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Core Temperature Measurement During Submaximal Exercise: Esophageal, Rectal, and Intestinal Temperatures

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April 2000

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ABSTRACT

The purpose of this study was to determine if intestinal temperature (T_{in}) might be an acceptable alternative to esophageal (T_{es}) and rectal temperature (T_{rec}) to assess thermoregulation during supine exercise. We hypothesized that T_{in} would have values similar to T_{es} and a response time similar to T_{rec}, but the rate of temperature change across time would not be different between measurement sites.

Seven subjects (5 male, 2 female; 38 ± 3 yrs; 173.5 ± 4.2 cm; 75.9 ± 10.6 kg) completed a continuous supine protocol of 20 min of rest, 20 min of cycle exercise at 40% peak oxygen consumption (VO_{2pk}), 20 min of cycle exercise at 65% VO_{2pk}, and 20 min of recovery. T_{es}, T_{rec}, and T_{in} were recorded each min throughout the test. Temperatures were not different after 20 min of rest, but T_{rec} was less than the T_{es} and T_{in} at the end of the 40% (T_{rec}: 37.20 ± 0.10; T_{es}: 37.38 ± 0.11; T_{in}: 37.35 ± 0.06°C) and 65% VO_{2pk} stages (T_{rec}: 37.63 ± 0.08; T_{es}: 37.83 ± 0.10; T_{in}: 37.75 ± 0.05°C). After 20 min of recovery, T_{es} (37.24 ± 0.011°C) was less than either T_{rec} or T_{in}, which were not different from each other (T_{rec}: 37.44 ± 0.09; T_{in}: 37.39 ± 0.09°C). Time to threshold for increased temperature from rest (+0.10°C) was greater for T_{rec} (15.7 ± 1.6 min) than T_{es} (10.0 ± 1.1 min) but not different from T_{in} (14.0 ± 1.2 min). Time to reach peak temperature was greater for T_{in} (40.6 ± 0.9 min) and T_{rec} (41.4 ± 0.5 min) than T_{es} (36.6 ± 1.8 min). Similarly, time to a decrease in temperature (-0.10°C) after exercise was greater for T_{rec} (10.6 ± 1.9) than T_{es} (3.7 ± 0.4 min), but not different from T_{in} (7.1 ± 1.5 min). The rate of temperature change from threshold to the end of the 40% VO_{2pk} stage was not different between measurement sites (T_{es}: 0.022 ± 0.005; T_{rec}: 0.016 ± 0.004; T_{in}: 0.021 ± 0.004°C/min). However, the rate of change during recovery was more negative for T_{es} (-0.030 ± 0.002°C/min) than T_{in} (-0.023 ± 0.003°C/min) and T_{rec} (-0.010 ± 0.003°C/min), which were different from each other.

In summary, T_{in} values were not different from T_{es} during exercise, but T_{es} was greater than T_{rec}. The rate of temperature change was not different between measurement sites although time to threshold for T_{in} was intermediate to those of T_{es} and T_{rec}. During recovery, time to threshold and rate of change in T_{in} was intermediate to T_{es} and T_{rec}. Measurement of T_{in} may be an acceptable alternative to T_{es} and T_{rec} with an understanding of its limitations.

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Tables

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ACRONYMS AND NOMENCLATURE

ANOVA	analysis of variance
bpm	beats per minute
cm	centimeters
DBP	diastolic blood pressure
EMI	electromagnetic interference
hr	hour(s)
HR	heart rate
kg	kilogram
L	liter
lb	pound(s)
MHz	megaherz
min	minute(s)
rpm	revolutions per minute
SBP	systolic blood pressure
SD	standard deviation
SE	standard error
T_{core}	core temperature
T_{es}	esophageal temperature
T_{in}	intestinal temperature
T_{rec}	rectal temperature
VO_2	oxygen consumption
VO_{2pk}	peak oxygen consumption
W	watts
yrs	years

INTRODUCTION

Body core temperature (T_{core}) measurement during exercise is integral to studies of thermoregulation. Measurement of blood temperature passing the hypothalamus, the site of thermoregulatory control in the brain, may be the ideal method for such investigations (1). Tympanic temperature has been suggested as a noninvasive alternative, but this technique can be painful to the subject, may lead to difficulties to secure the measurement probe (2), and may result in membrane perforation (3). Further, this measurement technique may suffer from artifact. For example, tympanic temperature may change with no actual change in T_{core} during local heating (4, 5, 6) or cooling (7, 4, 5, 6, 8) of the head.

Esophageal (T_{es}) and rectal temperatures (T_{rec}) are two measurement sites that are commonly employed in thermoregulatory investigations (9). T_{es} is preferred by many as the site to measure T_{core} (9) because of the deep body location, the close proximity to the left ventricle (10), aorta (11) and direct blood flow to the central thermoreceptors in the hypothalamus (12), and its rapid response to changes in heat storage (12). However, this method is undesirable in many settings due to the difficulty of insertion of the thermistor (vomiting), irritation to nasal passages and/or throat, and general subject discomfort (1, 2, 9). T_{rec} has gained wide acceptance due to its relative ease of use and its stability during steady-state conditions (13). However, T_{rec} may be influenced by changes in leg blood flow (14) and may have an attenuated response time compared to other techniques during rapid changes in T_{core} (10, 12, 13). There are sanitary concerns with regard to the use of esophageal and rectal probes for the measurement of T_{core}, especially during spaceflight, and their use may be inappropriate for long-term monitoring, such as for circadian rhythm.

A relatively new technique for the estimation of T_{core} is the measurement of intestinal temperature (T_{in}). Subjects swallow a small silicon-coated pill (CorTemp, Human Technologies, Inc., St. Petersburg, FL) containing a crystal quartz oscillator, which transmits a low-frequency radio wave to an external receiver/data logger worn by the subject. The frequency of the radio wave varies proportionally to the temperature of the pill (15, 16). The manufacturer individually calibrates each pill such that frequencies recorded by the data logger can be related to temperature. Data recorded on the logger are downloaded to a computer after data collection for later analysis.

The purpose of this investigation was to compare measurements of T_{in} to T_{es} and T_{rec} during a specific supine exercise protocol chosen for spaceflight and bed rest investigations. Because of the relative location of the measurement sites, we hypothesized that T_{in} would be quantitatively similar to T_{es} and would have a response time similar to T_{rec}, but the rate of change in T_{in} across time would not be different from the other measurement sites. Previous studies have performed similar measurements during upright exercise (17, 18), exercise in protective clothing (19), exercise in cold air (18), and while immersed in water (16). However, no study has yet made observations during supine exercise, which most closely simulates the blood flow distribution during microgravity.

METHODS

Overall Protocol

Seven volunteers (5 men, 2 women) participated in this investigation. Subjects completed a health screening, similar to the Air Force Class III physical, which was administered by a qualified physician in the NASA-Johnson Space Center Human Test Subject Facility. Subjects also were screened for cardiovascular disease with a Bruce protocol treadmill test with 12-lead electrocardiogram (ECG), for diverticulitis (a contraindication to use of the ingestible pill), for deviated nasal septum (a contraindication for use of the esophageal thermistors), and a history of rectal inflammation (a contraindication for the use of rectal thermistors). Subjects received written and verbal descriptions of all procedures to be performed and signed informed consent forms acknowledging understanding of testing procedures and voluntary participation in the investigation. Testing procedures were reviewed and approved by the NASA-Johnson Space Center Institutional Review Board.

Subjects in this investigation completed a supine graded exercise test on a cycle ergometer to determine peak oxygen consumption (VO_{2pk}) in this posture. From these data, exercise intensities corresponding to 40 and 65% of supine VO_{2pk} were determined for use during the subsequent submaximal exercise test. During the submaximal exercise test, simultaneous measurements of T_{core} (esophageal, rectal, and intestinal temperatures) were made for later comparisons.

Probe and Pill Calibration

Before data collection, the ingestible pill and esophageal and rectal thermistors were calibrated in a beaker of heated water on stirring plate with a calibrated mercury thermometer (Ever Ready Thermometer Co., Inc., New York, NY). Water temperature was increased to approximately 30, 34, 38, and 42°C and allowed to stabilize for at least 2 min while measurements were recorded. Individual calibration curves were constructed for each measurement technique versus the calibrated thermometer. These calibration curves later were applied to the data collected during the submaximal exercise test.

VO_{2pk} Exercise Test

Subjects first completed a supine graded cycle exercise test to volitional fatigue using a protocol developed for spaceflight (20) and bed rest (21) investigations. Subjects completed a 2-min warm-up at an exercise intensity of 50 W followed by three 5-min stages of 100, 125, and 150 W. Thereafter, exercise intensity was increased in 25 W increments each minute until volitional fatigue (Figure 1). Subjects pedaled at a constant cadence of 60 rpm. Expired gases were collected and analyzed by a Qplex-I Metabolic Cart (Quinton Instrument Company, Seattle, WA) interfaced with a mass spectrometer (Model 1100, Marquette Electronics, Inc., Minneapolis, MN). VO_{2pk} was taken as the highest 1-min measurement of oxygen consumption (VO_2) obtained during the test.

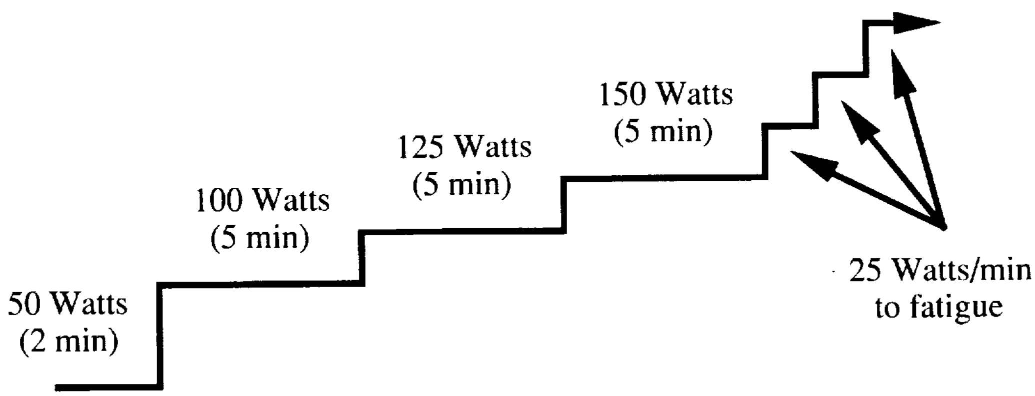


Figure 1: VO_{2pk} test protocol

VO_2 from the last 2 min of each 5-min stage were averaged. A linear regression describing the relationship between VO_2 and exercise intensity was generated for each subject. From this equation, two exercise intensities which corresponded to approximately 40% and 65% of supine VO_{2pk} were calculated for use during the submaximal exercise test.

Submaximal Exercise Test

Subjects completed a supine submaximal exercise test which consisted of 20 min of supine rest, 20 min at 40% of supine VO_{2pk}, 20 min at 65% VO_{2pk}, and 20 min of supine passive recovery (Figure 2). This protocol was used previously in spaceflight (20) and bed rest studies (21). At least three days separated the VO_{2pk} test and the submaximal exercise test to avoid interference of fatigue subsequent to the VO_{2pk} test.

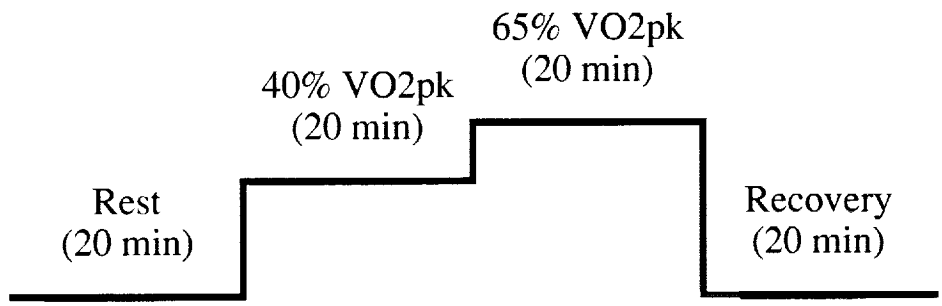


Figure 2: Submaximal exercise test protocol.

The esophageal thermistor (Series 4400, Yellow Springs Instrument Co., Inc., Yellow Springs, OH) was inserted through the nasal pharynx and down the esophagus to a level estimated to be equal to that of the fourth intercostal space. Once the esophageal thermistor was inserted, the thermistor was moved to a position which elicited the highest temperature reading (Kolka, 1993; Kolka, 1997). The rectal thermistor (Series 4400, Yellow Springs Instrument Co., Inc., Yellow Springs, OH) was inserted 15 cm past the rectal sphincter. Rectal and esophageal thermistors were inserted approximately 10 min before data collection and allowed to stabilize. T_{es} and T_{rec} were recorded by a 1250 series Squirrel meter/logger (Science Electronics, Inc., Dayton, OH).

The ingestible pill was swallowed approximately 6 hr before the test with a small amount of water and food. Subjects refrained from eating within 4 hr and from drinking within 2 hr of the test. Prior experience with this measurement technique has suggested that this protocol results in the most stable temperature readings. Telemetered signals from the pill were received by a double bandoleer-style antenna and recorded using a data logger (Human Technologies, Inc., St. Petersburg, FL). T_{es}, T_{rec}, and T_{in} temperatures were recorded once each minute.

Heart rate was recorded each minute using a telemetered heart rate monitor system previously validated in our laboratory (22). Trained personnel measured auscultatory blood pressure manually with a stethoscope and sphygmomanometer every 5 min throughout the test.

Statistical Analyses

We compared water bath temperatures recorded with the calibrated thermometer and the ingestible pill temperatures using a four-by-two analysis of variance (ANOVA) in which the water bath temperature was a repeated measure factor (30, 34, 38, and 42°C) and measurement method (calibrated thermometer and ingestible pill) was a non-repeated measure factor. Also, the difference between the calibrated thermometer and pill temperatures were compared across temperatures using a one-way ANOVA.

T_{es}, T_{rec}, and T_{in} were compared at the beginning of rest, end of rest, end of 40% VO_{2pk}, end of 65% VO_{2pk}, and end of 20 min of recovery using a three-by-five-way ANOVA in which site temperature (T_{es}, T_{rec}, and T_{in}) was the non-repeated measure factor and time (beginning of rest, end of rest, end of 40% VO_{2pk}, end of 65% VO_{2pk}, and end of recovery) was the repeated measure factor. Data are presented as mean ± standard error (SE).

Time to threshold for measured increase in T_{core} (an increase of 0.1°C from end of rest) and time to threshold for decrease in T_{core} (a decrease of 0.1°C from the peak temperature measured at the end of exercise) were measured. Difference in time to threshold between measurement sites was compared using a one-way ANOVA in which in temperature measurement site (T_{es}, T_{rec}, and T_{in}) was a non-repeated factor. Data are presented as mean ± SE.

The rate of temperature change (°C/min) at each measurement site was calculated during both exercise and recovery. The rate of temperature change during exercise was calculated from the threshold response to end of the 40% VO_{2pk} stage at each measurement site (T_{es}, T_{rec}, and T_{in}). The rates of change at the measurement sites were compared using a one-way ANOVA. The rate of the decreasing temperature was calculated from the peak temperature during recovery from exercise to end of the 20-min recovery period at the measurement sites (T_{es}, T_{rec}, and T_{in}). These rates also were compared between measurement sites using a one-way ANOVA. Data are presented as mean ± SE.

RESULTS

Thermistor and Pill Calibration

All T_{core} measurement devices (esophageal and rectal thermistors and ingestible pill) were calibrated before each test. A linear regression was developed for each calibration across four calibration temperatures, approximately 30, 34, 38, and 42°C, and the result applied to the data collected during the submaximal exercise tests. The correlation coefficient for these regressions were $r^2 > 0.99$. A composite of all calibrations for each measurement technique are presented in Figure 3.

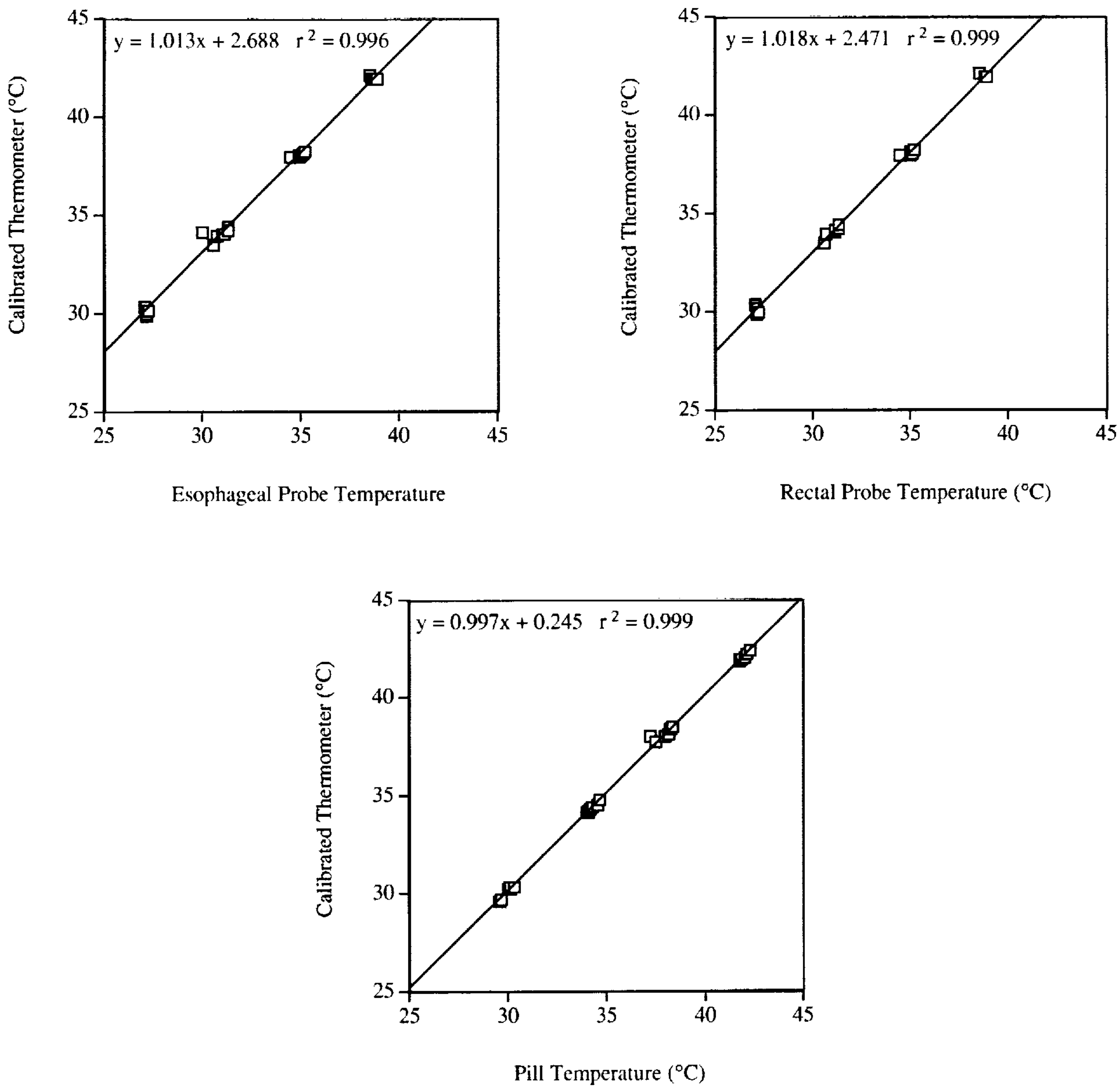


Figure 3: Composite of all esophageal thermistor, rectal thermistor, and pill calibrations (n = 28) against calibrated thermometer.

Measured pill temperatures were found to be significantly lower than calibrated thermometer temperatures at each water bath temperature (30, 34, 38, and 42°C). However, the offset between calibrated thermometer and observed pill temperatures was not different across the range of calibration temperatures.

Subject Characteristics and VO_{2pk} Test Results

Seven volunteers, 5 men and 2 women, participated in this investigation. Subjects (mean ± SD) were 38 ± 3 yrs, 173.5 ± 4.2 cm (68.3 ± 0.6 in), and 75.9 ± 10.6 kg (166.9 ± 23.4 lb). Individual subject characteristics can be found in Appendix A.

Subjects attained a mean (± SD) supine VO_{2pk} of 2.55 ± 0.61 L/min (33.4 ± 5.2 mL/kg/min) and peak heart rate of 160 ± 15 bpm at a peak exercise intensity of 161 ± 48 W in a mean test time of 14.8 ± 4.6 min. The peak respiratory exchange ratio was 1.14 ± 0.09 and the peak expired ventilation was 99.0 ± 30.7 L/min. Tests generally were terminated due to leg fatigue rather than cardiorespiratory limits. Individual VO_{2pk} test results can be found in Appendix B.

Submaximal Exercise Test

All subjects were able to complete the entire submaximal exercise test protocol. Mean VO_2 (± SD) was predicted to be 1.02 ± .0.09 L/min and 1.66 ± 0.15 L/min at mean exercise intensities of 51 ± 5 and 94 ± 10 W, respectively. Heart rate and blood pressure during pre-exercise rest, exercise, and recovery are displayed in Figure 4. Individual submaximal exercise intensity data can be found in Appendix C.

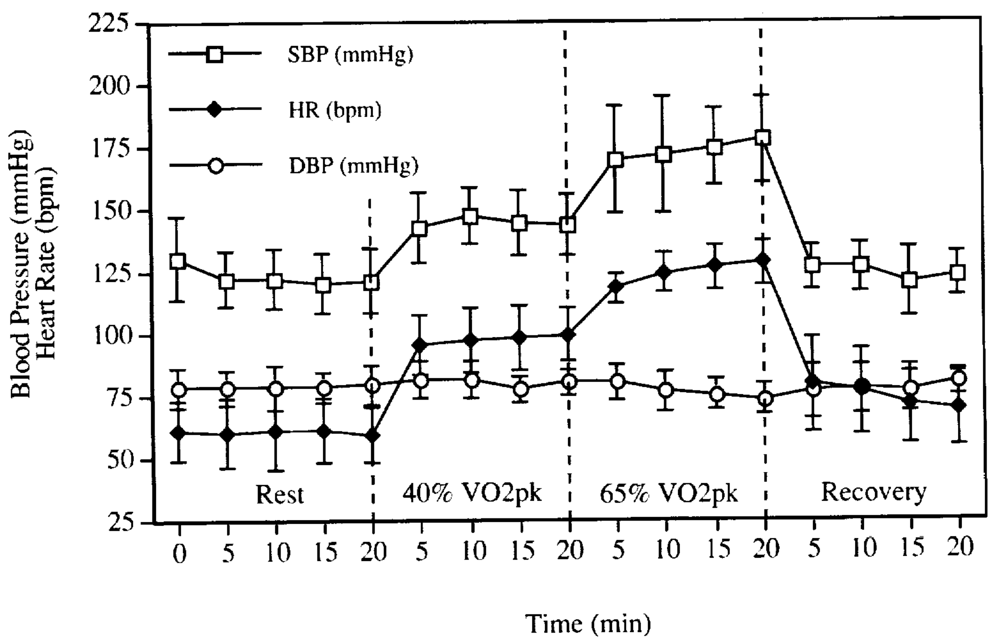


Figure 4: Mean (±SD) heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise test.

Measured Temperature and Change in Temperature

Mean T_{es}, T_{rec}, and T_{in} are displayed in Figure 5. At the start of supine rest, T_{es} and T_{rec} were not different from each other, but T_{in} was significantly greater than T_{es} (Table 1). However, T_{rec} was not different from T_{in}. By the end of 20 min of supine rest, T_{es}, T_{rec}, and T_{in} were not different from each other. At the end of the 20-min supine rest, neither T_{es} nor T_{rec} were significantly different from their respective values at the beginning of supine rest. T_{in} tended to be less ($p = 0.07$) at the end of the supine rest period compared to the beginning of rest.

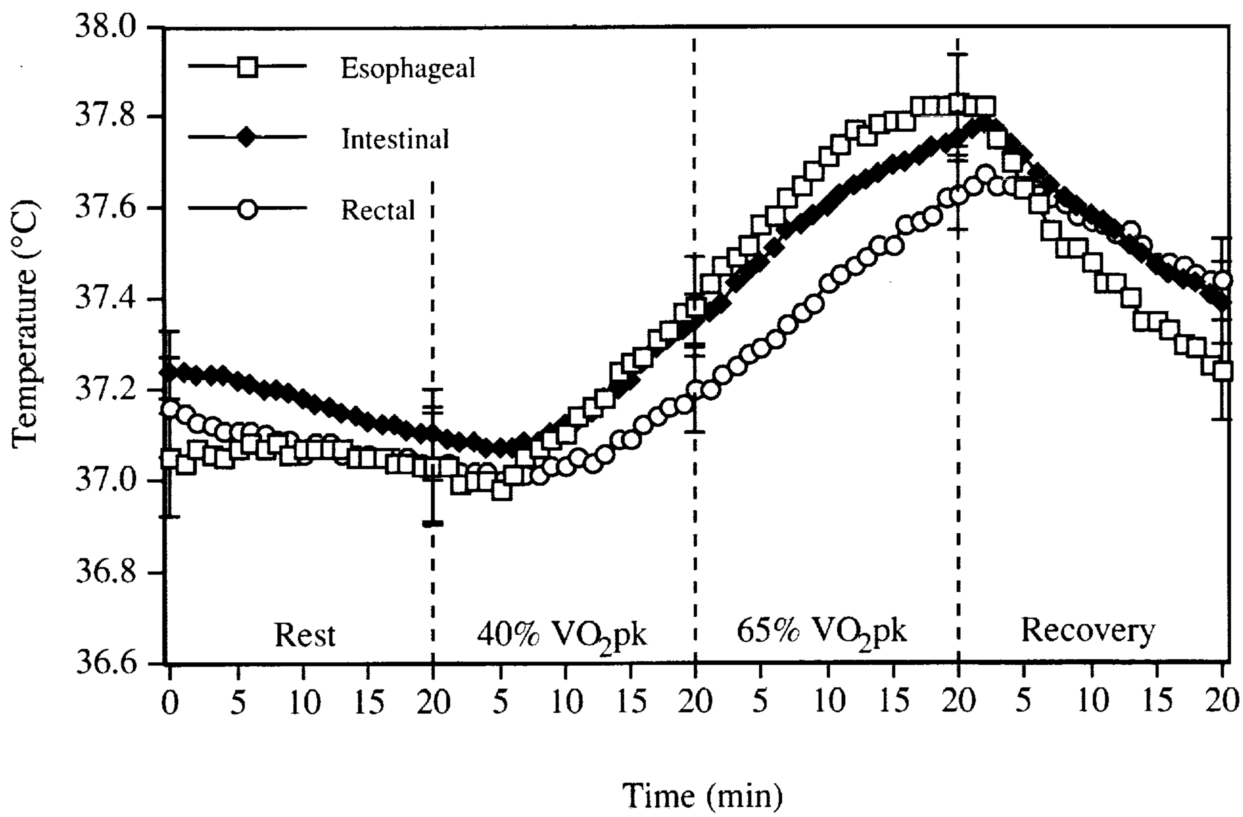


Figure 5: Mean esophageal, intestinal, and rectal temperatures during submaximal exercise.

Table 1: Mean (± SE) Esophageal, Rectal, and Intestinal Temperatures During Submaximal Exercise

Time	Esophageal (°C)	Rectal (°C)	Intestinal (°C)
Start of Rest	37.06 ± 0.13	37.16 ± 0.11	37.24 ± 0.09*
End of Rest	37.03 ± 0.13	37.02 ± 0.12	37.10 ± 0.10
End of 40% VO_{2pk}	37.38 ± 0.11	37.20 ± 0.10*	37.35 ± 0.06†
Change From End of Rest to End of 40% VO_{2pk} (°C)	0.35 ± 0.04	0.17 ± 0.04*	0.25 ± 0.05
End of 65% VO_{2pk}	37.83 ± 0.10	37.63 ± 0.08*	37.75 ± 0.05
Change From End of Rest to End of 65% VO_{2pk} (°C)	0.80 ± 0.11	0.60 ± 0.09*	0.66 ± 0.10
Peak Temperature (°C)	37.84 ± 0.10	37.68 ± 0.08	37.78 ± 0.05
Change in Temperature From End of Rest to Peak Temperature (°C)	0.80 ± 0.11	0.65 ± 0.09*	0.069 ± 0.11
End of Recovery	37.24 ± 0.011	37.44 ± 0.09*	37.39 ± 0.09*
Change in Temperature From End of 65% VO_{2pk} to End of Recovery (°C)	-0.59 ± 0.04	-0.19 ± 0.06*	-0.36 ± 0.06*†

* Significantly different from T_{es} † Significantly different than T_{rec}

After 20 min of exercise at 40% VO_{2pk}, T_{es}, T_{rec}, and T_{in} were significantly greater than their respective measures at the end of supine rest. However, T_{rec} was significantly less than T_{es} and T_{in}, which were not different from each other. The change of the measured temperature from the end of supine rest to the end of the 40% VO_{2pk} stage was significantly greater in T_{es} than in T_{rec}. There was no difference between the T_{es} and T_{in} changes, and no difference between T_{in} and T_{rec}.

After 20 min of exercise at 65% VO_{2pk}, T_{es}, T_{rec}, and T_{in} were significantly greater than their respective measures at the end of the 40% VO_{2pk} stage. T_{es} was significantly greater than T_{rec}, but was not different from T_{in}. However, T_{in} was not different from T_{rec}. The temperature change from the end of rest to the end of the 65% VO_{2pk} stage was significantly greater in T_{es} than in T_{rec}, but not different from T_{in}. There was no difference between the T_{in} and T_{rec} change.

Peak temperature measured tended to be different (p = 0.07) between the sites. Measured peak temperatures were highest in the T_{es} followed by the T_{in} and T_{rec}, respectively. The change of the temperature from the end of rest to the peak measured temperature was significantly greater in T_{es} than in T_{rec}, but not different from T_{in}. There was no difference between the T_{in} and T_{rec} change.

After 20 min of supine recovery, T_{es}, T_{rec}, and T_{in} were significantly less than their respective measures at the end of 65% VO_{2pk} exercise. T_{es} was significantly less than T_{rec} and T_{in}, which were not different from each other. All three temperatures remained greater than supine rest. The change in temperature from the end of the 65% VO_{2pk} stage to the end of recovery was significantly greater in T_{es} than in both the T_{rec} and T_{in}, which were also different from each other.

Time Course of Temperature Change

Time to threshold for an increase in T_{core} from the measured temperature at the end of supine rest was significantly different between measurement sites (Table 2). Time to threshold was significantly less for T_{es} compared to T_{rec} and tended to be less ($p = 0.07$) than T_{in}. Time to threshold was not different between T_{rec} and T_{in}. Also, the time to reach peak temperature was significantly less for T_{es} compared to both the T_{rec} and T_{in}, which were not different from each other.

Time to threshold for a decrease in temperature from the end of exercise also was significantly different between measurement sites. Time to threshold was significantly less for T_{es} compared to the T_{rec}, but was not different from the time to threshold for T_{in}. There were no differences between time to threshold in the T_{rec} and T_{in}.

Table 2: Threshold of Temperature Responses in Esophageal, Rectal, and Intestinal Measurements

	Esophageal	Rectal	Intestinal
Temperature Threshold (°C)	37.14 ± 0.13	37.11 ± 0.11	37.20 ± 0.10
Time to Threshold From Start of Exercise (min)	10 ± 1.1	15.7 ± 1.6*	14.0 ± 1.2
Time to Peak Temperature (min)	36.6 ± 1.8	40.6 ± 0.9*	41.4 ± 0.5*
Temperature Recovery Threshold (°C)	37.72 ± 0.09	37.57 ± 0.08	37.69 ± 0.05
Time to Recovery Threshold From End of Exercise (min)	3.7 ± 0.4	10.6 ± 1.9*	7.1 ± 1.5

*Significantly different from esophageal

Rate of Temperature Change

There was no difference between the rate of the temperature change from the threshold temperature to the end of the 40% VO_{2pk} stage (T_{es}: 0.022 ± 0.005; T_{rec}: 0.016 ± 0.004; T_{in}: 0.021 ± 0.004°C/min). However, the rate of change in temperature from the threshold for decreasing temperature after the cessation of exercise was different between the three measurement sites. The slope of the response was more negative for T_{es} (-0.030 ± 0.002°C/min) than for T_{rec} (-0.010 ± 0.003°C/min) and T_{in} (-0.023 ± 0.003°C/min). Also, the rate of change for T_{in} was more negative than T_{rec}.

DISCUSSION

The purpose of this investigation was to compare the measurement characteristics of T_{in} with regard to two frequently used measurement sites, T_{es} and T_{rec}. Previous studies had characterized these responses during upright exercise, during water immersion, during cold exposure, and while wearing protective clothing. However, we sought to determine whether results from these previous studies could be extrapolated to temperature measurements during supine exercise. Specifically, we sought to determine whether T_{in} during supine rest, exercise, and recovery from exercise would be a suitable alternative to T_{es} and T_{rec} for the estimation of T_{core}. To determine this we examined temperatures at specific time points during the protocol, the time required to measure a temperature change, and the rate of temperature change once it was initiated. The results of this study suggest that T_{in} was not different from T_{es} during exercise at specific time points, and the time to a measured response of 0.10°C was intermediate between those of T_{es} and T_{rec}. However, the rate of temperature change during exercise was not different between measurement sites. During recovery from exercise, the time to threshold for a decrease in temperature of 0.10°C for T_{in} was intermediate to those of T_{es} and T_{rec} and the rate of temperature change during recovery from exercise was most negative for T_{es} and least negative for T_{rec}. As a result, the temperature at the end of recovery was lowest for T_{es} and highest for T_{rec}.

Pill Calibration

Any measurement technique to be employed in research or field monitoring must be calibrated for accuracy before use. Kolka and coworkers (17, 19) did not report the method of calibration of the pills before human subject testing, but did emphasize the importance of preliminary screening of the pills to determine which pills were accurate enough for use. However, they did not report their criteria for accuracy. In six pills tested by Sparling et al. (23), three were lower than a calibrated thermometer by an average of 0.08°C and three were higher by an average of 0.37°C. The authors reported that the offset was constant across the measurement range

(35-40°C) and that the data were corrected for this factor. O'Brien et al. (16) performed a three-point calibration (33, 37, and 41 °C) and noted that a linear relationship existed between water bath temperature and pill temperature, and applied this calibration to data collected. However, they did not report the difference in the temperatures between the pill and the calibrated thermometer.

In the present study, we performed a four-point calibration and found that the mean pill temperature was significantly lower than the temperature measured with a calibrated thermometer. In previous experience with the pill calibration, we observed that the time to steady-state temperature in the pill was 1-2 min after steady state was achieved in the water bath. Mittal et al. (15) reported that 90% of the response was measured by 115 ± 8 sec when a pill was transferred from a water bath at 35°C to a water bath at 50°C. Therefore, all our temperatures were taken at least 2 min after the water bath temperature was stable. Like previous authors, we applied the linear equation describing each individual pill's performance to the data before subsequent analysis. The mean difference between the pill and calibrated thermometer was 0.15 ± 0.02°C but the difference in an individual pill was as high as 0.80°C. Although the mean difference was within ± 0.20°C as recommended by the Hyperthermia Physics Center (15), we recommend that these pills be calibrated before use in similar investigations, especially when examining changes in thermoregulatory responses which may be as small as 0.10°C.

Temperatures at Rest

At the beginning of supine rest when the subjects made the transition from standing, T_{es} and T_{rec} were not different from each other, but T_{in} was significantly higher than T_{es}. Over the course of the 20-min supine rest, T_{es} was steady, but both T_{rec} and T_{in} decreased. At the end of the 20-min rest, the temperatures were not significantly different from each other. Lower T_{core} during supine rest than upright rest have been reported previously, and may be related to either a lower metabolic rate (24) or higher heat exchange due to greater skin perfusion while supine (25, 26, 27). The lack of change in T_{es} may be due to the rapid response time of T_{es} to a change in blood flow distribution (26). T_{es} may have decreased to a new steady state by the time we completed instrumenting the subject and data collection began. The decline in T_{rec} and T_{in} due to the change in posture therefore would have been more easily observed due to their slower response times. Kolka et al. (17) also observed decreases in T_{in} during seated resting but did not report any statistical analyses of these changes or whether similar changes were observed in the other measurement sites. Livingstone et al. (18) reported a significant increase in T_{in} during 90 min of seated rest, but this was likely the result of ingestion of the pill, presumably with fluid, near the start of data collection.

The temperatures recorded at each site during rest in this study are not in complete agreement with previous investigations. The different results obtained between our investigation and previous studies may be related to the difference in posture during testing and the unreported method of calculating resting temperatures by previous investigators. Kolka et al. (17) reported that T_{rec} was higher than T_{es} at rest and that T_{in} was intermediate between the two. The rest period in their investigation was 15 min. O'Brien et al. (16) had similar findings with regard to T_{es}, T_{rec}, and T_{in} during rest before their immersion studies, but did not report on the duration of this resting period. Sparling et al. (29) measured only T_{rec} and T_{in}, but found that T_{rec} was significantly greater than T_{in} during a 10-min rest period. Kolka et al. (11) reported no difference in resting T_{es} and T_{in} during a 15- to 30-min equilibration to a warm environment (30°C) while wearing protective clothing.

Temperatures During Exercise

At the onset of exercise, there was no difference in temperature measurement at any of the three sites. However, by 20 min of exercise at 40% and 20 min of exercise at 65% VO_{2pk}, T_{rec} was lower than both T_{es} and T_{in}, which were not different from each other. This is likely to be the result of a slower response time in T_{rec}, as seen previously by Kolka et al. (10). In the present study, the time to measure a 0.10°C change in T_{rec} was 50% greater than the time required to measure the same change in T_{es}. Similar to Kolka et al. (10), the response time of T_{in} was intermediate between T_{es} and T_{rec}.

Kolka et al. (10) reported that T_{rec} was significantly greater than T_{es} and T_{in} during steady-state exercise. Similarly, Sparling et al. (29) reported that peak exercise T_{rec} was significantly greater than peak T_{in}. In contrast, we observed that T_{rec} was lower than both T_{es} and T_{in} throughout the exercise bout. This may be partially explained by a slower response time of T_{rec}, but also a posture-related distribution of blood flow. In the upright posture, skin blood flow relative to T_{core} is reduced compared to the supine posture at rest (24) or during exercise (8, 23). T_{rec} is influenced by venous blood returning from the metabolically active muscle mass of the legs (21), and lower skin blood flow would reduce the capacity to transfer heat from the legs (2, 18). In contrast, during supine exercise, skin blood flow would be increased and the capacity to dissipate heat from the legs would be increased, thus possibly reducing the influence of warmed venous blood on T_{rec}.

There was no difference in the peak temperature recorded at any of the three sites, but the time to reach the peak temperature was significantly less in T_{es}, similar to Kolka et al. (10). Although the T_{es} appeared to have reached steady-state before exercise cessation in our study, T_{rec} and T_{in}

did not reach their respective peaks until near the end or after exercise. Perhaps related to this, however, we found that the change in temperature from supine rest to peak exercise temperature was significantly less in T_{rec}. At the time that T_{rec} reached its peak, whole body heat storage was decreasing since heat production had decreased at the cessation of exercise. In contrast, Kolka et al. (10) found no difference in the change in temperature from rest to end of exercise between the three measurement sites. The difference in the results of the two studies is likely to be the result of different exercise protocols. Subjects in the study by Kolka et al. (10) exercised for 40 min at one exercise intensity (40% VO_{2pk}). In contrast, subjects in our study exercised at two different intensities (40 and 65% VO_{2pk}) for a total of 40 min. Our results emphasize that unless all temperatures have reached steady state, comparison of absolute values or their respective changes at specific time points between the three techniques are not valid.

The rate of temperature change from threshold to the end of the 40% VO_{2pk} stage was not different between measurement sites. This would suggest that the rate of heat storage independent of the onset of storage was not different in each body region at this single workload. It was not possible to analyze the entire change from threshold to peak temperature nor from the end of the 40% $VO2_{pk}$ stage to peak temperature. The change in heat production from one exercise intensity to the next and the differences in the time course of heat storage in each body region would influence the resulting slope. However, it appears that the mean rate of rise in T_{es} and T_{rec} were unaltered by the change in exercise intensity. In contrast, visual inspection of the data suggests that the rate of rise in T_{in} decreased despite the increase in heat production. A change in the rate of T_{in} increase may be influenced by a decreased splanchnic blood flow with increased exercise intensity (24).

Comparison of our temperature data during exercise with that of other investigators is problematic. Sparling et al. (29) collected data during progressive treadmill tests of exercise intensities greater 85% of maximum heart rate. Subjects were unlikely to have reached a steady-state T_{core} and the protocols varied between subjects. Kolka et al. (10) collected 40 min of steady-state exercise to which our testing protocol is most comparable. However, subjects then performed three cycles of short, intense exercise (5 min, 80% VO_{2pk}) separate by 5-min rest periods. T_{core} was unlikely to have reached steady state during these interval exercise bouts. Further, no investigators other than Kolka et al. (10) reported time to threshold of temperature responses, and no investigators examined the rate of change in temperature. In a separate study, Kolka et al. (11) analyzed the relationship between T_{es} and T_{in} only through correlations. O'Brien et al. (22) made their comparisons primarily through the analysis of root mean square deviation.

Temperatures During Recovery From Exercise

After exercise, the time to a measured decrease in temperature of 0.10°C was significantly less for T_{es} than T_{rec} but not different than T_{in}. Also, the rate of the temperature change was more negative for T_{es} than T_{rec}. The rate of the decrease in T_{in} was less than T_{es} but greater than T_{rec}. Similarly, Kolka et al. (10) observed that T_{es} and T_{in} appeared to be responsive to changes in metabolic heat production during 5-min bouts of intense exercise interspersed with 5-min rest periods, but T_{rec} was not. These findings with regard to T_{es} and T_{rec} are not new (3, 25). The responses seen during recovery from exercise at each of the measurement sites would be reflective of metabolic heat produced in the region, blood flow, and proximity to regions of the body storing heat, similar to the responses seen during exercise. T_{es} would be expected to decrease the most rapidly as heart rate and systolic blood pressures quickly declined after exercise, suggesting a lessening of metabolic heat produced in the region, and the heart region would be receiving cooled blood from the periphery as exercise-induced vasoconstriction lessened and heat exchange between the skin and air increased. Although receiving a mixture of cooled and warmed blood from the heart, T_{in} would be expected to decline as exercise-induced vasoconstriction in this region also was reduced, and heat stored there would be transported by increasing blood flow. T_{rec} also would decline as a result of increased skin blood flow after exercise, but would continue to be influenced by the relatively higher heat stored in the muscles of the lower body (25).

Timing of Pill Ingestion

Pill location in the intestinal tract may influence temperature measurements and the measured response during body heating or cooling. If the pill is located in the stomach or upper intestinal tract, it may be influenced by ingestion of saliva, food, or liquids, similar to T_{es}. Livingstone et al. (13) found that T_{in} readings taken soon after pill ingestion often followed the same pattern as T_{es} with an offset. Presumably, deeper locations in the intestinal tract would be subject to less variation (22) and may be more similar to T_{rec} (13). We and others (11) have found that the ingestion of a small meal can aid in passing the pill out of the stomach. However, beginning data collection soon after a meal may be influenced by diet-induced thermogenesis, which can increase whole body resting metabolism by approximately 10% (15).

In previous studies (10, 11), subjects have swallowed the pill 2-3 hr before data collection. These reports suggested that pill temperature may be subject to variation as it passes through the intestinal tract. More recently, O'Brien et al. (22) suggested that their measurements were more stable because they had waited at least 12 hr after pill ingestion to begin data collection. While this time period may be more favorable for stable temperature measurements, experience in our laboratory has suggested that an extended length of time from pill ingestion to start of data collection may result in other problems. Although the pills are inactive, pill battery power may be drained by long storage and result in failure during or soon after the start of data collection if there is a long delay from the time of pill activation and ingestion. Although the mean passage time observed by Kolka et al. (10) was 30.4 ± 8.9 hr, subjects with fast intestinal transit times may expel the pill before data collection. In our experience, one subject excreted the pill in as short as 8 hr after ingestion. In an unpublished report (Keilson, L., 1988), the author reported that one subject excreted the pill in 7 hr 15 min. The time for pill ingestion chosen for this study, 6 hr, was intermediate between previous studies. Sparling et al. (29) found no difference in the offset between T_{rec} and T_{in} during rest and exercise in subjects who swallowed the pill 3 to 4 hr before exercise and those who swallowed the pill 8 to 9 hr before exercise.

Limitations

The data collected during this investigation were limited to a submaximal exercise test protocol similar to one used in two previous investigations (6, 12) and similar to one planned for future spaceflight studies. Future investigations should evaluate these measurement techniques in longer or more intense exercise protocols, across a range of exercise intensities, and in different postures. The results of this present study may be applicable only to exercise in the supine position. Differences in blood flow and distribution associated with posture may alter the time course of site-specific temperature responses. In addition, an examination of T_{in} as a substitute for T_{rec} during long periods of ambulatory monitoring, such as circadian investigations, is strongly recommended.

When planning an investigation for specific environments, the investigator should be cognizant of the limitations of the ingestible pill and its data logger as a result of electromagnetic interference (EMI). Mittal et al. (17) reported that no readings were obtained during EMI produced at 80, 100, and 120 MHz by an annular phase applicator during deep heating studies. However, they were able to record accurate readings soon after the power was turned off. In our own experience, EMI produced by computer screens and holter monitors (a portable ECG monitoring system) have precluded obtaining accurate data. In an extreme case, while performing data collection for an experiment in Star City, Russia, shielding of our testing room was required due to a high-powered military radio station nearby.

Data collected in this investigation may be influenced by the responsiveness of the individual measurement devices. Thermistors used for T_{es} and T_{rec} respond to changes in temperature rapidly, but the ingestible pill has a longer delay (17), perhaps due to the silicone rubber coating.

This may have effected the time course and slope of the measurement changes in T_{in} relative to the other measurement sites.

SUMMARY

T_{in} was similar to T_{es} during exercise, but was higher than T_{es} at the end of recovery. T_{rec} was different from T_{es} throughout exercise and recovery. The time to a measured temperature response in T_{in} during exercise and recovery was intermediate between T_{es} and T_{rec}. The rate of temperature change during exercise was not different between the measurement sites and was not different during exercise. However, during recovery from exercise the rate of change in T_{es} was most negative and the slope of T_{rec} was least. These results suggest that T_{in} may be acceptable alternative to T_{es} and T_{rec} during some investigations with an understanding of the limitations of this measurement.

T_{core} measurement using an ingestible pill may be more appropriate in exercise testing, circadian monitoring, protective clothing monitoring and testing, and other field environments, such as microgravity, where instrumenting subjects for T_{es} or T_{rec} may not be feasible. The ease of use of this hardware and relatively few sanitary concerns in comparison to the esophageal and rectal thermistors makes it an ideal candidate for studies involving exercise or which take place in noncontrolled environments. However, the delay in detecting increases in T_{core}, similar to that seen with T_{rec} monitoring, suggests that this technique may not be appropriate to prevent heat injury in conditions of rapidly changing body temperatures (10). Further, data must be collected in such a manner as to control for pill location in the body and to be interpreted with respect to the thermal response at the site under the specific experimental conditions (13).

REFERENCES

1. Stitt, J.T. Central regulation of body temperature. In: *Perspectives in Exercise Science and Sports Medicine, Volume 6: Exercise, Heat, and Thermoregulation.* C.V. Gisolfi, D.R. Lamb, and E.R. Nadel (Eds.). Dubuque, IA: Brown & Benchmark, 1993, pp. 1-39.

2. Sato, K.T., N.L. Kane, G. Soos, C.V. Gisolfi, N. Kondo, and K. Sato. Reexamintion of tympanic membrane temperature as a core temperature. *J. Appl. Physiol. 80*: 1233-1239, 1996.

3. Wallace, C.T., W.E. Marks, W.Y. Adkins, and J.E. Mahaffey. Perforation of the tympanic membrane, a complication of tympanic thermometry during anesthesia. *Anesthesiology 41*: 290-291, 1974.

4. Marcus, P. Some effects of cooling and heating areas of the head and neck on body temperature measurements at rest. *Aerosp. Med. 44*: 397-402, 1973.

5. McCaffrey, T.V., G.S. Geis, J.M. Chung, and R.D. Wurster. Effect of isolated head heating and cooling on sweating in man. *Aviat. Space Environ. Med. 46*: 1353-1357, 1975.

6. Nadel, E.R., and S.M. Horvath. Comparison of tympanic membrane and deep body temperatures in man. *Life Sci. 9*: 869-875, 1970.

7. Brengelmann, G.L. Specialized brain cooling in humans? *FASEB J 7*: 1148-1152, 1993.

8. Shiraki, K., S. Sagawa, F. Tajima, A. Yokota, M. Hashimoto, and G.L. Brengelmann. Independence of brain and tympanic temperatures in an unanesthetized human. *J. Appl. Physiol. 65*: 482-486, 1988.

9. Sawka, M.N. and C.B. Wenger. Physiologic responses to acute exercise heat stress. In: *Human Performance Physiology and Environmental Medicine at Terrestrial Extremes*. K.B. Pandolf, M.N. Sawka, and R.R. Gonzalez (Eds.), Indianapolis: Benchmark Press, 1988, pp. 97-151.

10. Rowell, L.B. Thermal Stress. In: *Human Circulation: Regulation During Physical Stress.* Oxford: Oxford University Press, 1986, pp. 174-212.

11. Cooper, K.E. and J.R. Kenyon. A comparison of temperatures measured at the rectum, esophagus, and the surface of the aorta during hypothermia in man. *Br. J. Surg. 44*: 616-619, 1957.

12. Gerbrandy, J., E.S. Snall, and W.I. Cranston. Oral, rectal, and oesophageal temperatures in relation to central temperature control in man. *Clin. Sci. 13*: 615-624, 1954.

13. Eichna, L.W., A.R. Berger, B. Rader, and W.H. Becker. Comparison of intrathoracic and intravascular temperatures with rectal temperatures in man. *J. Clin. Invest. 30*: 353-359, 1951.

14. Saltin, B. and L. Hermansen. Esophageal, rectal, and muscle temperature during exercise. *J. Appl. Physiol. 21*: 1757-1762, 1966.

15. Mittal, B.B., V. Sathiaseelan, A.W. Rademaker, M.C. Pierce, P.M. Johnson, and W.N. Brand. Evaluation of an ingestible telemetric temperature sensor for deep hyperthermia applications. *J. Radiation Oncology Biol. Phys. 21*: 1353-1361, 1991.

16. O'Brien, C., R.W. Hoyt, M.J. Buller, J.W. Castellani, and A.J. Young. Telemetry pill measurement of core temperature in humans during active heating and cooling. *Med. Sci. Exerc. Sports 30*: 468-472, 1998.

17. Kolka, M.A., M.D. Quigley, L.A. Blanchard, D.A. Toyota, and L.A. Stephenson. Validation of a temperature telemetry system during moderate and strenuous exercise. *J. Thermal Biol. 18*: 203-210, 1993.

18. Livingstone, S.D., J. Grayson, J. Frim, C.L. Allen, and R.E. Limmer. Effect of cold exposure on various sites of core temperature measurements. *J. Appl. Physiol. 54*: 1025-1031, 1983.

19. Kolka, M.A., L. Levine, and L.A. Stephenson. Use of an ingestible telemetry system to measure core temperature under chemical protective clothing. *J. Thermal Biol. 22*: 343-349, 1997.

20. Fortney, S.M., V. Mikhaylov, S.M.C. Lee, Y. Kobzev, R.R. Gonzalez, and J.E. Greenleaf. Body temperature and thermoregulation during submaximal exercise after 115-day spaceflight. *Aviat. Space Environ. Med. 69*: 137-141, 1998.

21. Lee, S.M.C., W.J. Williams, J.E. Greenleaf, and S.M. Schneider. Exercise thermoregulation after 13-day bed rest. *Med. Sci. Sports Exerc.*, 31: 5309, 1999.

22. Moore, A.D., S.M.C. Lee, M.C. Greenisen, and P.A. Bishop. Validity of the heart rate monitor for use during work in the laboratory and on the Space Shuttle. *Am. Industrial Hygiene Assoc. J. 58*: 299-301, 1997.

23. Sparling, P.B., T.K. Snow, and M.L. Millard-Stafford. Monitoring core temperature during exercise: ingestible sensor vs. rectal thermistor. *Aviat. Space Environ. Med. 64*: 760-763, 1993.

24. Kleitman, N. and A. Doktorsky. Studies on the physiology of sleep, VII: the effect of position of the body and of sleep on rectal temperature in man. *Am. J. Physiol. 104*: 340-343, 1933.

25. Cranston, W.I., J. Gerbrandy, and E.S. Snell. Oral, rectal, and oesophageal temperatures and some factors affecting them in man. *J. Physiol. (London) 126*: 347-358, 1954.

26. Tanabe, M. and O. Shido. Changes in core temperatures and heat balance after an abrupt release of lower body negative pressure in humans. *Int. J. Biometeorol. 38*: 48-54, 1994.

27. Tikuisis, P. and M.B. Ducharme. The effect of postural changes on body temperature and heat balance. *Eur. J. Appl. Physiol. 72*: 451-459, 1996.

28. Johnson, J.M., L.B. Rowell, and G.L. Brengelmann. Modification of the skin blood flow-body temperature relationship by upright exercise. *J. Appl. Physiol. 37*: 880-886, 1974.

29. Roberts, M.F., and C.B. Wenger. Control of skin blood flow during exercise by thermal and baroreflexes. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 48*: 717-723, 1980.

30. Nielsen, B. and M. Nielsen. Body temperature during work. *Acta Physiol. Scand. 56*: 120-129, 1962.

31. Collins, K.J., J.C. Easton, and A.N. Exton-Smith. Body temperature afterdrop: a physical or phsyiological phenomenon? *J. Physiol. (London) 328*: 72P-73P, 1982.

32. Mittleman, K.D. and I.B. Mekjavic. Effect of occluded venous return on core temperature during cold water immersion. *J. Appl. Physiol. 65*: 2709-2713, 1988.

33. McArdle, W.D., F.I. Katch, and V.L. Katch. Human energy expenditure during rest and physical activity. In: *Exercise Physiology: Energy, Nutrition, and Human Performance*. Baltimore: Williams & Wilkins, 1996, pp. 151-164.

APPENDIX A:
INDIVIDUAL SUBJECT CHARACTERISTICS

Subject	Gender	Age (yrs)	Height (in)	Height (cm)	Weight (lb)	Weight (kg)	VO_{2pk} (L/min)	VO_{2pk} (mL/kg/min)
1	M	38	70	178.0	190	86.4	2.47	28.6
2	F	43	66	167.6	121	55.0	1.65	30.0
3	M	31	69	175.0	175	79.5	2.93	36.8
4	M	34	70	177.8	177	80.5	3.22	40.0
5	M	30	67	170.2	178	80.7	2.99	37.1
6	F	46	67	170.0	151	68.6	1.79	26.1
7	M	44	69	176.0	177	80.5	2.81	34.9
Mean		38	68.3	173.5	166.9	75.9	2.55	33.4
SD		7	1.6	4.2	23.4	10.6	0.61	5.2
SE		3	0.6	1.6	8.8	4.0	0.23	1.9

APPENDIX B: INDIVIDUAL VO_{2pk} TEST RESULTS

Subject	Time (min)	Workload (W)	VO_{2pk} (L/min)	VO_{2pk} (mL/kg/min)	Heart Rate (bpm)	RER	VE (L/min)
1	15.0	150	2.47	28.6	135	1.11	77.7
2	7.0	100	1.65	30.0	165	1.23	74.0
3	17.0	150	2.93	36.8	171	1.19	143.0
4	19.5	225	3.22	40.0	174	1.23	121.3
5	20.0	225	2.99	37.1	162	1.14	113.3
6	12.0	125	1.79	26.1	145	1.02	55.7
7	13.0	150	2.81	34.9	170	1.03	107.9
Mean	14.8	161	2.55	33.4	160	1.14	99.0
SD	4.6	48	0.61	5.2	15	0.09	30.7
SE	1.7	18	0.23	1.9	6	0.03	11.6

APPENDIX C:
INDIVIDUAL SUBMAXIMAL TEST EXERCISE INTENSITIES

Subject	40% VO_{2pk} (L/min)	Workload (W)	65% VO_{2pk} (L/min)	Workload (W)
1	0.99	50	1.61	90
2	0.66	40	1.07	60
3	1.17	60	1.90	100
4	1.29	70	2.09	130
5	1.20	60	1.94	120
6	0.72	30	1.16	70
7	1.12	50	1.83	90
Mean	1.02	51	1.66	94
SD	0.24	14	0.40	25
SE	0.09	5	0.15	10

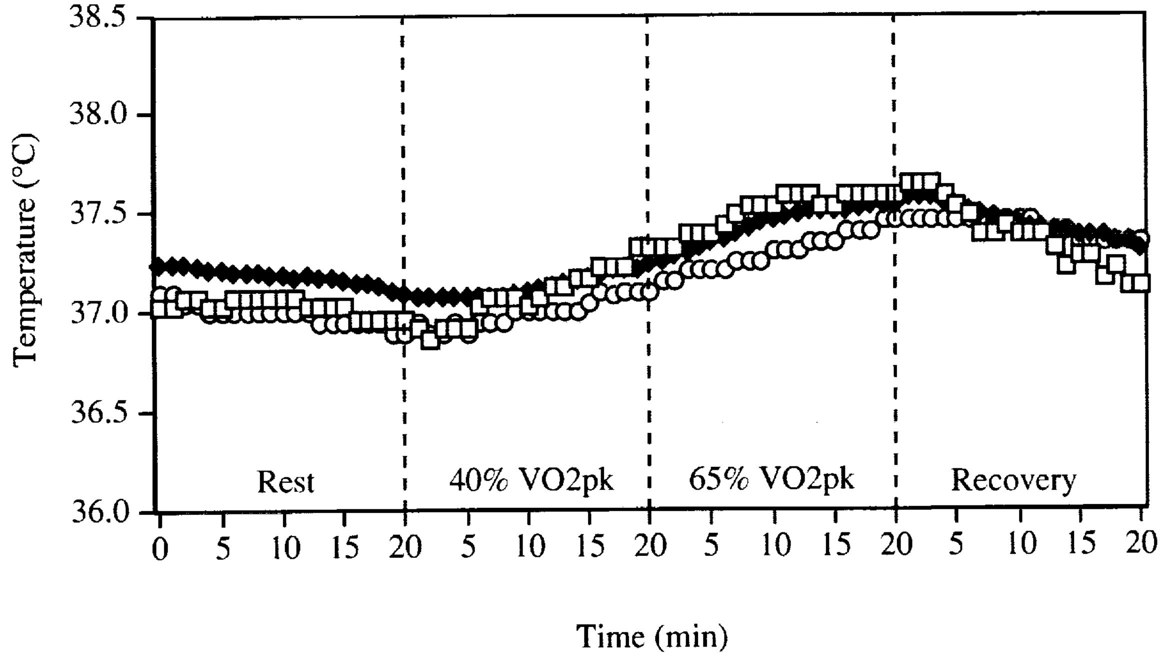
APPENDIX D:
INDIVIDUAL SUBMAXIMAL EXERCISE TEST RESULTS

Subject 1

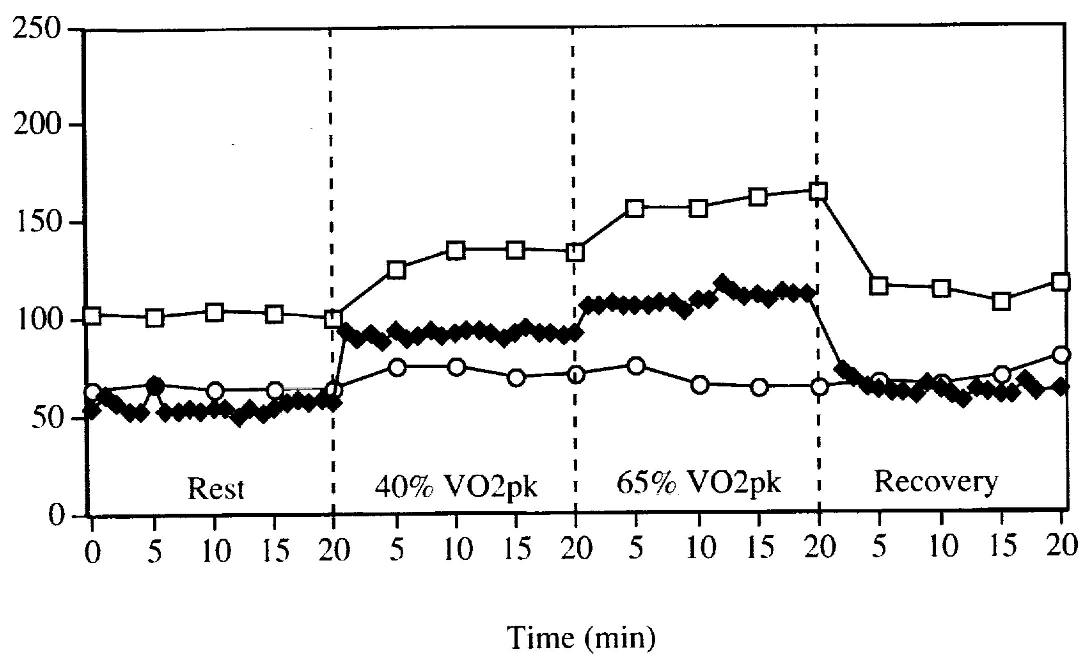
Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
0	Rest	37.08	37.10	37.26	55	104	65
1		37.03	37.10	37.24	62		
2		37.08	37.05	37.24	58		
3		37.08	37.05	37.23	53		
4		37.03	37.00	37.22	53		
5		37.03	37.00	37.21	67	102	68
6		37.08	37.00	37.20	53		
7		37.08	37.00	37.20	54		
8		37.08	37.00	37.20	55		
9		37.08	37.00	37.19	54		
10		37.08	37.00	37.19	55	105	65
11		37.08	37.00	37.18	55		
12		37.03	37.00	37.19	51		
13		37.03	36.95	37.18	55		
14		37.03	36.95	37.17	52		
15		37.03	36.95	37.16	55	103	65
16		36.97	36.95	37.14	57		
17		36.97	36.95	37.14	59		
18		36.97	36.95	37.13	57		
19		36.97	36.90	37.10	59		
20		36.97	36.90	37.09	58	100	64
1	40% VO_{2pk}	36.92	36.95	37.07	94		
2		36.87	36.90	37.07	90		
3		36.92	36.90	37.07	93		
4		36.92	36.95	37.07	88		
5		36.92	36.90	37.07	94	125	76
6		37.03	36.95	37.07	90		
7		37.08	36.95	37.08	91		
8		37.08	36.95	37.08	94		
9		37.08	37.00	37.09	91		
10		37.03	37.00	37.10	92	136	76
11		37.08	37.00	37.12	94		
12		37.13	37.00	37.13	94		
13		37.13	37.00	37.15	92		
14		37.18	37.00	37.16	89		
15		37.18	37.05	37.18	92	135	70
16		37.23	37.10	37.19	95		
17		37.23	37.09	37.21	92		
18		37.23	37.10	37.21	92		
19		37.33	37.10	37.22	91		
20		37.33	37.10	37.24	92	134	72

Subject 1

Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
1	65% VO_{2pk}	37.33	37.16	37.26	106		
2		37.33	37.16	37.28	106		
3		37.39	37.21	37.30	107		
4		37.39	37.21	37.33	106		
5		37.39	37.21	37.35	106	156	75
6		37.44	37.21	37.37	106		
7		37.49	37.26	37.40	108		
8		37.54	37.26	37.42	107		
9		37.54	37.26	37.45	104		
10		37.54	37.31	37.47	109	156	66
11		37.59	37.31	37.48	109		
12		37.59	37.31	37.49	117		
13		37.59	37.36	37.50	113		
14		37.54	37.36	37.50	110		
15		37.54	37.36	37.51	112	162	64
16		37.59	37.41	37.51	109		
17		37.59	37.41	37.52	113		
18		37.59	37.41	37.53	112		
19		37.59	37.46	37.54	112		
20		37.59	37.46	37.54		165	65
1	Recovery	37.64	37.46	37.57			
2		37.64	37.46	37.58	73		
3		37.64	37.46	37.57	69		
4		37.59	37.46	37.55	65		
5		37.54	37.46	37.53	63	116	68
6		37.49	37.46	37.51	62		
7		37.39	37.46	37.49	62		
8		37.39	37.46	37.48	61		
9		37.44	37.46	37.45	66		
10		37.39	37.46	37.44	63	114	66
11		37.39	37.46	37.42	61		
12		37.39	37.41	37.42	58		
13		37.33	37.41	37.41	63		
14		37.23	37.41	37.39	62		
15		37.28	37.36	37.38	61	108	70
16		37.28	37.36	37.38	60		
17		37.18	37.36	37.38	67		
18		37.23	37.36	37.36	62		
19		37.13	37.36	37.35			
20		37.13	37.36	37.31	63	118	80



Esophageal (open square), rectal (open circle), and intestinal (solid diamond) temperatures during submaximal exercise in subject 1



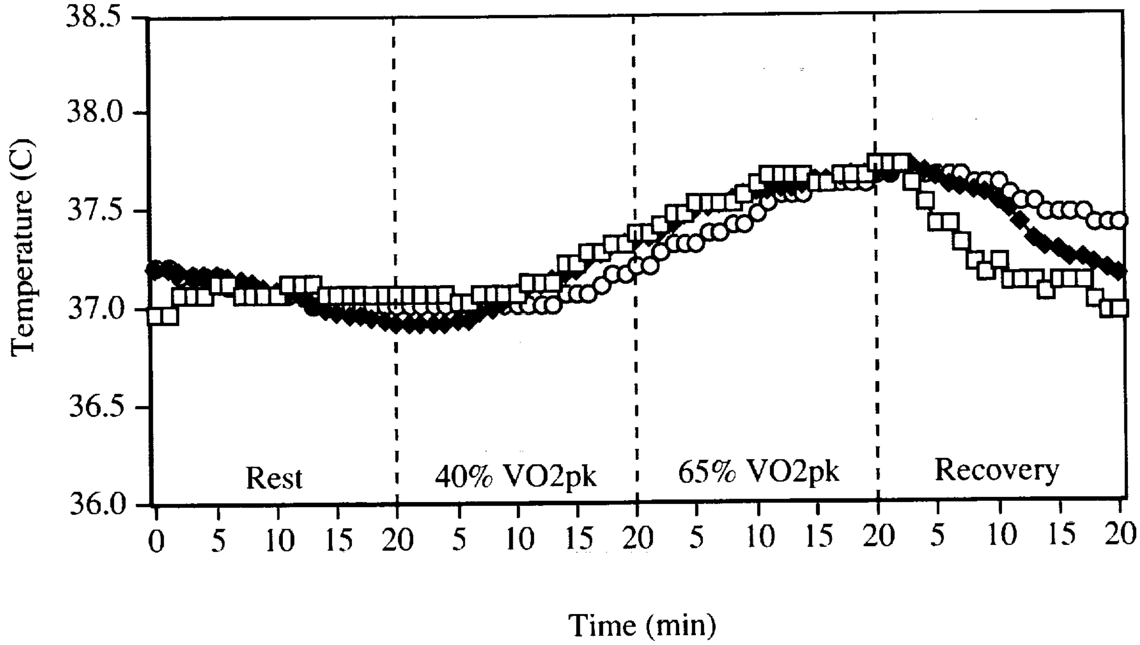
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 1

Subject 2

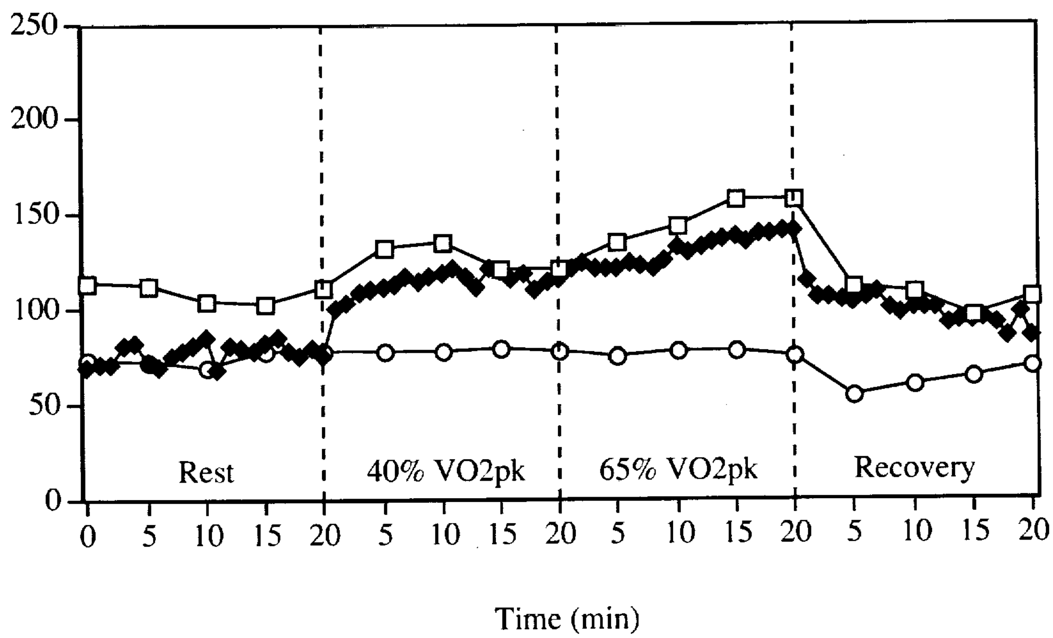
Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
0	Rest	36.98	37.22	37.20	70	115	74
1		36.98	37.22	37.20	72		
2		37.08	37.17	37.19	72		
3		37.08	37.17	37.18	81		
4		37.08	37.17	37.18	83		
5		37.13	37.17	37.18	73	113	73
6		37.13	37.12	37.16	70		
7		37.08	37.12	37.15	76		
8		37.08	37.12	37.13	78		
9		37.08	37.07	37.10	81		
10		37.08	37.07	37.09	86	105	70
11		37.13	37.07	37.07	69		
12		37.13	37.07	37.06	81		
13		37.13	37.02	37.02	80		
14		37.08	37.02	36.99	79		
15		37.08	37.02	36.98	82	104	78
16		37.08	37.02	36.97	85		
17		37.08	37.02	36.97	79		
18		37.08	37.02	36.95	76		
19		37.08	37.02	36.94	80		
20		37.08	37.02	36.93	75	112	78
1	40% VO_{2pk}	37.08	37.02	36.93	101		
2		37.08	37.02	36.93	103		
3		37.08	37.02	36.93	109		
4		37.08	37.02	36.93	110		
5		37.03	37.02	36.94	112	132	78
6		37.03	37.02	36.94	113		
7		37.08	37.02	36.98	117		
8		37.08	37.02	36.99	114		
9		37.08	37.02	37.04	117		
10		37.08	37.02	37.08	119	135	78
11		37.13	37.02	37.10	122		
12		37.13	37.02	37.12	118		
13		37.13	37.02	37.15	112		
14		37.23	37.07	37.17	122		
15		37.23	37.07	37.19	120	122	80
16		37.28	37.07	37.24	116		
17		37.28	37.12	37.27	119		
18		37.33	37.17	37.31	111		
19		37.33	37.17	37.33	114		
20		37.38	37.22	37.34	116	122	78

Subject 2

Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
1	65% VO_{2pk}	37.38	37.22	37.36	122		
2		37.43	37.28	37.38	124		
3		37.48	37.33	37.43	121		
4		37.48	37.33	37.46	121		
5		37.53	37.33	37.49	122	135	75
6		37.53	37.38	37.51	124		
7		37.53	37.38	37.52	123		
8		37.53	37.43	37.55	122		
9		37.58	37.43	37.57	126		
10		37.63	37.48	37.59	132	144	78
11		37.68	37.53	37.59	130		
12		37.68	37.58	37.60	132		
13		37.68	37.58	37.60	136		
14		37.68	37.58	37.62	137		
15		37.63	37.63	37.64	138	158	78
16		37.63	37.63	37.65	136		
17		37.68	37.63	37.66	140		
18		37.68	37.63	37.67	139		
19		37.68	37.63	37.68	141		
20		37.73	37.68	37.68	141	158	75
1	Recovery	37.73	37.68	37.68	114		
2		37.73	37.73	37.71	106		
3		37.63	37.68	37.71	106		
4		37.53	37.68	37.69	105		
5		37.43	37.68	37.66	103	112	55
6		37.43	37.68	37.62	106		
7		37.33	37.68	37.61	109		
8		37.23	37.63	37.59	101		
9		37.18	37.63	37.57	98		
10		37.23	37.63	37.53	101	109	60
11		37.13	37.58	37.49	100		
12		37.13	37.53	37.42	100		
13		37.13	37.53	37.34	93		
14		37.08	37.48	37.30	94		
15		37.13	37.48	37.28	94	96	64
16		37.13	37.48	37.24	95		
17		37.13	37.48	37.24	92		
18		37.03	37.43	37.21	86		
19		36.98	37.43	37.19	98		
20		36.98	37.43	37.16	85	106	70



Esophageal (open square), rectal (open circle), and intestinal (solid diamond) temperatures during submaximal exercise in subject 2



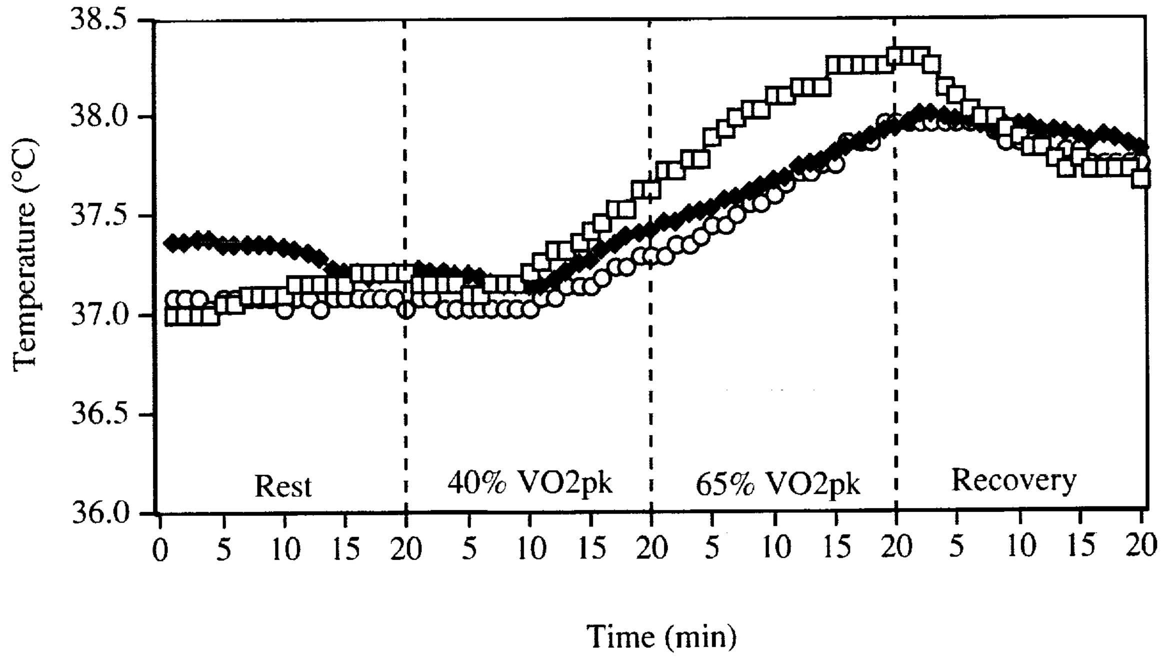
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 2

Subject 3

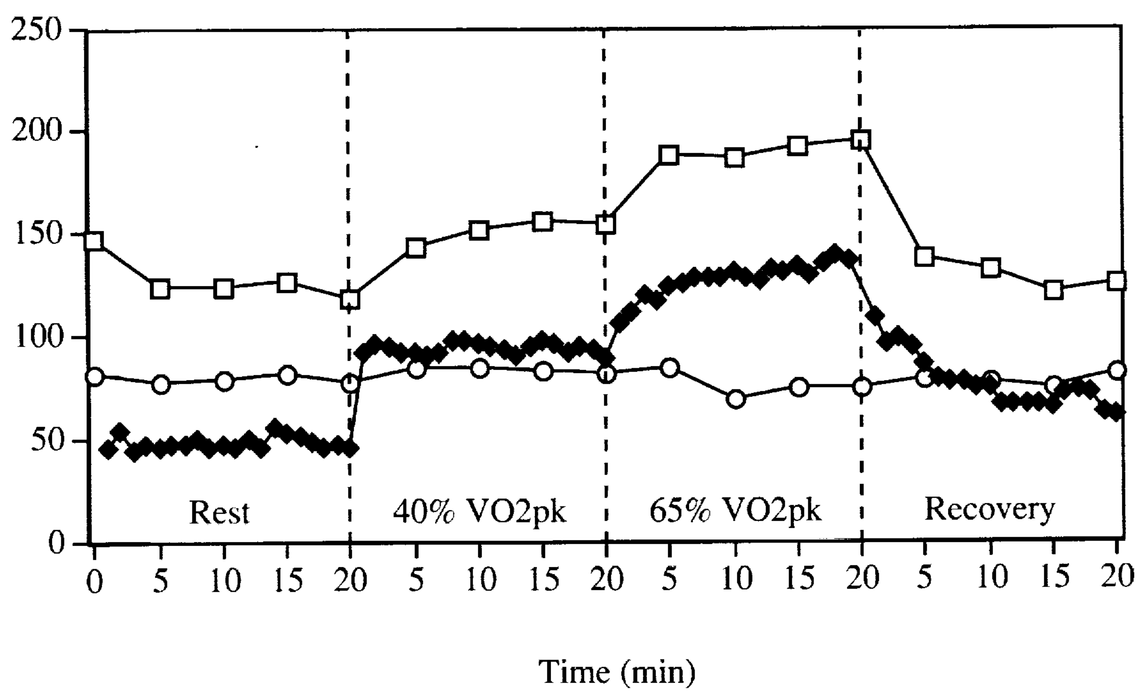
Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
0	Rest					148	82
1		37.01	37.09	37.37	46		
2		37.01	37.09	37.37	55		
3		37.01	37.09	37.38	45		
4		37.01	37.04	37.38	48		
5		37.06	37.09	37.36	47	124	78
6		37.06	37.09	37.35	48		
7		37.11	37.09	37.35	48		
8		37.11	37.09	37.35	51		
9		37.11	37.09	37.35	46		
10		37.11	37.04	37.34	48	124	80
11		37.16	37.09	37.33	46		
12		37.16	37.09	37.31	50		
13		37.16	37.04	37.28	47		
14		37.16	37.09	37.23	56		
15		37.16	37.09	37.22	54	127	82
16		37.22	37.09	37.22	52		
17		37.22	37.09	37.19	49		
18		37.22	37.09	37.20	47		
19		37.22	37.09	37.21	48		
20		37.22	37.04	37.22	46	119	78
1	40% VO_{2pk}	37.16	37.09	37.23	92		
2		37.16	37.09	37.22	96		
3		37.16	37.04	37.21	95		
4		37.16	37.04	37.20	93		
5		37.11	37.04	37.20	93	144	85
6		37.11	37.04	37.19	91		
7		37.16	37.04	37.16	93		
8		37.16	37.04	37.14	98		
9		37.16	37.04	37.14	98		
10		37.22	37.04	37.15	97	152	85
11		37.27	37.09	37.15	95		
12		37.32	37.09	37.18	94		
13		37.32	37.14	37.22	91		
14		37.37	37.14	37.25	95		
15		37.42	37.14	37.27	98	156	84
16		37.47	37.19	37.32	97		
17		37.53	37.24	37.36	93		
18		37.53	37.24	37.39	95		
19		37.63	37.30	37.41	94		
20		37.63	37.30	37.43	89	155	82

Subject 3

Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
1	65% VO_{2pk}	37.73	37.30	37.46	106		
2		37.73	37.35	37.46	112		
3		37.78	37.35	37.50	120		
4		37.78	37.40	37.52	118		
5		37.89	37.45	37.53	124	188	86
6		37.94	37.45	37.57	125		
7		37.99	37.50	37.59	128		
8		38.04	37.56	37.62	128		
9		38.04	37.56	37.65	129		
10		38.10	37.61	37.67	131	187	70
11		38.10	37.66	37.69	129		
12		38.15	37.71	37.74	127		
13		38.15	37.71	37.75	132		
14		38.15	37.76	37.77	131		
15		38.25	37.76	37.81	134	192	75
16		38.25	37.87	37.84	130		
17		38.25	37.87	37.87	135		
18		38.25	37.87	37.90	139		
19		38.25	37.97	37.92	137		
20		38.30	37.97	37.94		195	75
1	Recovery	38.30	37.97	37.97	109		
2		38.30	37.97	38.00	96		
3		38.25	37.97	38.01	99		
4		38.15	37.97	37.99	95		
5		38.10	37.97	37.98	87	138	80
6		38.04	37.97	37.98	80		
7		37.99	37.97	37.95	78		
8		37.99	37.92	37.94	78		
9		37.94	37.87	37.95	76		
10		37.89	37.87	37.95	76	132	78
11		37.84	37.87	37.95	68		
12		37.84	37.87	37.93	68		
13		37.78	37.87	37.93	67		
14		37.73	37.82	37.91	67		
15		37.78	37.82	37.89	66	122	75
16		37.73	37.76	37.87	73		
17		37.73	37.76	37.89	74		
18		37.73	37.76	37.88	73		
19		37.73	37.76	37.86	63		
20		37.68	37.76	37.82	62	125	82



Esophageal (open square), rectal (open circle), and intestinal (solid diamond) temperatures during submaximal exercise in subject 3



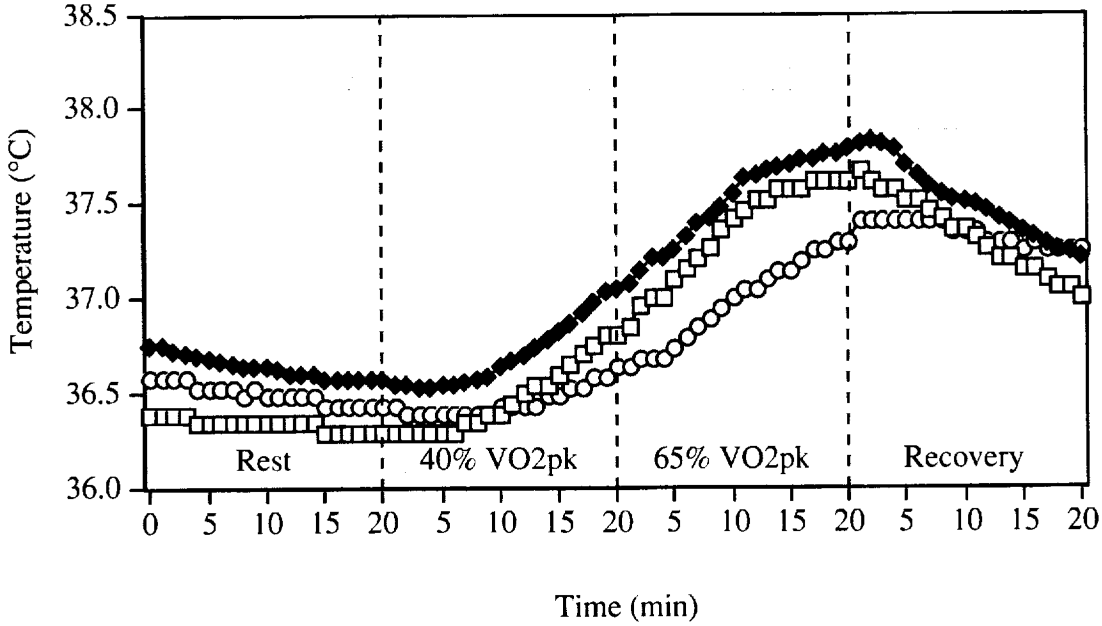
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 3

Subject 4

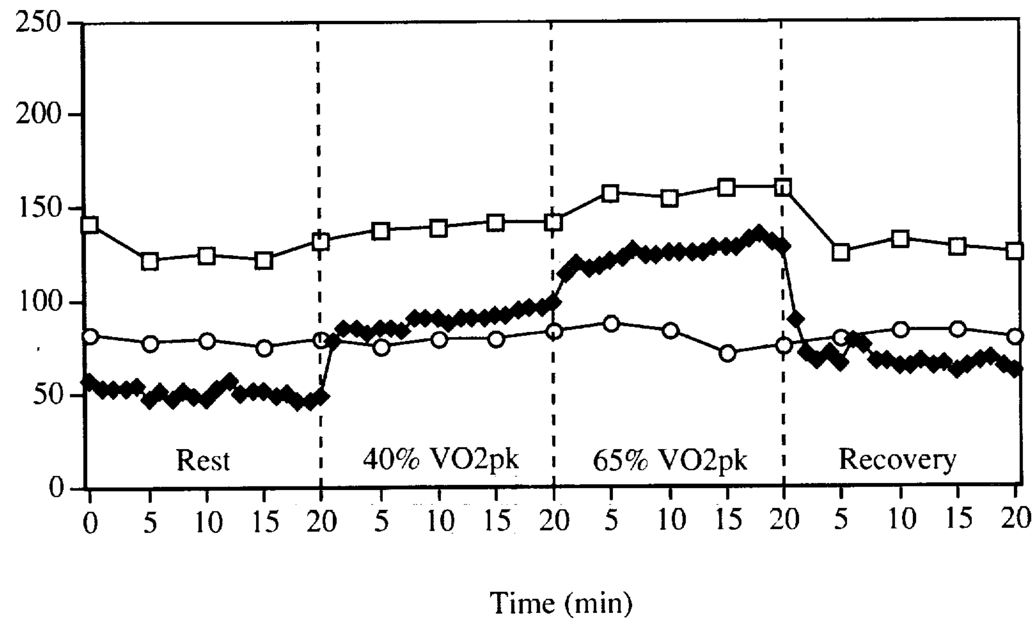
Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
0	Rest	36.40	36.59	36.76	57	142	82
1		36.40	36.59	36.75	54		
2		36.40	36.59	36.73	54		
3		36.40	36.59	36.72	54		
4		36.35	36.54	36.70	55		
5		36.35	36.54	36.69	48	123	78
6		36.35	36.54	36.67	52		
7		36.35	36.54	36.66	48		
8		36.35	36.49	36.64	52		
9		36.35	36.54	36.64	49		
10		36.35	36.49	36.64	48	126	80
11		36.35	36.49	36.63	53		
12		36.35	36.49	36.61	57		
13		36.35	36.49	36.61	51		
14		36.35	36.49	36.60	52		
15		36.30	36.44	36.58	52	123	75
16		36.30	36.44	36.58	49		
17		36.30	36.44	36.58	51		
18		36.30	36.44	36.58	47		
19		36.30	36.44	36.58	47		
20		36.30	36.44	36.58	49	132	80
1	40% VO_{2pk}	36.30	36.44	36.55	78		
2		36.30	36.39	36.55	85		
3		36.30	36.39	36.54	85		
4		36.30	36.39	36.54	82		
5		36.30	36.39	36.55	85	138	75
6		36.30	36.39	36.55	85		
7		36.35	36.39	36.56	84		
8		36.35	36.39	36.58	91		
9		36.40	36.39	36.59	91		
10		36.40	36.44	36.64	91	140	80
11		36.45	36.44	36.67	88		
12		36.50	36.44	36.70	91		
13		36.55	36.44	36.74	91		
14		36.55	36.49	36.78	91		
15		36.61	36.49	36.82	92	142	80
16		36.66	36.54	36.87	93		
17		36.71	36.54	36.93	95		
18		36.76	36.59	36.98	97		
19		36.81	36.59	37.03	96		
20		36.81	36.64	37.05	99	143	84

Subject 4

Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
1	65% VO_{2pk}	36.86	36.64	37.08	115		
2		36.96	36.69	37.15	120		
3		37.01	36.69	37.22	118		
4		37.01	36.69	37.22	119		
5		37.11	36.74	37.25	121	158	88
6		37.16	36.80	37.33	123		
7		37.22	36.85	37.40	127		
8		37.27	36.90	37.43	124		
9		37.37	36.95	37.48	124		
10		37.42	37.00	37.55	125	155	84
11		37.47	37.05	37.63	126		
12		37.52	37.05	37.65	125		
13		37.52	37.10	37.67	126		
14		37.57	37.15	37.69	128		
15		37.57	37.15	37.70	129	161	72
16		37.57	37.20	37.73	128		
17		37.62	37.25	37.73	132		
18		37.62	37.25	37.75	135		
19		37.62	37.30	37.76	131		
20		37.62	37.30	37.78	129	160	76
1	Recovery	37.67	37.41	37.81	90		
2		37.62	37.41	37.82	72		
3		37.57	37.41	37.81	68		
4		37.57	37.41	37.78	71		
5		37.52	37.41	37.70	66	126	80
6		37.52	37.41	37.64	78		
7		37.47	37.41	37.59	75		
8		37.42	37.41	37.55	68		
9		37.37	37.35	37.52	68		
10		37.37	37.35	37.51	64	133	84
11		37.32	37.35	37.49	65		
12		37.27	37.30	37.46	68		
13		37.22	37.30	37.42	65		
14		37.22	37.30	37.39	66		
15		37.16	37.25	37.35	62	128	84
16		37.16	37.30	37.32	65		
17		37.11	37.25	37.29	67		
18		37.06	37.25	37.26	69		
19		37.06	37.25	37.24	65		
20		37.01	37.25	37.22	62	125	80



Esophageal (open square), rectal (open circle), and intestinal (solid diamond) temperatures during submaximal exercise in subject 4



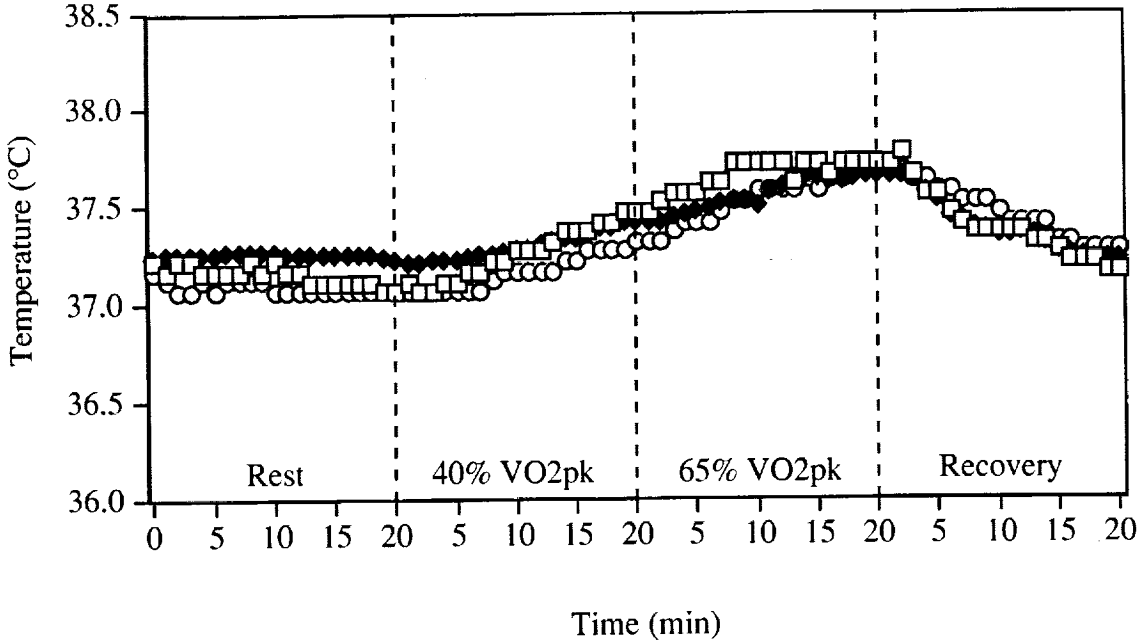
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 4

Subject 5

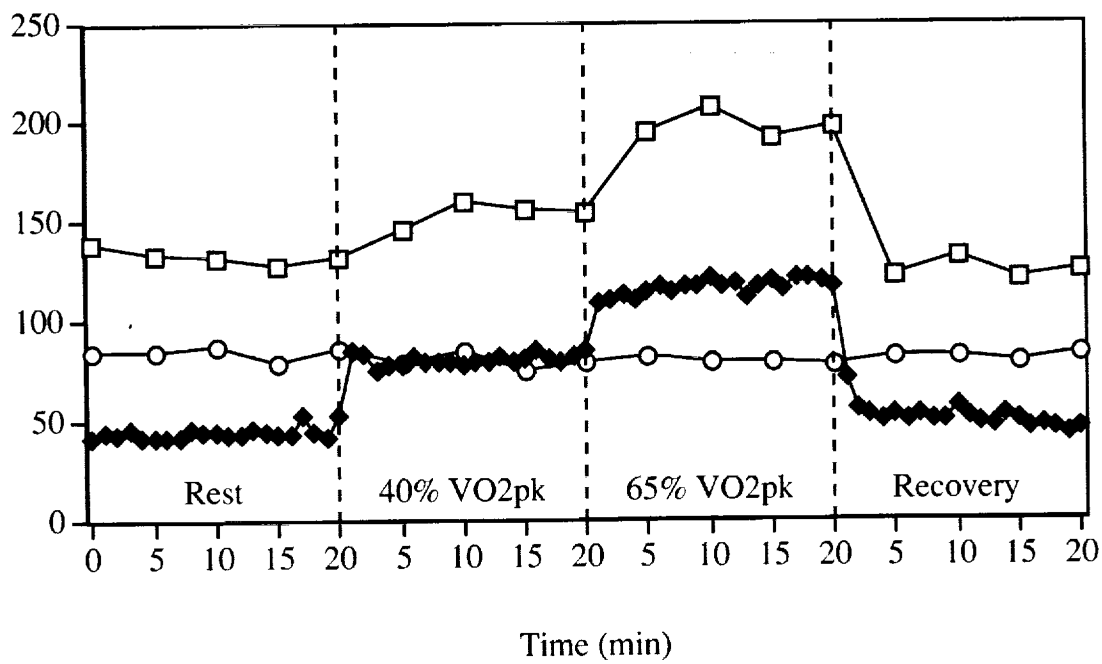
Time	Stage	Esoph.	Rectal	Intestinal	HR	SBP	DBP
0	Rest	37.23	37.18	37.24	43	140	85
1		37.17	37.13	37.25	45		
2		37.23	37.08	37.25	44		
3		37.23	37.08	37.25	46		
4		37.17	37.13	37.26	43		
5		37.17	37.08	37.26	43	134	86
6		37.17	37.13	37.27	42		
7		37.17	37.13	37.27	42		
8		37.23	37.13	37.27	47		
9		37.17	37.13	37.27	45		
10		37.23	37.08	37.27	45	132	88
11		37.17	37.08	37.26	44		
12		37.17	37.08	37.26	44		
13		37.12	37.08	37.26	46		
14		37.12	37.08	37.26	45		
15		37.12	37.08	37.26	44	128	80
16		37.12	37.08	37.26	44		
17		37.12	37.08	37.26	53		
18		37.12	37.08	37.26	45		
19		37.07	37.08	37.24	43		
20		37.07	37.08	37.23	54	133	87
1	40% VO_{2pk}	37.12	37.08	37.22	85		
2		37.07	37.08	37.22	84		
3		37.07	37.08	37.23	76		
4		37.12	37.08	37.23	78		
5		37.12	37.08	37.23	79	146	80
6		37.17	37.08	37.24	82		
7		37.17	37.08	37.26	80		
8		37.23	37.13	37.26	80		
9		37.23	37.18	37.27	80		
10		37.28	37.18	37.28	78	160	85
11		37.28	37.18	37.29	80		
12		37.28	37.18	37.31	80		
13		37.33	37.18	37.33	82		
14		37.38	37.23	37.34	80		
15		37.38	37.23	37.34	81	156	75
16		37.38	37.28	37.37	86		
17		37.43	37.28	37.40	81		
18		37.43	37.28	37.40	80		
19		37.48	37.28	37.42	83		
20		37.48	37.33	37.43	86	155	80

Subject 5

Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
1	65% VO_{2pk}	37.48	37.33	37.43	109		
2		37.53	37.33	37.43	110		
3		37.58	37.38	37.45	113		
4		37.58	37.43	37.47	111		
5		37.58	37.43	37.48	115	195	82
6		37.63	37.43	37.49	117		
7		37.63	37.48	37.52	114		
8		37.73	37.53	37.53	118		
9		37.73	37.53	37.54	117		
10		37.73	37.59	37.51	122	208	80
11		37.73	37.59	37.58	118		
12		37.73	37.59	37.61	119		
13		37.63	37.59	37.64	112		
14		37.73	37.64	37.64	118		
15		37.73	37.59	37.64	120	192	80
16		37.68	37.64	37.63	116		
17		37.73	37.64	37.63	121		
18		37.73	37.69	37.64	122		
19		37.73	37.69	37.66	120		
20		37.73	37.69	37.66	118	198	78
1	Recovery	37.73	37.69	37.66	71		
2		37.78	37.69	37.66	56		
3		37.68	37.64	37.65	54		
4		37.58	37.64	37.58	51		
5		37.58	37.59	37.53	53	123	82
6		37.48	37.59	37.45	50		
7		37.43	37.53	37.44	53		
8		37.38	37.53	37.40	50		
9		37.38	37.53	37.38	51		
10		37.38	37.48	37.36	57	132	82
11		37.38	37.43	37.36	52		
12		37.38	37.43	37.37	49		
13		37.33	37.43	37.36	48		
14		37.33	37.43	37.31	54		
15		37.28	37.33	37.27	50	122	80
16		37.23	37.33	37.26	46		
17		37.23	37.28	37.24	48		
18		37.23	37.28	37.23	46		
19		37.17	37.28	37.23	44		
20		37.17	37.28	37.23	46	125	84



Esophageal (open square), rectal (open circle), and intestinal (solid diamond) temperatures during submaximal exercise in subject 5



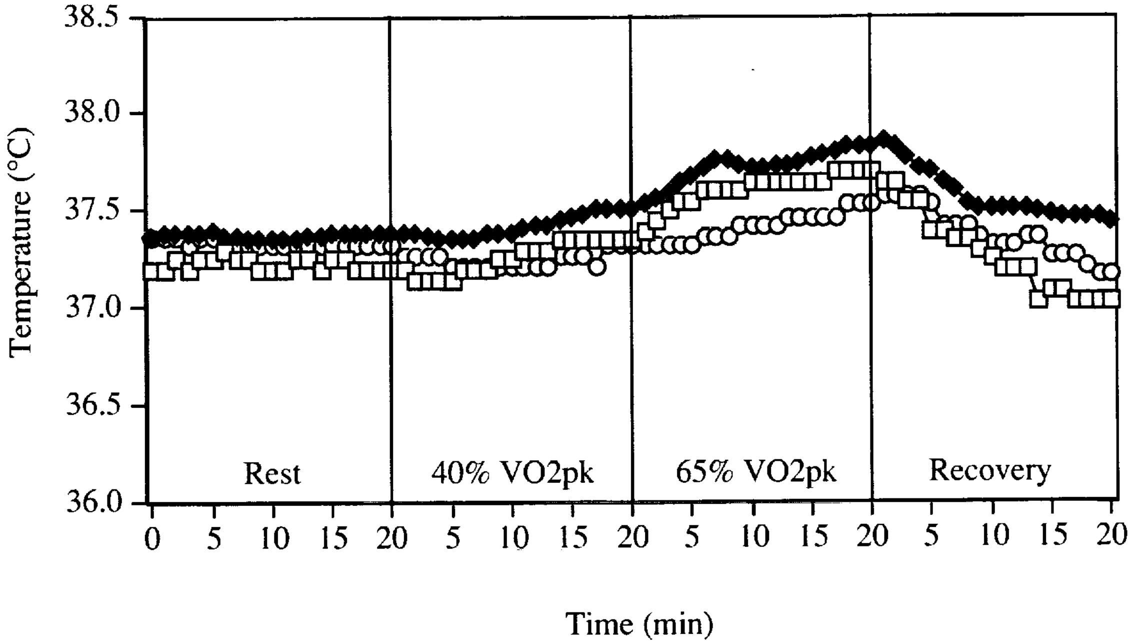
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 5

Subject 6

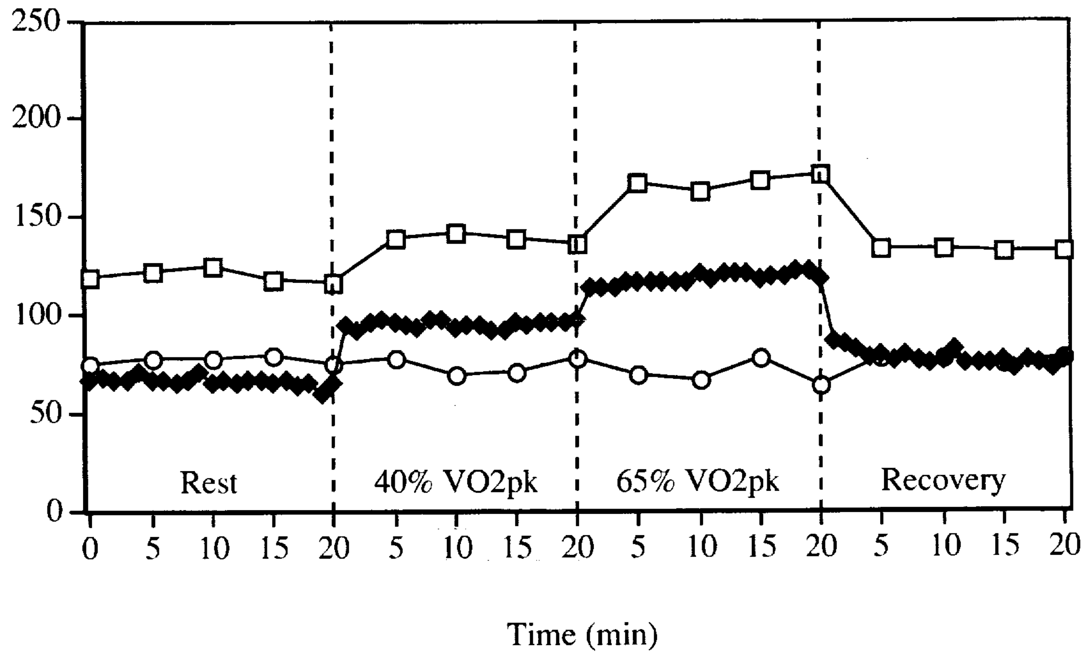
Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
0	Rest	37.20	37.37	37.37	68	120	75
1		37.20	37.37	37.38	69		
2		37.25	37.37	37.38	68		
3		37.20	37.32	37.38	67		
4		37.25	37.37	37.38	72		
5		37.25	37.37	37.39	67	123	78
6		37.30	37.32	37.37	67		
7		37.25	37.32	37.37	66		
8		37.25	37.32	37.35	67		
9		37.20	37.32	37.35	72		
10		37.20	37.32	37.35	66	125	78
11		37.20	37.32	37.35	67		
12		37.25	37.32	37.36	66		
13		37.25	37.32	37.37	68		
14		37.20	37.32	37.37	67		
15		37.25	37.32	37.38	66	119	80
16		37.25	37.32	37.38	67		
17		37.20	37.32	37.38	65		
18		37.20	37.32	37.38	66		
19		37.20	37.32	37.38	61		
20		37.20	37.32	37.38	66	117	75
1	40% VO_{2pk}	37.20	37.27	37.38	95		
2		37.15	37.27	37.38	93		
3		37.15	37.27	37.37	97		
4		37.15	37.27	37.35	98		
5		37.15	37.22	37.35	97	140	78
6		37.20	37.22	37.35	95		
7		37.20	37.22	37.36	94		
8		37.20	37.22	37.38	98		
9		37.25	37.22	37.38	98		
10		37.25	37.22	37.38	94	143	70
11		37.30	37.22	37.41	95		
12		37.30	37.22	37.42	95		
13		37.30	37.22	37.43	93		
14		37.35	37.27	37.45	93		
15		37.35	37.27	37.47	96	139	72
16		37.35	37.27	37.48	95		
17		37.35	37.22	37.50	96		
18		37.35	37.32	37.51	97		
19		37.35	37.32	37.51	96		
20		37.35	37.32	37.50	98	137	78

Subject 6

Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
1	65% VO_{2pk}	37.40	37.32	37.53	115		
2		37.45	37.32	37.56	114		
3		37.50	37.32	37.59	115		
4		37.55	37.32	37.64	118		
5		37.55	37.32	37.68	118	168	70
6		37.60	37.37	37.71	118		
7		37.60	37.37	37.76	118		
8		37.60	37.37	37.75	118		
9		37.60	37.42	37.73	118		
10		37.65	37.42	37.71	121	163	68
11		37.65	37.42	37.72	119		
12		37.65	37.42	37.73	122		
13		37.65	37.47	37.73	122		
14		37.65	37.47	37.74	121		
15		37.65	37.47	37.77	119	169	78
16		37.65	37.47	37.79	120		
17		37.70	37.47	37.80	120		
18		37.70	37.53	37.83	123		
19		37.70	37.53	37.83	123		
20		37.70	37.53	37.83	119	172	64
1	Recovery	37.65	37.58	37.86	87		
2		37.65	37.58	37.83	86		
3		37.55	37.58	37.77	82		
4		37.55	37.58	37.72	79		
5		37.40	37.53	37.70	80	134	78
6		37.40	37.42	37.65	77		
7		37.35	37.42	37.60	80		
8		37.35	37.42	37.53	77		
9		37.30	37.37	37.51	75		
10		37.25	37.32	37.50	77	134	78
11		37.20	37.32	37.50	83		
12		37.20	37.32	37.50	76		
13		37.20	37.37	37.50	75		
14		37.04	37.37	37.49	76		
15		37.09	37.27	37.48	77	133	75
16		37.09	37.27	37.47	73		
17		37.04	37.27	37.47	77		
18		37.04	37.22	37.47	76		
19		37.04	37.17	37.46	73		
20		37.04	37.17	37.44	77	133	79



Esophageal (open square), rectal (open circle), and intestinal (solid diamond) temperatures during submaximal exercise in subject 6



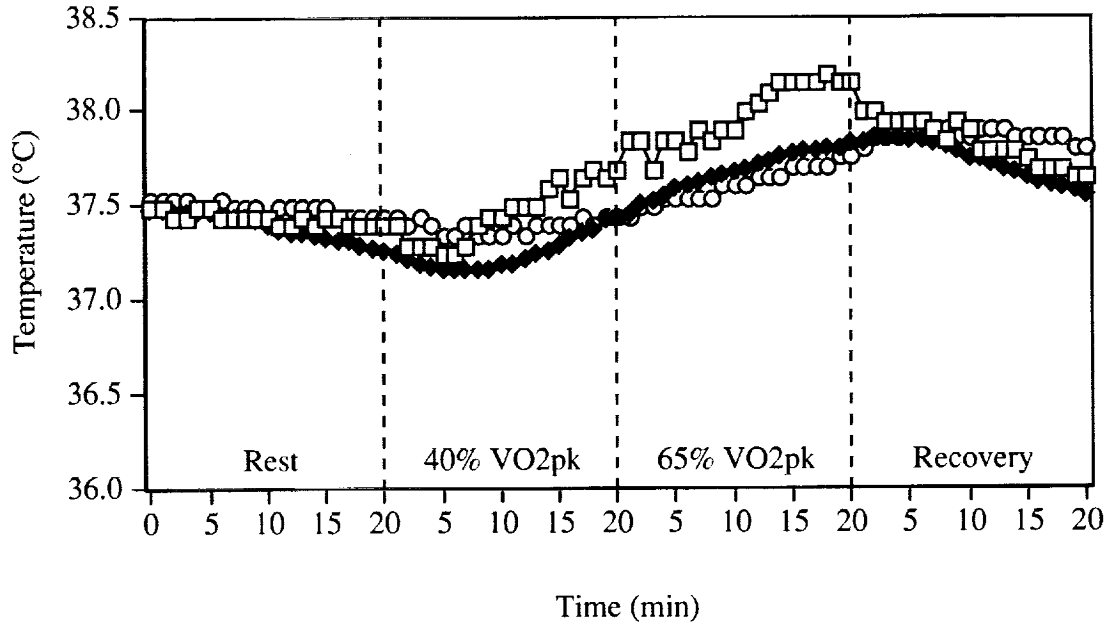
Heart rate (sold diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 6

Subject 7

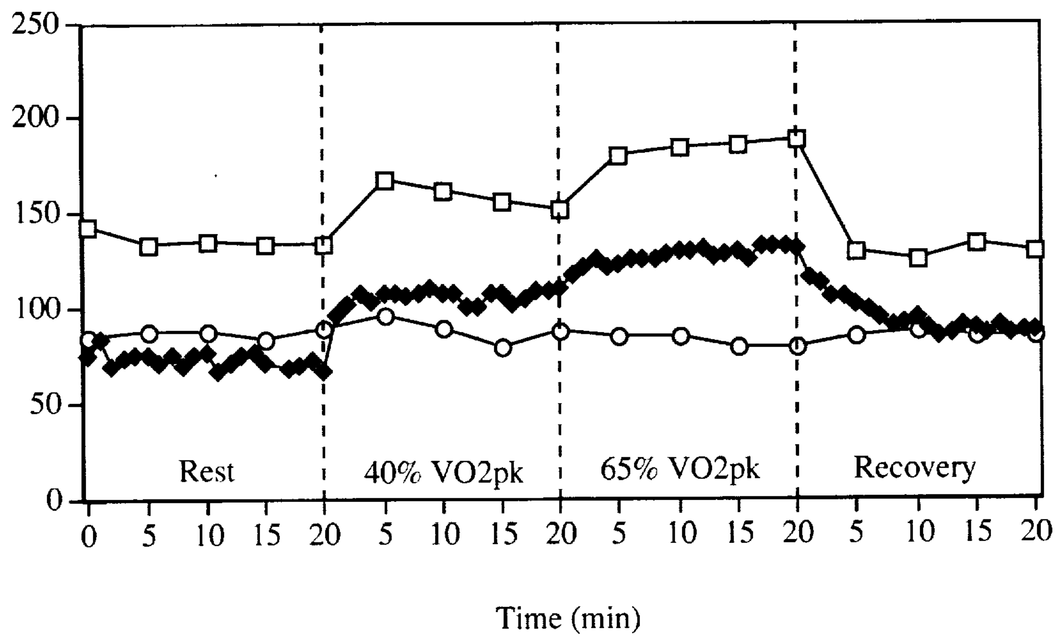
Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
0	Rest	37.49	37.54	37.48	75	144	86
1		37.49	37.54	37.48	84		
2		37.44	37.54	37.47	70		
3		37.44	37.54	37.47	74		
4		37.49	37.49	37.47	76		
5		37.49	37.49	37.46	75	134	88
6		37.44	37.54	37.45	72		
7		37.44	37.49	37.44	75		
8		37.44	37.49	37.44	70		
9		37.44	37.49	37.43	75		
10		37.44	37.44	37.40	77	136	88
11		37.39	37.49	37.37	68		
12		37.39	37.49	37.36	71		
13		37.44	37.49	37.35	75		
14		37.39	37.49	37.34	77		
15		37.44	37.49	37.33	71	134	84
16		37.44	37.44	37.31			
17		37.39	37.44	37.31	69		
18		37.39	37.44	37.29	70		
19		37.39	37.44	37.27	73		
20		37.39	37.44	37.25	68	134	90
1	40% VO_{2pk}	37.39	37.44	37.24	97		
2		37.29	37.39	37.22	102		
3		37.29	37.44	37.19	107		
4		37.29	37.39	37.18	104		
5		37.24	37.34	37.16	108	168	96
6		37.24	37.34	37.16	107		
7		37.29	37.39	37.16	106		
8		37.39	37.34	37.16	108		
9		37.44	37.34	37.16	110		
10		37.44	37.34	37.19	107	162	90
11		37.49	37.39	37.19	108		
12		37.49	37.34	37.22	101		
13		37.49	37.39	37.24	101		
14		37.59	37.39	37.25	107		
15		37.64	37.39	37.29	108	156	80
16		37.54	37.39	37.32	102		
17		37.64	37.44	37.35	105		
18		37.69	37.39	37.37	109		
19		37.64	37.44	37.42	109		
20		37.69	37.44	37.43	111	152	88

Subject 7

Time	Stage	T_{es}	T_{rec}	T_{in}	HR	SBP	DBP
1	65% VO_{2pk}	37.84	37.44	37.45	118		
2		37.84	37.49	37.50	121		
3		37.69	37.49	37.52	125		
4		37.84	37.54	37.55	122		
5		37.84	37.54	37.59	123	180	86
6		37.79	37.54	37.61	126		
7		37.89	37.54	37.62	126		
8		37.84	37.54	37.65	125		
9		37.89	37.60	37.66	128		
10		37.89	37.60	37.68	130	184	86
11		37.99	37.60	37.69	130		
12		38.04	37.65	37.71	131		
13		38.09	37.65	37.73	127		
14		38.14	37.65	37.75	129		
15		38.14	37.70	37.77	130	186	80
16		38.14	37.70	37.78	126		
17		38.14	37.70	37.78	132		
18		38.19	37.70	37.80	132		
19		38.14	37.75	37.80	132		
20		38.14	37.75	37.82	131	188	80
1	Recovery	37.99	37.80	37.83	116		
2		37.99	37.85	37.85	113		
3		37.94	37.85	37.85	106		
4		37.94	37.85	37.85	106		
5		37.94	37.90	37.84	102	130	86
6		37.94	37.90	37.84	99		
7		37.89	37.85	37.83	95		
8		37.84	37.90	37.81	91		
9		37.94	37.85	37.79	92		
10		37.89	37.85	37.74	95	126	88
11		37.79	37.90	37.74	89		
12		37.79	37.90	37.71	86		
13		37.79	37.90	37.69	87		
14		37.79	37.85	37.67	91		
15		37.74	37.85	37.65	89	134	86
16		37.69	37.85	37.62	87		
17		37.69	37.85	37.61	91		
18		37.69	37.85	37.59	87		
19		37.64	37.80	37.57	88		
20		37.64	37.80	37.55	88	130	86



Esophageal (open square), rectal (open circle), and intestinal (solid diamond) temperatures during submaximal exercise in subject 7



Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 7

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13. ABSTRACT *(Maximum 200 words)*
The purpose of this study was to determine if intestinal temperature (Tin) might be an acceptable alternative to esophageal (Tes) and rectal temperature (Trec) to assess thermoregulation during supine exercise. We hypothesized that Tin would have values similar to Tes and a response time similar to Trec, but the rate of temperature change across time would not be different between measurement sites. Seven subjects completed a continuous supine protocol of 20 min of rest, 20 min of cycle exercise at 40% peak oxygen consumption (VO2pk), 20 min of cycle exercise at 65% VO2pk, and 20 min of recovery. Tes, Trec, and Tin were recorded each min throughout the test. Temperatures were not different after 20 min of rest, but Trec was less than the Tes and Tin at the end of the 40% and 65% VO2pk stages. After 20 min of recovery, Tes was less than either Trec or Tin, which were not different from each other. Time to threshold for increased temperature from rest was greater for Trec than Tes but not different from Tin. Time to reach peak temperature was greater for Tin and Trec than Tes. Similarly, time to a decrease in temperature after exercise was greater for Trec than Tes, but not different from Tin. The rate of temperature change from threshold to the end of the 40% VO2pk stage was not different between measurement sites. However, the rate of change during recovery was more negative for Tes than Tin and Trec, which were different from each other.
Measurement of Tin may be an acceptable alternative to Tes and Trec with an understanding of its limitations.

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