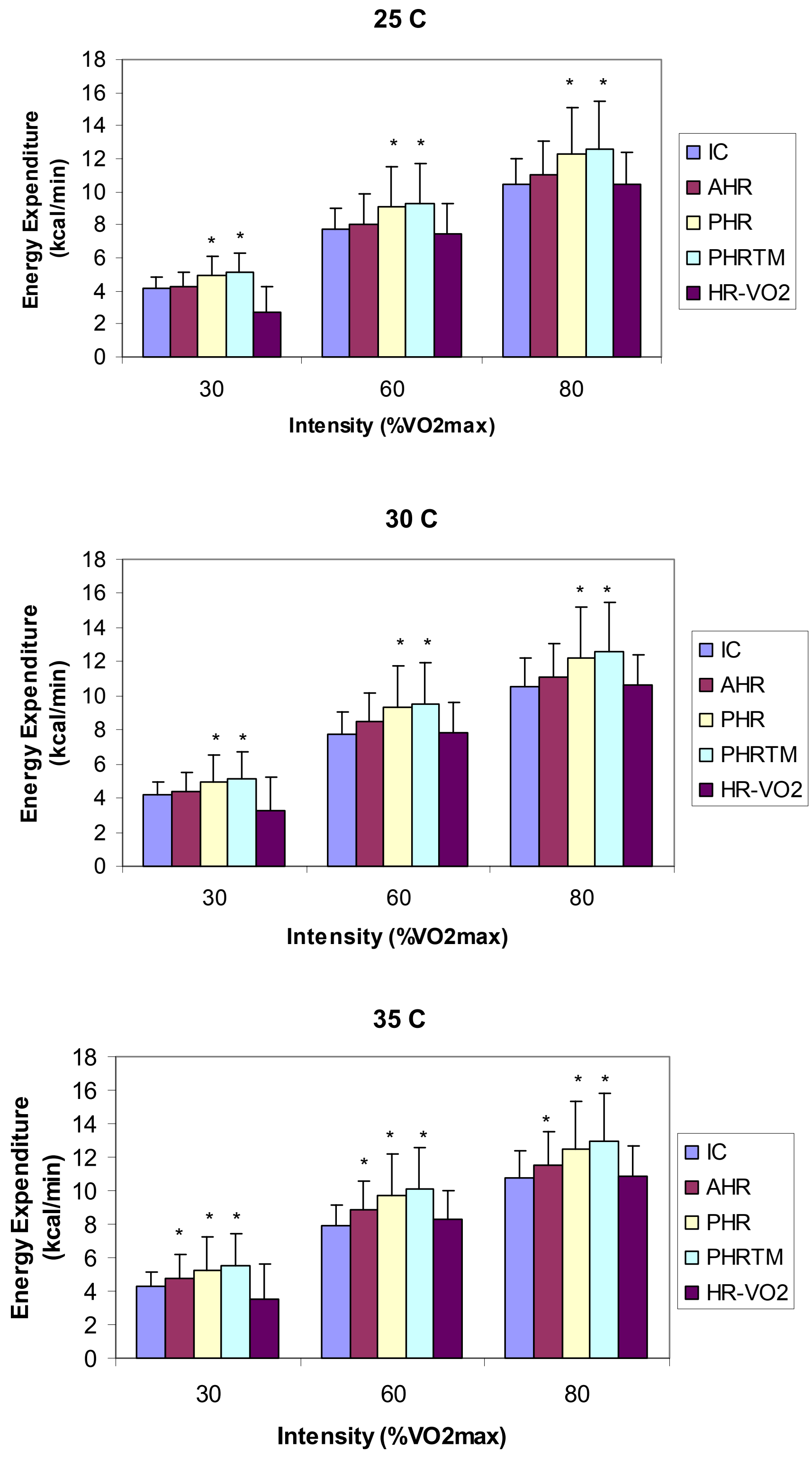

Figure 4: Estimates of EE for each method in the three temperature conditions. Values are presented as means (SD). * Significantly different from indirect calorimetry (p<0.005).

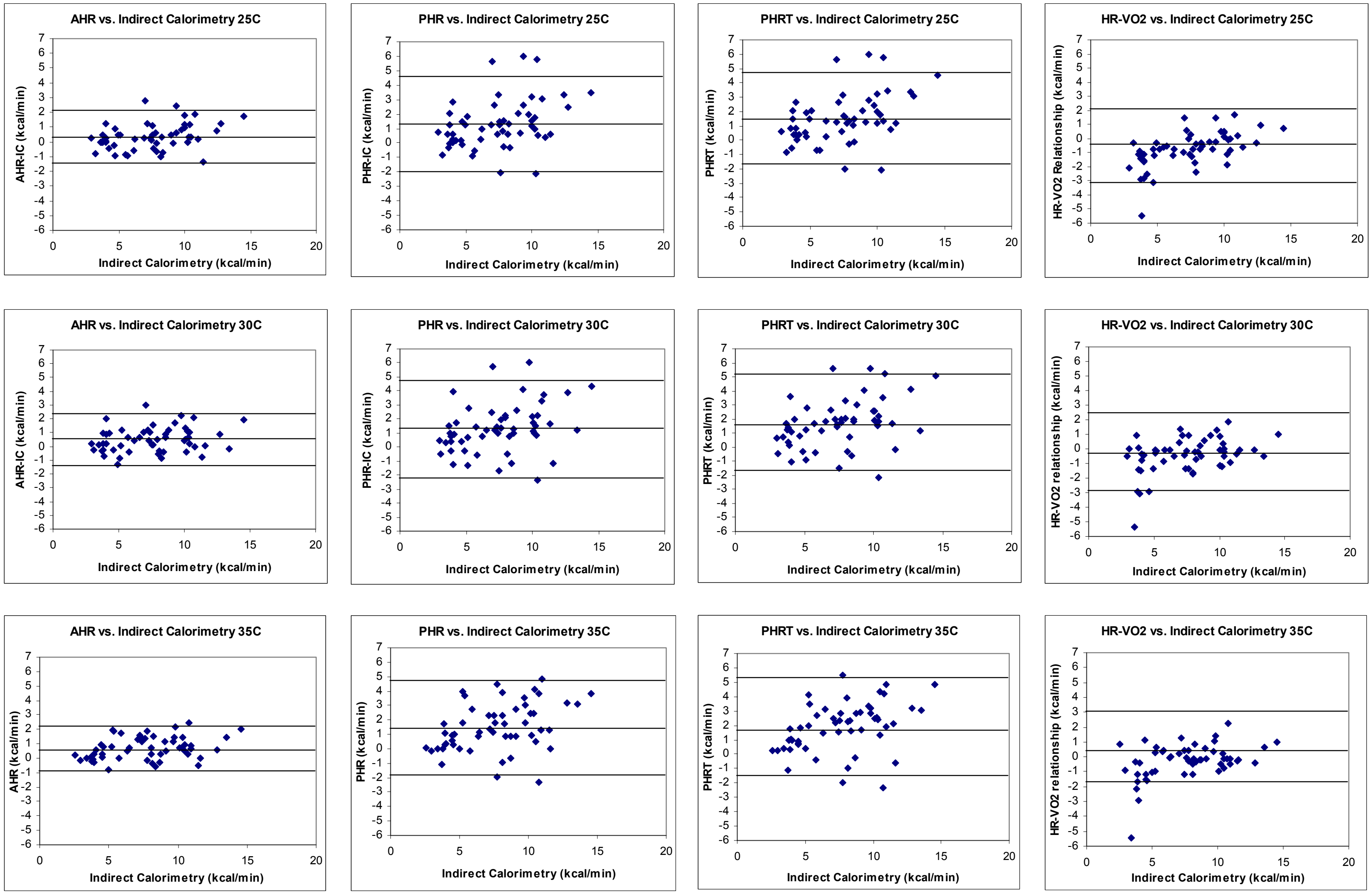

Figure 5: Bland-Altman plots depicting the individual error associated with each method, in each temperature condition, as compared to indirect calorimetry.

Discussion

The findings of this study confirmed the three hypotheses posed for the study. When an error criterion of 10% is used, the Polar S410 provided relatively accurate mean estimates of EE for this sample of females, when the user's actual HRmax and $\dot{V}O_{2max}$ are input into the watch receiver (4%-9% overestimation). However, there is substantial individual error associated with this method. The use of the measured HRmax and $\dot{V}O_{2max}$ in the estimation of EE by the Polar S410 reduces the size of the 95% confidence interval compared to the use of the predicted values of HRmax and $\dot{V}O_{2max}$. The estimates of EE from the Polar S410 using measured values for $\dot{V}O_{2max}$ and HRmax were similar in accuracy to prediction of EE using traditional HR monitoring based on individual relationships between HR and $\dot{V}O_2$ when the estimates of both methods are compared to IC. Additionally, as hypothesized, when EE was estimated by the Polar S410 during exercise in the heat, the amount of error associated with the estimation was slightly increased.

The protocol used to determine the relationship between HR and $\dot{V}O_2$ was designed to elicit a maximal effort, yet still allow for a "steady-state" of HR and $\dot{V}O_2$ to be reached during each stage. The protocol succeeded in eliciting $\dot{V}O_{2max}$; a plateau in $\dot{V}O_2$ as described by Taylor et al. (42), was observed in each subject either during the initial graded exercise test or on the following test. The protocol was also successful in determining the relationship between HR and $\dot{V}O_2$. Individual HR-$\dot{V}O_2$ relationships were very strong ($r = 0.95$-0.99). Many studies have measured HR and $\dot{V}O_2$ over a 24-hour period via whole-body indirect calorimetry, or during periods of seated or supine rest (12; 15; 28; 38; 44). These resting measures of HR and $\dot{V}O2$ are used in addition to the measurement of HR and $\dot{V}O_2$ during exercise, to develop the individualized relationships. The current study did not incorporate resting HR and $\dot{V}O_2$ measures when establishing the individualized HR-$\dot{V}O_2$ relationships used to estimate EE. The purpose of the current study was to validate the Polar S410 HR monitor for the estimation of EE during periods of activity. Therefore, the inclusion of resting data was not necessary for the individual HR-$\dot{V}O_2$ relationships established from the GXT, and only those values obtained during exercise were represented by the regression equations. When heart rate monitoring is used to estimate daily EE during which large periods of time are spent at low levels of EE, and subsequently low HRs, HR-$\dot{V}O_2$ relationships traditionally include resting data recorded during various postures, in order to represent the low HRs. The "OwnCal" software used by the Polar S410 HR monitor only functions during periods of activity, when HR exceeds 90 bpm, therefore establishing HR-$\dot{V}O_2$ relationships that incorporated large periods of resting data may not be appropriate or necessary for comparison with this method.

Much of the error associated with the estimates of EE obtained by the "OwnCal" software is related to the estimate of $\dot{V}O2_{max}$ and HRmax used by the software. The estimates of $\dot{V}O2_{max}$ obtained by the "OwnIndex" software were significantly different from the $\dot{V}O2_{max}$ measured during the graded exercise test ($p<0.008$). Individual differences between the predicted $\dot{V}O_{2max}$ and the actual $\dot{V}O_{2max}$ ranged from -7.6 to +18.3 $ml \cdot kg^{-1} \cdot min^{-1}$. The mean values for the predicted HRmax in all conditions were not significantly different from the mean value for the measured HRmax obtained from the graded exercise test ($p>0.008$). However, individual differences between the predicted HRmax and the actual HRmax ranged from -12 to +19 bpm. These discrepancies led to the errors in estimations of EE obtained by the methods which used the predicted values for $\dot{V}O_{2max}$ and HRmax.

The submaximal protocol used was similar to that used by Crouter et al. (11) in their validation of the Polar S410. The initial 5 minutes of each 10-minute bout of exercise was used to allow the subjects' HR and $\dot{V}O_2$ to reach a steady-state at the specified intensity, and the second 5 minutes were used in the estimation of EE by each method. For all of the submaximal exercise bouts, the Polar S410 overestimated the energy expended. Much of the overestimation of EE by the PHR and PHRTM methods can be attributed to the error in the prediction of $\dot{V}O_{2max}$ and HRmax. The explanation for the overestimation of EE by the AHR method is less obvious, but must be related to error associated with the equation used by the "OwnCal" software to estimate EE. The exact equation, and weighting of each variable included in the equation are not know and, therefore, the exact source of error cannot be determined.

The error observed in the women in this study was smaller than that observed by Crouter et al.(11). In their study, the use of the predicted values for $\dot{V}O_{2max}$ and HRmax resulted in a mean (SD) error of 33% (20.9) in the estimation of EE. The use of the actual values improved the mean error to 12% (13) in the women. By comparison, the PHR method in this study produced a mean error of 17% (in the 25˚C condition) and this error was reduced to 4% when the actual values for $\dot{V}O_{2max}$ and HRmax (AHR method) were used. These values were similar to what Crouter et al. observed for the men in their study. The improved estimates of EE obtained by the Polar S410 in the women in this study can be attributed to the larger, more diverse sample of females, as compared to the sample of women in the previous study.

One of the aims of this study was to compare the estimation of EE by the Polar S410 with the traditional method of using individualized HR-$\dot{V}O_2$ relationships to estimate EE. The results of this study suggested that the estimation of EE from the AHR method is not significantly different from the HR-$\dot{V}O_2$ method, in any of the temperature conditions. However, in the 35˚C condition the AHR method was significantly different from IC, while the HR-$\dot{V}O_2$ method was not. This would suggest that for exercise in increased ambient temperatures, the HR-$\dot{V}O_2$ method is more accurate than the Polar S410, even when the actual values for HRmax and $\dot{V}O_{2max}$ are used in the estimation of EE by the Polar S410.

In this study, the estimates of EE obtained by the HR-$\dot{V}O_2$ method actually improved with the increase in temperature. It was hypothesized, however, that due to the dissociation between HR and $\dot{V}O_2$ with increased ambient temperature, the HR-$\dot{V}O_2$ method would be subject to more error. The use of only exercise HRs and $\dot{V}O_2$ recorded during the graded exercise test, to develop the individualized HR-$\dot{V}O_2$ relationships may have contributed to the decrease in the error associated with this method, with increasing temperatures observed in this study. The lower heart rates obtained during the exercise bouts in the 25˚C condition were not observed during the GXT, and therefore were not represented in the linear regression equations developed for each subject. When the heart rates recorded during the 25˚C condition were used in the individualized regression equations, the resulting $\dot{V}O2$ was underestimated compared to IC. This resulted in an underestimation of EE for the group in this condition. Therefore, as the ambient temperature increased, and HR increased independently of $\dot{V}O_{2,}$ the resulting estimates of EE were actually closer to the estimates obtained by IC.

The effect of heat on the accuracy of the Polar S410 estimation of EE was, for the most part, what was expected. The error in estimation of EE by each of the watches, as compared to IC, increased with each increase in temperature. The increase in error can be attributed to the higher heart rates associated with the higher temperatures. These heart rates, however, did not increase to the extent that was reported by Kamon et al.(23). This can be explained by the relatively short duration of the exercise and small increases in core temperature, which in turn resulted in small increases in total body temperature. Had the 1 beat per minute increase in HR with each 1˚C increase in ambient temperature (23) occurred, the systematic error associated with each watch may have been larger. The largest effect of the increased ambient temperature was seen in the AHR method from 25˚C to 35˚C, with the bias increasing from 4% to 9%, respectively.

Crouter et al. (11) attempted to determine how the Polar S410 estimates EE, by examining the relationship between estimated EE and HR when the actual $\dot{V}O_{2max}$ and HRmax were programmed into the watch receiver. They found a strong relationship between the percentage of HRmax and the percentage of EE max that was similar for all participants, regardless of fitness level, gender, or other variables. From their results, they reasoned that the Polar S410 was using the percentage of HRmax to estimate the percentage of $\dot{V}O_{2max}$, which is then converted to Caloric expenditure. This study attempted to expand upon the Crouter results in an attempt to provide additional insight into the method the Polar S410 uses to estimates EE. Recent studies have shown that the relationship between the percentage of the difference between resting HR and maximal HR (%HRReserve), and the percentage of the difference between resting $\dot{V}O_2$ and maximal $\dot{V}O_2$ ($\dot{V}O_2$ Reserve) provides another method by which EE can be estimated (40; 41). By converting the recorded heart rates to %HRR, the %$\dot{V}O_2$R can be determined and converted to $\dot{V}O_2$ and subsequently an estimate of EE. The correlation between these variables resulted in an r = 0.97 however, the corrleation between %HRmax and %$\dot{V}O_{2max}$ also resulted in an r = 0.97. Therefore it is not known whether using the %HRR method for estimating EE from HR would be more or less accurate than using the relation of HRmax to $\dot{V}O_{2max}$.

In conclusion, the Polar S410 using the actual values for HRmax and $\dot{V}O_{2max}$ programmed into the watch receiver (AHR), provides estimates of EE for a group of young women that are within 10% of those from IC. These EE estimates are similar in accuracy (i.e. 4%-9% difference) to estimates from the traditional HR-$\dot{V}O_2$ relationship (i.e. 8%-1.4% difference). Estimates of EE from the Polar S410 based on estimates of $\dot{V}O_{2max}$ and HRmax (PHR and PHRTM) are unacceptably high (>10%), with errors ranging from 17%-24% difference in estimates of EE. This method could be useful to exercisers who would like to monitor their caloric expenditure, without the cumbersome individual calculations of the HR to $\dot{V}O_2$ relationship, necessary for the traditional HR-$\dot{V}O_2$ method. Alternatively, when the predicted values for HRmax and $\dot{V}O_{2max}$ are used in the estimation of EE, the Polar S410 is inaccurate.

Exercise in increased ambient temperatures will increase the error associated with this method, therefore the Polar S410 may not be useful when performing outdoor exercise in hotter climates. Future research of this instrument should include other exercise modes and longer exercise durations, other environmental conditions, and a larger and more heterogeneous sample.

CHAPTER 4

SUMMARY AND CONCLUSION

Heart rate (HR) and oxygen consumption ($\dot{V}O_2$) increase proportionately during continuous aerobic exercise. The linear relationship between HR and $\dot{V}O_2$ has been used to estimate energy expenditure (EE) from HR during periods of activity (12; 15; 27; 38; 44). HR monitoring has been shown to be a valid method of measuring EE when measurement of $\dot{V}O_2$ is not practical or possible, such as during activities performed outside of a laboratory or in the field. HR monitors are also appropriate for large-scale studies and can provide estimates of frequency, intensity and duration of habitual activity (16).

Recently, Polar Electro, Inc (Woodbury, NY), one of the leading manufacturers of HR monitors, developed software that utilizes the relationship between HR and $\dot{V}O_2$ to estimate EE during bouts of exercise. The Polar S410 HR monitor incorporates the individual user information into a non-exercise based estimate of maximal aerobic power ($\dot{V}O_{2max}$) and maximal HR. These predicted values along with HR during submaximal exercise are then used to estimate EE. Although the algorithms have not been disclosed, apparently the relationship between percentage of maximal HR and percentage $\dot{V}O_{2max}$ is used to estimate $\dot{V}O_2$ and EE from HRs recorded during a bout of exercise. The Polar S410 has recently been shown to provide a rough estimate of EE during several aerobic activities (11). The approach used for estimating EE from HR is different than the traditional method of using HR monitoring, which requires establishing each individual's HR-$\dot{V}O_2$ relation during an exercise test prior to the estimation of EE (9; 12; 28; 38; 44).

Although the use of HR monitoring and the HR-$\dot{V}O_2$ relationship has been shown to be an effective way to estimate EE, there are several non-exercise factors that influence HR, thereby dissociating it from $\dot{V}O_2$ (12; 23; 24; 44). One such factor is environmental temperature. As the temperature of the environment in which exercise is being performed increases, HR increases independently of $\dot{V}O_2$ (18; 23; 24; 34). For example, Kamon, et al. found an increase in HR of about 1 beat/min per rise of 1 ˚C in ambient temperature (dry heat) (23). The increase in HR with increased environmental temperature can be attributed primarily to autonomic influences (both vagal withdrawal and sympathetic activation) and partly to local temperature influences on pacemaker tissue (18). The dissociation between HR and $\dot{V}O_2$ is a source of error when using the HR-$\dot{V}O_2$ relationship to estimate EE.

The specific aims of this study were: (1) To compare estimates of EE from the HR monitor with estimates of EE obtained by indirect calorimetry (IC) and with the traditional use of individualized HR-$\dot{V}$O2 relationship to estimate EE in women (2) To compare estimates of EE from the Polar S410 based on estimated $\dot{V}O_{2max}$ and HRmax with estimates based on measured $\dot{V}O_{2max}$ and HRmax, and (3) and to determine the effect of environmental temperature on estimates of EE obtained by the Polar S410 HR monitor.

Eighteen females performed two discontinuous graded exercise tests designed to determine the HR-$\dot{V}O_2$ relationship and $\dot{V}O_{2max}$, and three submaximal protocols. The submaximal trials were performed in three different ambient temperatures: 25˚C, 30˚C, and 35˚C. Each trial consisted of three 10-minute bouts of cycling, separated by 15 minutes of rest. HR and $\dot{V}O_2$ were measured continuously, and three different Polar S410 watch receivers were used to estimate EE via three different methods. The AHR method utilized the actual values for HRmax and $\dot{V}O_{2max}$ programmed into the watch receiver, for the estimation of EE. The PHR method utilized the HRmax and $\dot{V}O_{2max}$ predicted by the "OwnIndex" software in the Polar S410 watch receiver, in the temperature corresponding with the specific submaximal trial. The PHRTM method utilized the utilized the HRmax and $\dot{V}O_{2max}$ predicted by the "OwnIndex" software in the Polar S410 watch receiver, in a thermoneutral condition. The estimations of EE obtained by these methods were compared to indirect calorimetry (IC). The traditional method of using individualized HR-$\dot{V}O_2$ relationship to estimate EE was also compared to IC and the Polar S410 methods.

When compared to IC, the AHR method overestimated EE by 4%, 7%, and 9% in the 25˚C, 30˚C, and 35˚C, respectively. The average error (AHR-IC) for the 25˚C condition was 0.3 kcal·min^{-1} (-1.4 to +2.0 kcal·min^{-1}, 95% CI). The average error for the 30˚C condition was 0.5 kcal·min^{-1} (-1.3 to +2.3 kcal·min^{-1}, 95% CI). The average error for the 35˚C condition was 0.7 kcal·min^{-1}(-0.9 to +2.3 kcal·min^{-1}, 95% CI).

The PHR method overestimated EE by 17%, 18%, and 19% in the 25˚C, 30˚C, and 35˚C, respectively. The average error (PHR-IC) for the 25˚C condition was 1.3 kcal·min^{-1} (-2.1 to + 4.6 kcal·min^{-1}, 95% CI). The average error for the 30˚C condition was 1.3 kcal·min^{-1} (-2.2 to + 4.8 kcal·min^{-1}, 95% CI). The average error for the 35˚C condition was 1.5 kcal·min^{-1} (-1.8 to + 4.8 kcal·min^{-1}, 95% CI).

The PHRTM method overestimated the EE by 20%, 22%, and 24% in the 25˚C, 30˚C, and 35˚C, respectively. The average error (PHRTM-IC) for the 25˚C condition was 1.5 kcal·min^{-1} (-1.9 to + 4.8 kcal·min^{-1}, 95% CI). The average error for the 30˚C condition was 1.7 kcal·min^{-1} (-1.8 to + 5.1 kcal·min^{-1}, 95% CI). The average error for the 35˚C condition was 1.9 kcal·min^{-1} (-1.5 to + 5.3 kcal·min^{-1}, 95% CI).

The HR-$\dot{V}O_2$ method underestimated EE by 8%, 4%, and 1.4%, in the 25˚C, 30˚C, and 35˚C, respectively. The average error (HR-$\dot{V}O_2$-IC) for the 25˚C condition was -0.6 kcal·min^{-1} (-3.2 to + 2.0 kcal·min^{-1}, 95% CI). The average error for the 30˚C condition was -0.3 kcal·min^{-1} (-3.1 to + 2.5 kcal·min^{-1}, 95% CI). The average error for the 35˚C condition was -0.1 kcal·min^{-1} (-2.7 to + 2.5 kcal·min^{-1}, 95% CI).

The use of the actual values of HRmax and $\dot{V}O_{2max}$ provided the best estimates of EE obtained by the Polar S410 monitor across all temperatures. This method produced estimates of EE that were not significantly different than those obtained by IC ($p>0.005$). The method using the individualized HR-$\dot{V}O_2$ relationships (HR-$\dot{V}O_2$) produced estimates of EE that were also not significantly different than IC ($p>0.005$).

The effect of heat on the accuracy of the Polar S410 estimation of EE was, for the most part, what was expected. The error of the estimation by each of the Polar S410 methods, as compared to IC, was increased with each increase in temperature. The largest effect of the increased ambient temperature was seen in the AHR method from 25˚C to 35˚C, with the error increasing from 4% to 9%, respectively.

In conclusion, the Polar S410 using the actual values for HRmax and $\dot{V}O_{2max}$ programmed into the watch receiver (AHR), provides estimates of EE for a group of young women that are within 10% of those from IC. These EE estimates are similar in accuracy (i.e. 4%-9% difference) to estimates from the traditional HR-$\dot{V}O_2$ relationship (i.e. 8%-1.4% difference). Estimates of EE from the Polar S410 based on estimates of $\dot{V}O_{2max}$ and HRmax (PHR and PHRTM) are unacceptably high (>10%), with errors ranging from 17%-24% difference in estimates of EE. This method could be useful to exercisers who would like to monitor their caloric expenditure, without the cumbersome individual calculations of the HR to $\dot{V}O_2$ relationship, necessary for the traditional HR-$\dot{V}O_2$ method. Alternatively, when the predicted values for HRmax and $\dot{V}O_{2max}$ are used in the estimation of EE, the Polar S410 is inaccurate.

Exercise in increased ambient temperatures will increase the error associated with this method, therefore the Polar S410 may not be useful when performing outdoor exercise in hotter climates. Future research of this instrument should include other exercise modes and longer exercise durations, other environmental conditions, and a larger and more heterogeneous sample.

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