

NASA/TP—2000—210133



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

*Stuart M.C. Lee  
Wyle Laboratories  
Houston, TX 77058-2787*

*W. Jon Williams  
Wyle Laboratories  
Houston, TX 77058-2787*

*Suzanne M. Schneider  
Johnson Space Center  
Houston, TX 77058-3696*

## The NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Help Desk at (301) 621-0134
- Telephone the NASA STI Help Desk at (301) 621-0390
- Write to:  
NASA STI Help Desk  
NASA Center for AeroSpace Information  
7121 Standard Drive  
Hanover, MD 21076-1320

NASA/TP—2000–210133



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

*Stuart M.C. Lee  
Wyle Laboratories  
Houston, TX 77058-2787*

*W. Jon Williams  
Wyle Laboratories  
Houston, TX 77058-2787*

*Suzanne M. Schneider  
Johnson Space Center  
Houston, TX 77058-3696*

National Aeronautics and  
Space Administration

Lyndon B. Johnson Space Center  
Houston, Texas 77058-3696

---

April 2000

## ACKNOWLEDGMENTS

The authors wish to thank the subjects for their participation in this project; Dr. Terry Pattinson for assistance with the esophageal probe insertions and his medical monitoring of the tests; Alice Rogers for her assistance with subject scheduling, report formatting, and publication coordination; and the Publications Department at NASA-JSC for formatting assistance, printing, and distribution of this report.

This work was supported by the NASA Contract NAS9-18492, the NASA-*Mir* Pathfinder Program, and the International Space Station Human Research Facility.

Available from:

NASA Center for AeroSpace Information  
7121 Standard Drive  
Hanover, MD 21076-1320  
301-621-0390

National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161  
703-605-6000

This report is also available in electronic form at <http://techreports.larc.nasa.gov/cgi-bin/NTRS>

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



# CONTENTS

	<b>Page</b>
ABSTRACT .....	iii
ACRONYMS AND NOMENCLATURE.....	vii
INTRODUCTION.....	1
METHODS.....	2
Overall Protocol .....	2
Probe and Pill Calibration.....	2
VO <sub>2pk</sub> Exercise Test .....	3
Submaximal Exercise Test.....	3
Statistical Analyses .....	4
RESULTS.....	5
Thermistor and Pill Calibration.....	5
Subject Characteristics and VO <sub>2pk</sub> Test Results.....	7
Submaximal Exercise Test.....	7
Measured Temperature and Change in Temperature .....	8
Time Course of Temperature Change .....	10
Rate of Temperature Change .....	11
DISCUSSION .....	11
Pill Calibration .....	11
Temperatures at Rest.....	12
Temperatures During Exercise.....	13
Temperatures During Recovery From Exercise.....	15
Timing of Pill Ingestion .....	15
Limitations .....	16
SUMMARY .....	17
REFERENCES.....	18
APPENDIX A: INDIVIDUAL SUBJECT CHARACTERISTICS.....	21
APPENDIX B: INDIVIDUAL VO <sub>2pk</sub> TEST RESULTS .....	22
APPENDIX C: INDIVIDUAL SUBMAXIMAL TEST EXERCISE INTENSITIES.....	23
APPENDIX D: INDIVIDUAL SUBMAXIMAL EXERCISE TEST RESULTS .....	24

**CONTENTS**  
(continued)

	<b>Page</b>
<b>Tables</b>	
Table 1: Mean ( $\pm$ SE) Esophageal, Rectal, and Intestinal Temperatures During Submaximal Exercise.....	9
Table 2: Threshold of Temperature Responses in Esophageal, Rectal, and Intestinal Measurements.....	10
<b>Figures</b>	
Figure 1: $VO_{2pk}$ test protocol .....	3
Figure 2: Submaximal exercise test protocol.....	4
Figure 3: Composite of all esophageal thermistor, rectal thermistor, and pill calibrations (n = 28) against calibrated thermometer.....	6
Figure 4: Mean ( $\pm$ SD) heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise test. ....	7
Figure 5: Mean esophageal, intestinal, and rectal temperatures during submaximal exercise .....	8

## 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	megahertz
min	minute(s)
rpm	revolutions per minute
SBP	systolic blood pressure
SD	standard deviation
SE	standard error
$T_{\text{core}}$	core temperature
$T_{\text{es}}$	esophageal temperature
$T_{\text{in}}$	intestinal temperature
$T_{\text{rec}}$	rectal temperature
$\text{VO}_2$	oxygen consumption
$\text{VO}_{2\text{pk}}$	peak oxygen consumption
W	watts
yrs	years



## INTRODUCTION

Body core temperature ( $T_{\text{core}}$ ) 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  $T_{\text{core}}$  during local heating (4, 5, 6) or cooling (7, 4, 5, 6, 8) of the head.

Esophageal ( $T_{\text{es}}$ ) and rectal temperatures ( $T_{\text{rec}}$ ) are two measurement sites that are commonly employed in thermoregulatory investigations (9).  $T_{\text{es}}$  is preferred by many as the site to measure  $T_{\text{core}}$  (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).  $T_{\text{rec}}$  has gained wide acceptance due to its relative ease of use and its stability during steady-state conditions (13). However,  $T_{\text{rec}}$  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  $T_{\text{core}}$  (10, 12, 13). There are sanitary concerns with regard to the use of esophageal and rectal probes for the measurement of  $T_{\text{core}}$ , 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  $T_{\text{core}}$  is the measurement of intestinal temperature ( $T_{\text{in}}$ ). 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  $T_{\text{in}}$  to  $T_{\text{es}}$  and  $T_{\text{rec}}$  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  $T_{\text{in}}$  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.

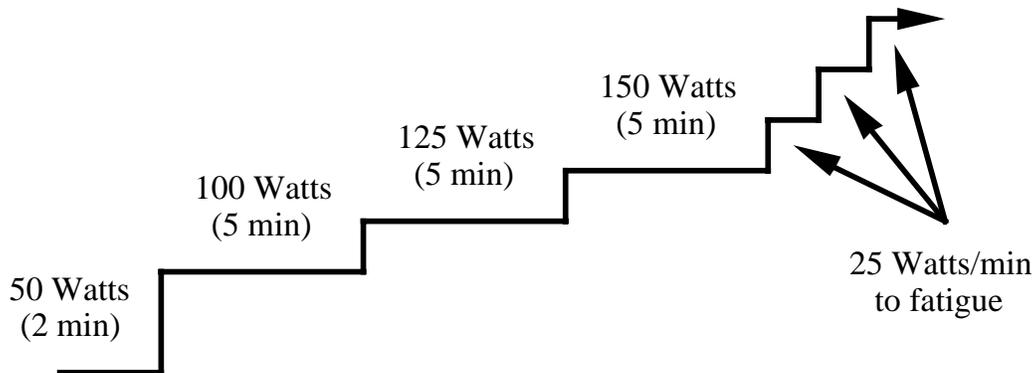
### ***Probe and Pill Calibration***

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<sub>2pk</sub> 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<sub>2pk</sub> was taken as the highest 1-min measurement of oxygen consumption (VO<sub>2</sub>) obtained during the test.



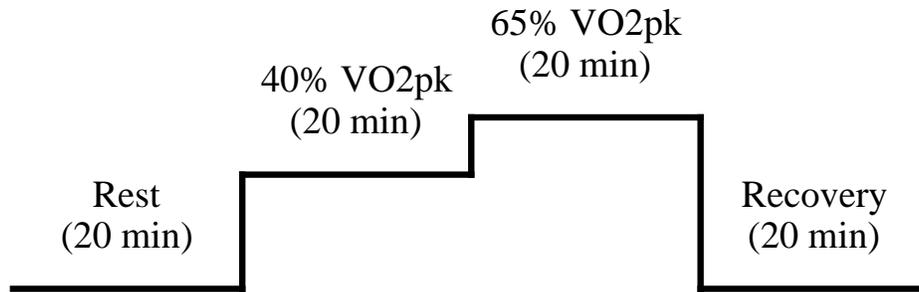
**Figure 1: VO<sub>2pk</sub> test protocol**

VO<sub>2</sub> from the last 2 min of each 5-min stage were averaged. A linear regression describing the relationship between VO<sub>2</sub> and exercise intensity was generated for each subject. From this equation, two exercise intensities which corresponded to approximately 40% and 65% of supine VO<sub>2pk</sub> 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<sub>2pk</sub>, 20 min at 65% VO<sub>2pk</sub>, 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  $\pm$  standard error (SE).

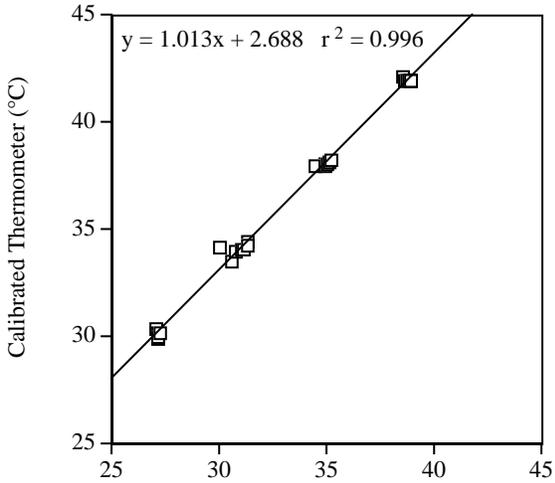
Time to threshold for measured increase in  $T_{core}$  (an increase of 0.1°C from end of rest) and time to threshold for decrease in  $T_{core}$  (a decrease of 0.1°C from the peak temperature measured at the end of exercise) were measured. Difference in time to threshold between measurement sites was 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  $\pm$  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  $\pm$  SE.

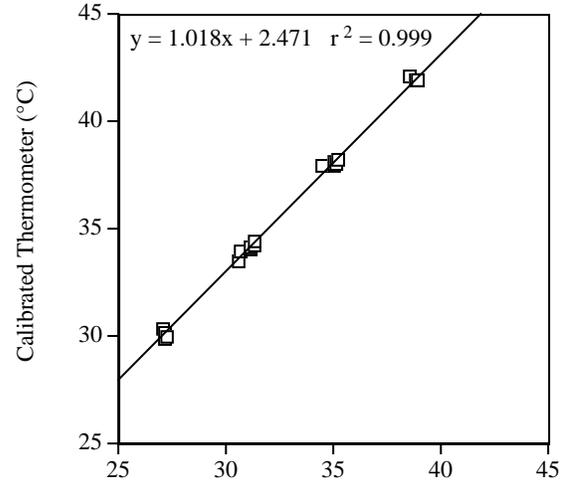
## **RESULTS**

### ***Thermistor and Pill Calibration***

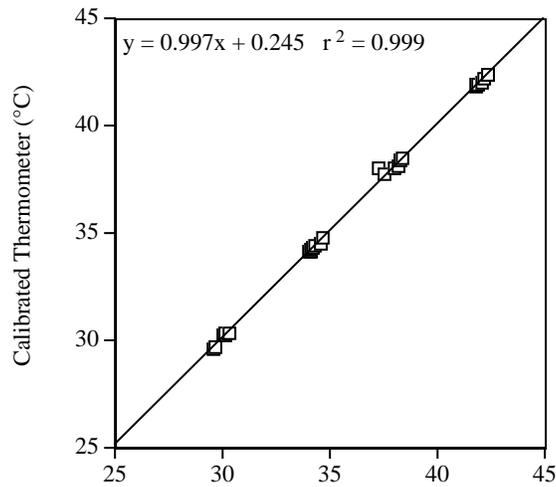
All  $T_{core}$  measurement devices (esophageal and rectal thermistors and ingestible pill) were calibrated before each test. A linear regression was developed for each calibration across four calibration temperatures, approximately 30, 34, 38, and 42°C, and the result applied to the data collected 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.



Esophageal Probe Temperature



Rectal Probe Temperature (°C)



Pill Temperature (°C)

**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.

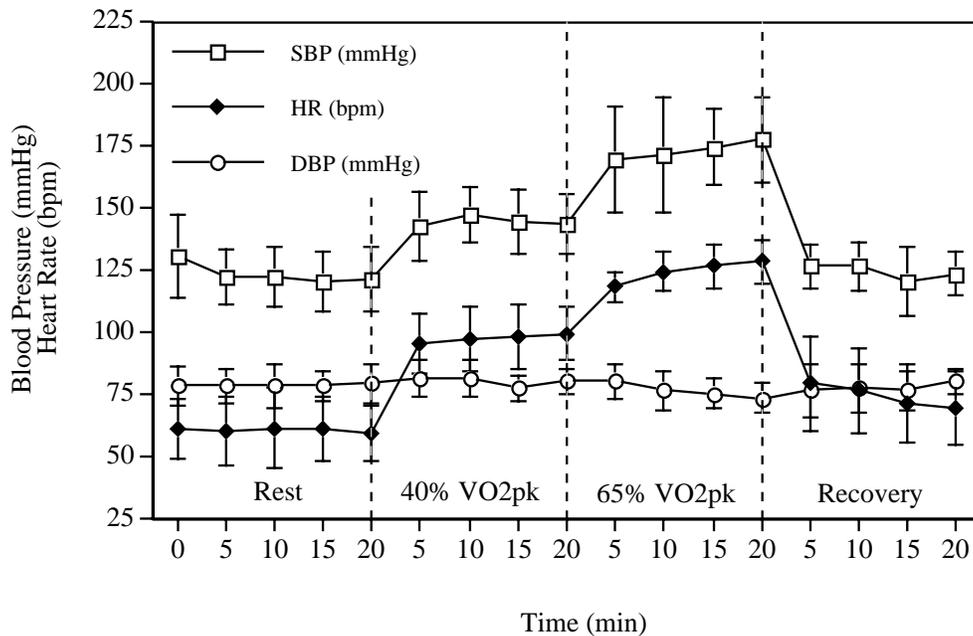
### **Subject Characteristics and $VO_{2pk}$ Test Results**

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

Subjects attained a mean ( $\pm$  SD) supine  $VO_{2pk}$  of  $2.55 \pm 0.61$  L/min ( $33.4 \pm 5.2$  mL/kg/min) and peak heart rate of  $160 \pm 15$  bpm at a peak exercise intensity of  $161 \pm 48$  W in a mean test time of  $14.8 \pm 4.6$  min. The peak respiratory exchange ratio was  $1.14 \pm 0.09$  and the peak expired ventilation was  $99.0 \pm 30.7$  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**

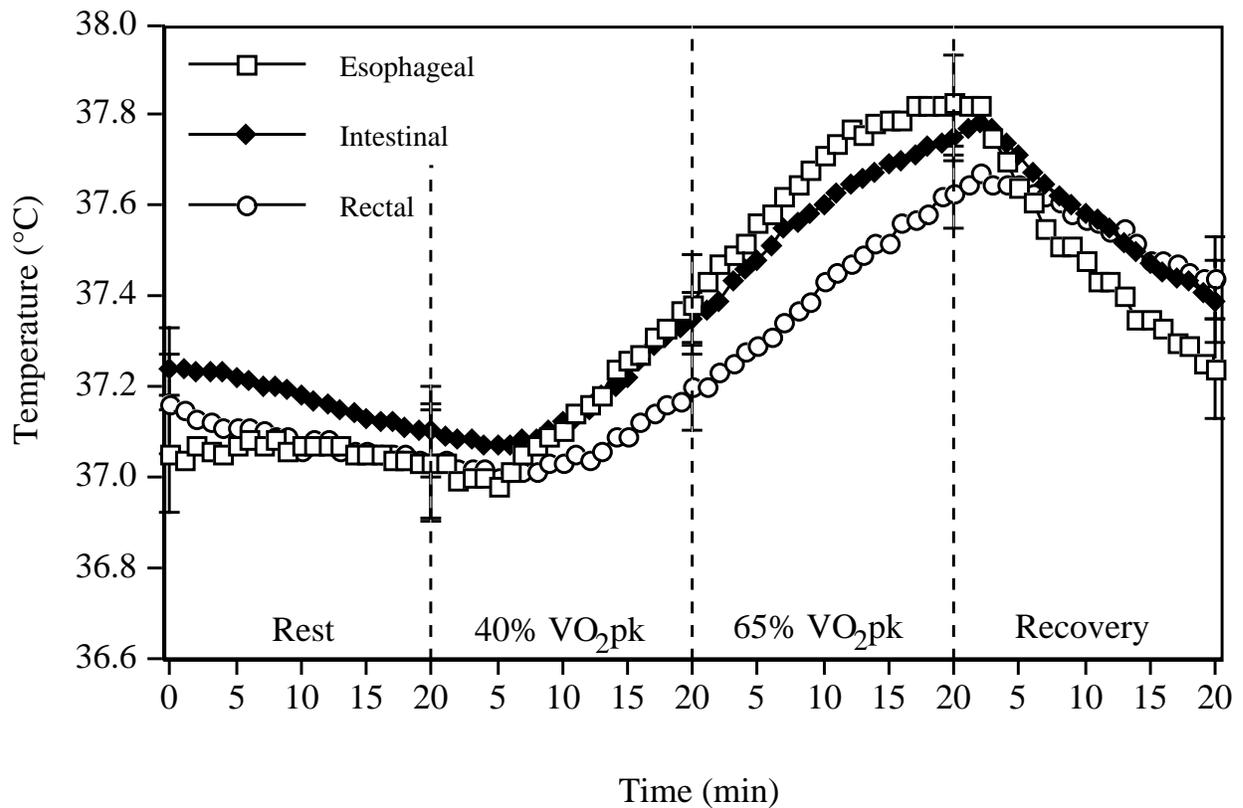
All subjects were able to complete the entire submaximal exercise test protocol. Mean  $VO_2$  ( $\pm$  SD) was predicted to be  $1.02 \pm .09$  L/min and  $1.66 \pm 0.15$  L/min at mean exercise intensities of  $51 \pm 5$  and  $94 \pm 10$  W, respectively. Heart rate and blood pressure during pre-exercise rest, exercise, and recovery are displayed in Figure 4. Individual submaximal exercise intensity data can be found in Appendix C.



**Figure 4: Mean ( $\pm$ 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 ( $\pm$  SE) Esophageal, Rectal, and Intestinal Temperatures During Submaximal Exercise**

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

\* Significantly different from T<sub>es</sub> † Significantly different than T<sub>rec</sub>

After 20 min of exercise at 40% VO<sub>2pk</sub>, T<sub>es</sub>, T<sub>rec</sub>, and T<sub>in</sub> were significantly greater than their respective measures at the end of supine rest. However, T<sub>rec</sub> was significantly less than T<sub>es</sub> and T<sub>in</sub>, 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<sub>2pk</sub> stage was significantly greater in T<sub>es</sub> than in T<sub>rec</sub>. There was no difference between the T<sub>es</sub> and T<sub>in</sub> changes, and no difference between T<sub>in</sub> and T<sub>rec</sub>.

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

Peak temperature measured tended to be different ( $p = 0.07$ ) between the sites. Measured peak temperatures were highest in the T<sub>es</sub> followed by the T<sub>in</sub> and T<sub>rec</sub>, 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%  $\text{VO}_{2\text{pk}}$  stage ( $T_{\text{es}}$ :  $0.022 \pm 0.005$ ;  $T_{\text{rec}}$ :  $0.016 \pm 0.004$ ;  $T_{\text{in}}$ :  $0.021 \pm 0.004^\circ\text{C}/\text{min}$ ). 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  $T_{\text{es}}$  ( $-0.030 \pm 0.002^\circ\text{C}/\text{min}$ ) than for  $T_{\text{rec}}$  ( $-0.010 \pm 0.003^\circ\text{C}/\text{min}$ ) and  $T_{\text{in}}$  ( $-0.023 \pm 0.003^\circ\text{C}/\text{min}$ ). Also, the rate of change for  $T_{\text{in}}$  was more negative than  $T_{\text{rec}}$ .

## **DISCUSSION**

The purpose of this investigation was to compare the measurement characteristics of  $T_{\text{in}}$  with regard to two frequently used measurement sites,  $T_{\text{es}}$  and  $T_{\text{rec}}$ . 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  $T_{\text{in}}$  during supine rest, exercise, and recovery from exercise would be a suitable alternative to  $T_{\text{es}}$  and  $T_{\text{rec}}$  for the estimation of  $T_{\text{core}}$ . 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  $T_{\text{in}}$  was not different from  $T_{\text{es}}$  during exercise at specific time points, and the time to a measured response of  $0.10^\circ\text{C}$  was intermediate between those of  $T_{\text{es}}$  and  $T_{\text{rec}}$ . 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  $0.10^\circ\text{C}$  for  $T_{\text{in}}$  was intermediate to those of  $T_{\text{es}}$  and  $T_{\text{rec}}$  and the rate of temperature change during recovery from exercise was most negative for  $T_{\text{es}}$  and least negative for  $T_{\text{rec}}$ . As a result, the temperature at the end of recovery was lowest for  $T_{\text{es}}$  and highest for  $T_{\text{rec}}$ .

### ***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  $0.08^\circ\text{C}$  and three were higher by an average of  $0.37^\circ\text{C}$ . 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  $115 \pm 8$  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  $0.15 \pm 0.02^\circ\text{C}$  but the difference in an individual pill was as high as  $0.80^\circ\text{C}$ . Although the mean difference was within  $\pm 0.20^\circ\text{C}$  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  $0.10^\circ\text{C}$ .

### ***Temperatures at Rest***

At the beginning of supine rest when the subjects made the transition from standing,  $T_{\text{es}}$  and  $T_{\text{rec}}$  were not different from each other, but  $T_{\text{in}}$  was significantly higher than  $T_{\text{es}}$ . Over the course of the 20-min supine rest,  $T_{\text{es}}$  was steady, but both  $T_{\text{rec}}$  and  $T_{\text{in}}$  decreased. At the end of the 20-min rest, the temperatures were not significantly different from each other. Lower  $T_{\text{core}}$  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  $T_{\text{es}}$  may be due to the rapid response time of  $T_{\text{es}}$  to a change in blood flow distribution (26).  $T_{\text{es}}$  may have decreased to a new steady state by the time we completed instrumenting the subject and data collection began. The decline in  $T_{\text{rec}}$  and  $T_{\text{in}}$  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  $T_{\text{in}}$  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  $T_{\text{in}}$  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%  $VO_{2pk}$  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  $0.10^{\circ}\text{C}$  was significantly less for  $T_{\text{es}}$  than  $T_{\text{rec}}$  but not different than  $T_{\text{in}}$ . Also, the rate of the temperature change was more negative for  $T_{\text{es}}$  than  $T_{\text{rec}}$ . The rate of the decrease in  $T_{\text{in}}$  was less than  $T_{\text{es}}$  but greater than  $T_{\text{rec}}$ . Similarly, Kolka et al. (10) observed that  $T_{\text{es}}$  and  $T_{\text{in}}$  appeared to be responsive to changes in metabolic heat production during 5-min bouts of intense exercise interspersed with 5-min rest periods, but  $T_{\text{rec}}$  was not. These findings with regard to  $T_{\text{es}}$  and  $T_{\text{rec}}$  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.  $T_{\text{es}}$  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,  $T_{\text{in}}$  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.  $T_{\text{rec}}$  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  $T_{\text{es}}$ . Livingstone et al. (13) found that  $T_{\text{in}}$  readings taken soon after pill ingestion often followed the same pattern as  $T_{\text{es}}$  with an offset. Presumably, deeper locations in the intestinal tract would be subject to less variation (22) and may be more similar to  $T_{\text{rec}}$  (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  $30.4 \pm 8.9$  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. Reexamination 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 physiological 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 <sub>2pk</sub> (L/min)	VO <sub>2pk</sub> (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<sub>2pk</sub> TEST RESULTS**

Subject	Time (min)	Workload (W)	VO <sub>2pk</sub> (L/min)	VO <sub>2pk</sub> (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 <sub>2pk</sub> (L/min)	Workload (W)	65% VO <sub>2pk</sub> (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

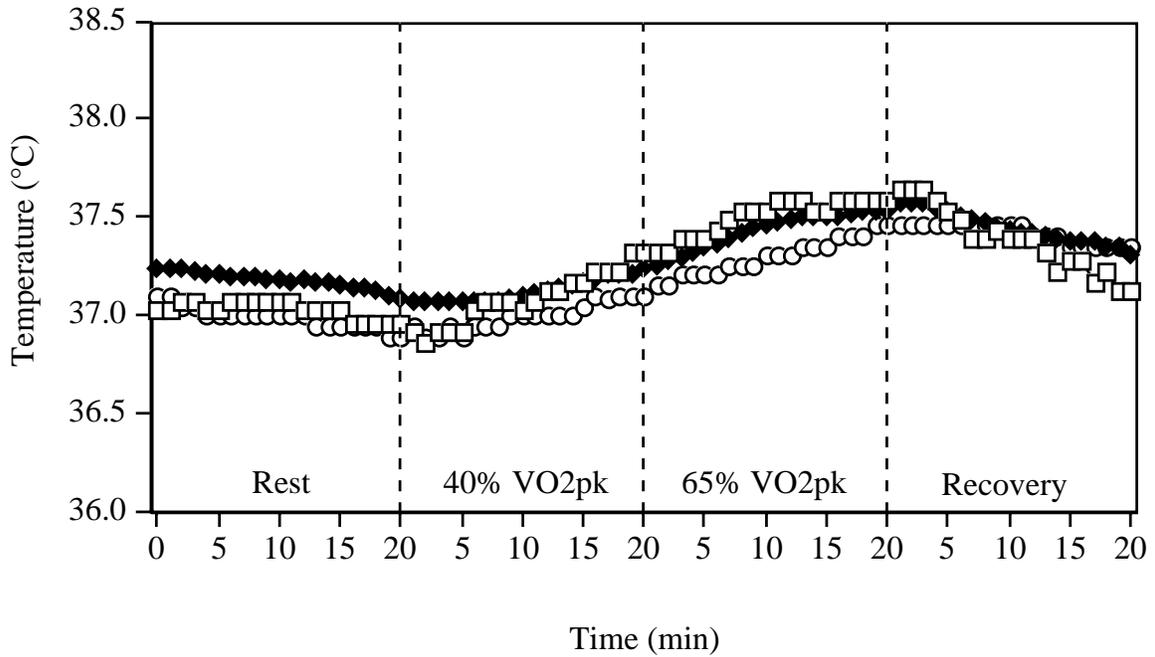
## APPENDIX D: INDIVIDUAL SUBMAXIMAL EXERCISE TEST RESULTS

### Subject 1

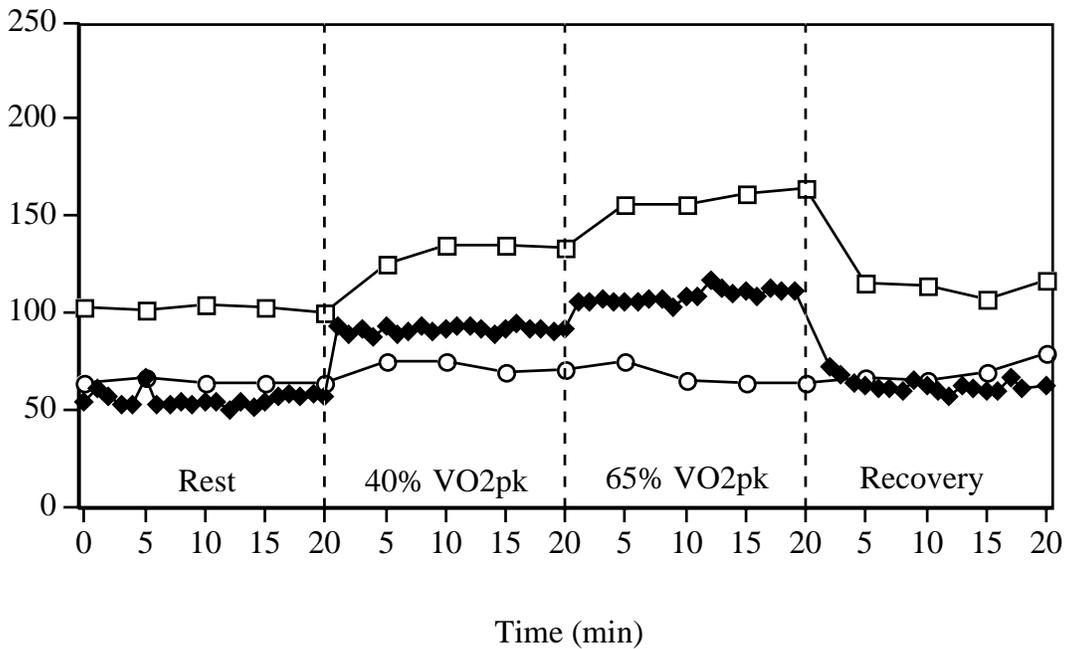
Time	Stage	T <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
0	Rest	37.08	37.10	37.26	55	104	65
1		37.03	37.10	37.24	62		
2		37.08	37.05	37.24	58		
3		37.08	37.05	37.23	53		
4		37.03	37.00	37.22	53		
5		37.03	37.00	37.21	67	102	68
6		37.08	37.00	37.20	53		
7		37.08	37.00	37.20	54		
8		37.08	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 <sub>2pk</sub>	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 <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
1	65% VO <sub>2pk</sub>	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



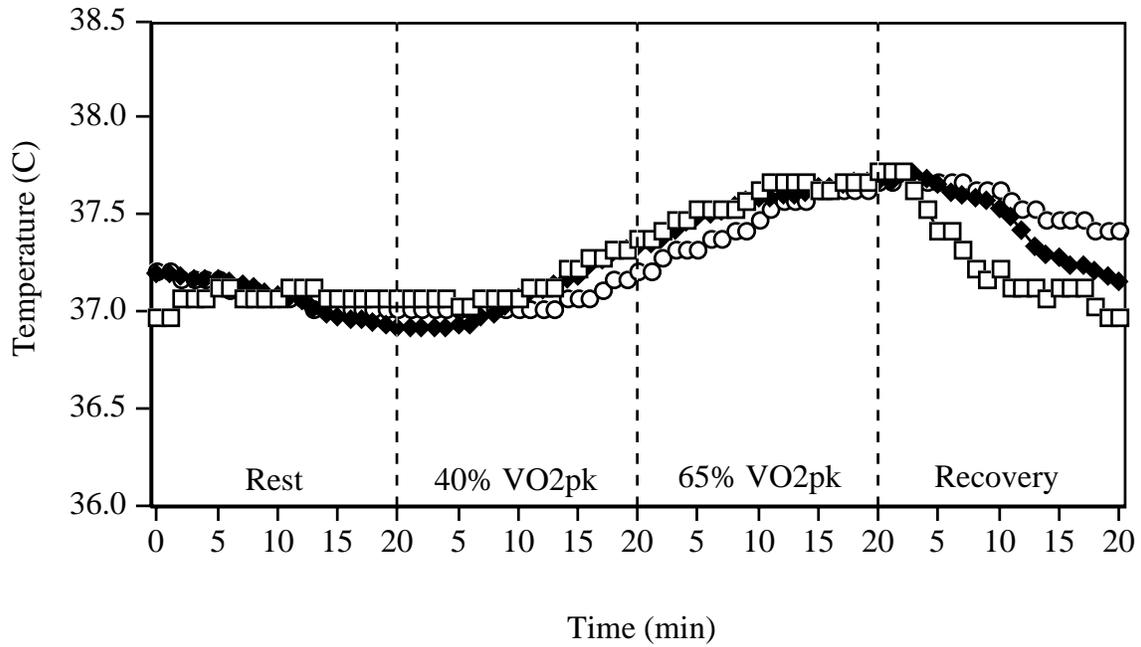
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 1

## Subject 2

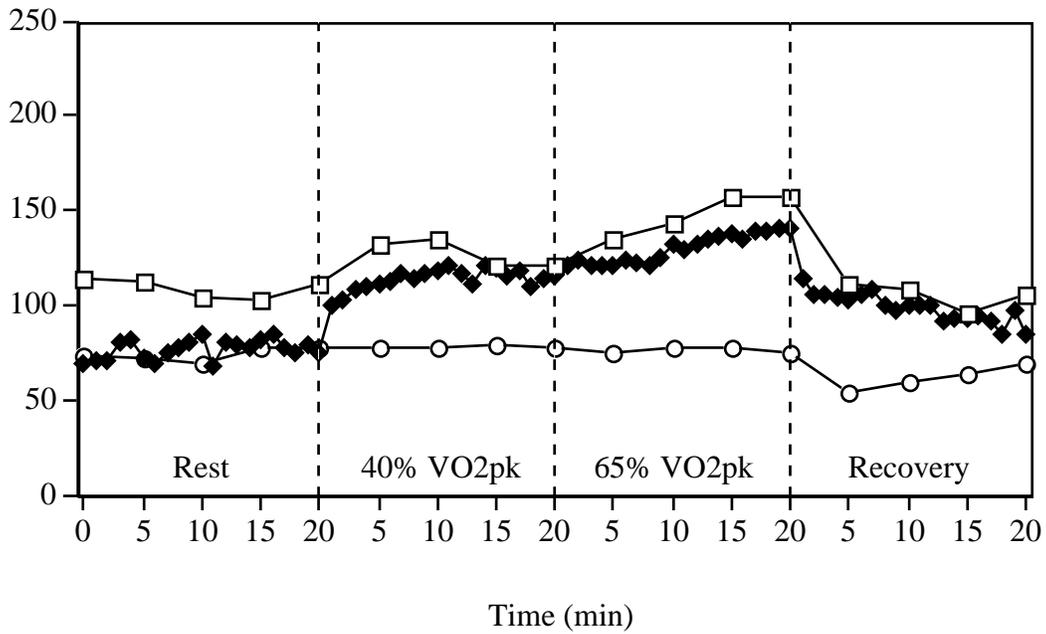
Time	Stage	T <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
0	Rest	36.98	37.22	37.20	70	115	74
1		36.98	37.22	37.20	72		
2		37.08	37.17	37.19	72		
3		37.08	37.17	37.18	81		
4		37.08	37.17	37.18	83		
5		37.13	37.17	37.18	73	113	73
6		37.13	37.12	37.16	70		
7		37.08	37.12	37.15	76		
8		37.08	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 <sub>2pk</sub>	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 <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
1	65% VO <sub>2pk</sub>	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



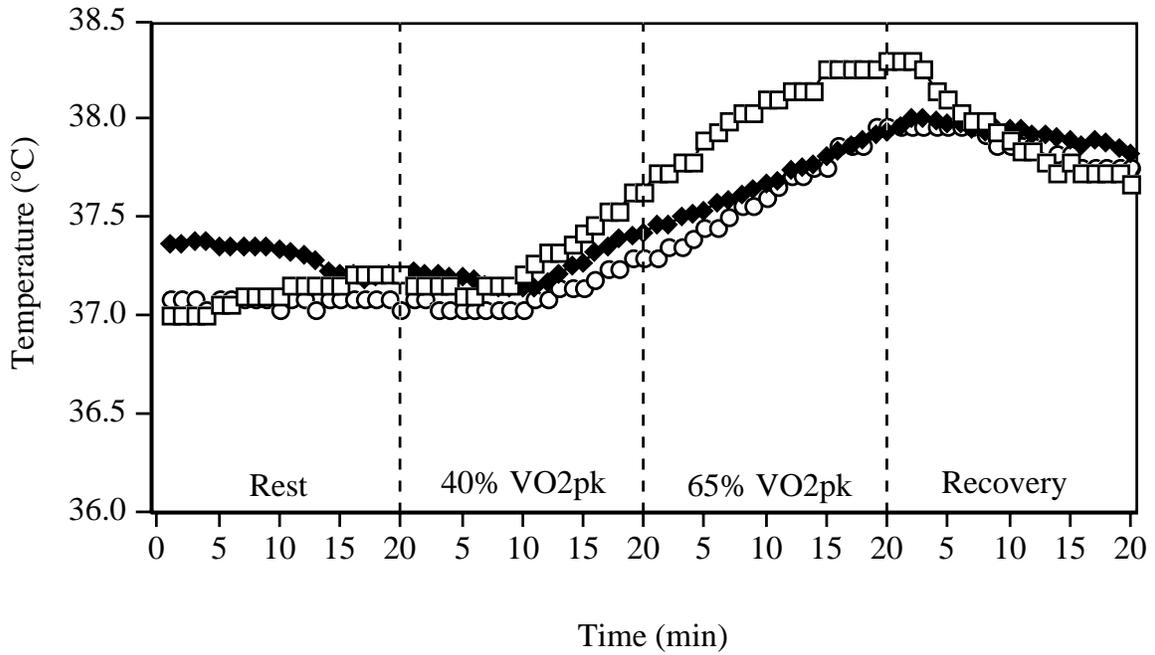
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 2

### Subject 3

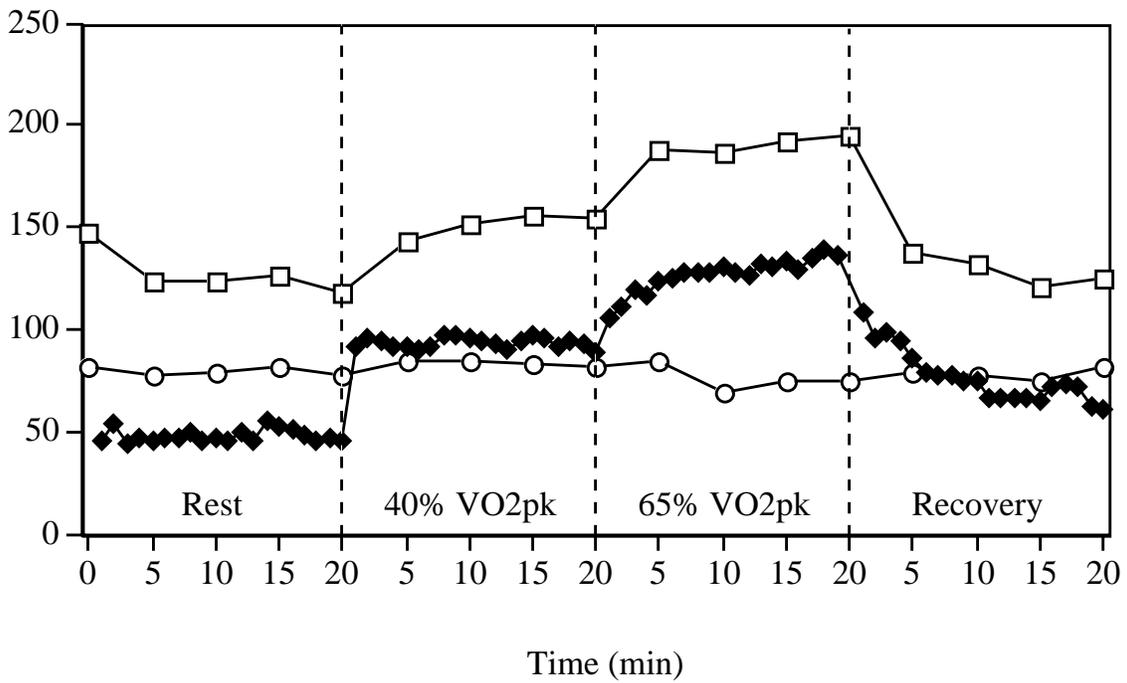
Time	Stage	T <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
0	Rest					148	82
1		37.01	37.09	37.37	46		
2		37.01	37.09	37.37	55		
3		37.01	37.09	37.38	45		
4		37.01	37.04	37.38	48		
5		37.06	37.09	37.36	47	124	78
6		37.06	37.09	37.35	48		
7		37.11	37.09	37.35	48		
8		37.11	37.09	37.35	51		
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 <sub>2pk</sub>	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 <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
1	65% VO <sub>2pk</sub>	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



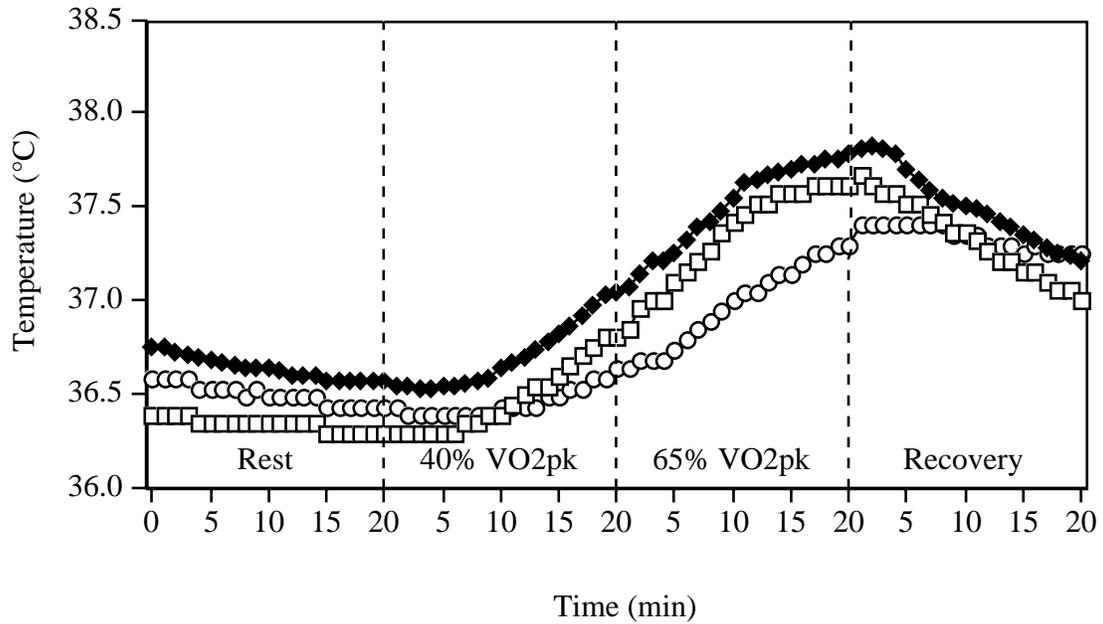
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 3

### Subject 4

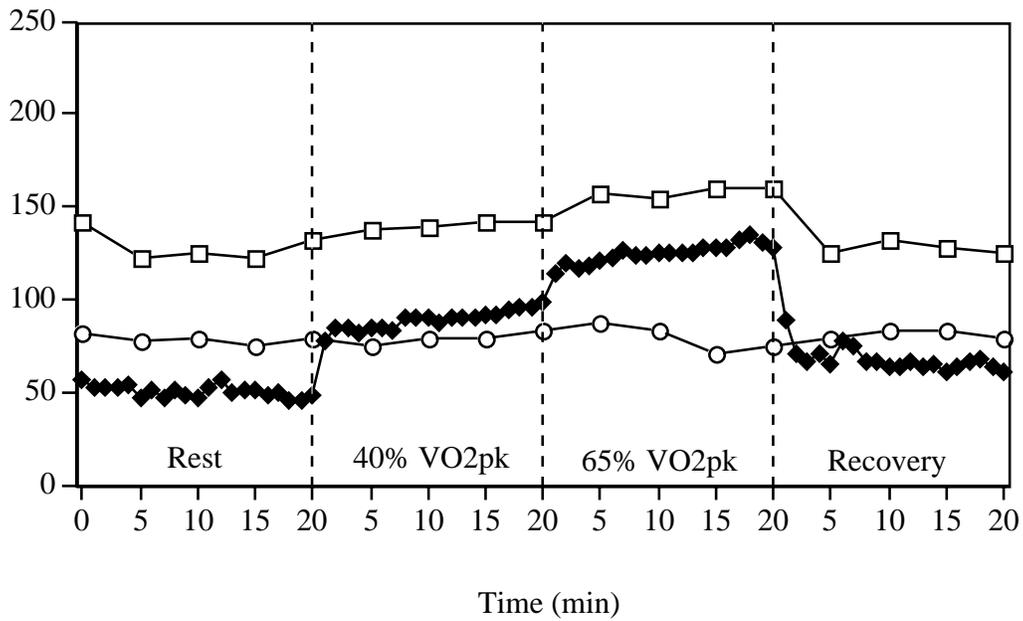
Time	Stage	T <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
0	Rest	36.40	36.59	36.76	57	142	82
1		36.40	36.59	36.75	54		
2		36.40	36.59	36.73	54		
3		36.40	36.59	36.72	54		
4		36.35	36.54	36.70	55		
5		36.35	36.54	36.69	48	123	78
6		36.35	36.54	36.67	52		
7		36.35	36.54	36.66	48		
8		36.35	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 <sub>2pk</sub>	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 <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
1	65% VO <sub>2pk</sub>	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



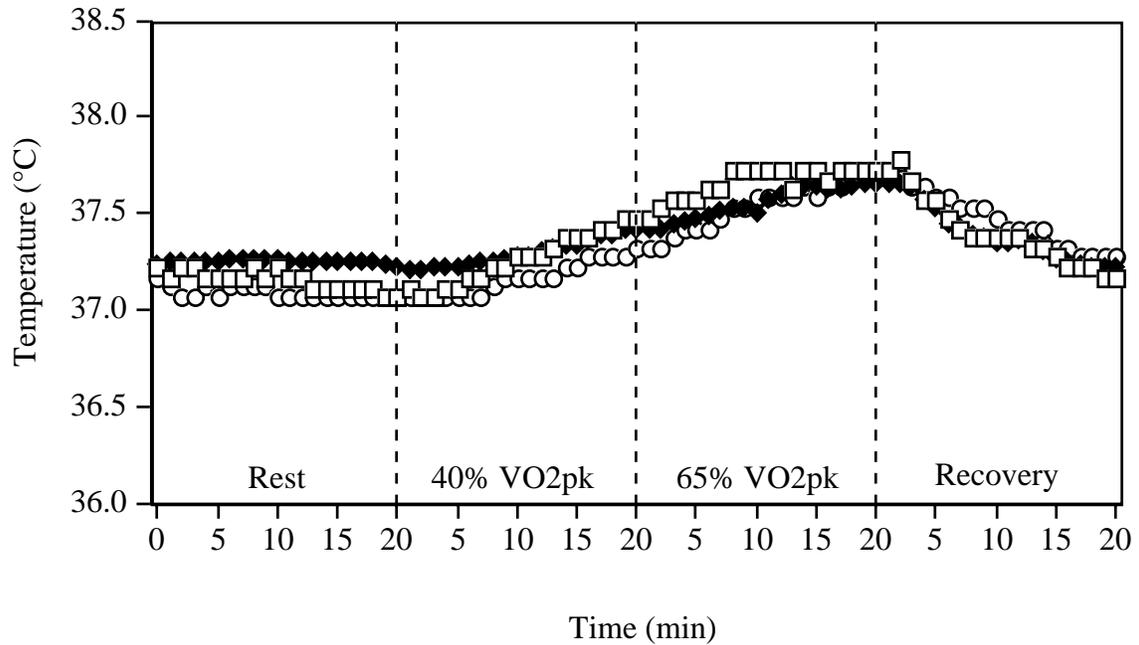
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 4

### Subject 5

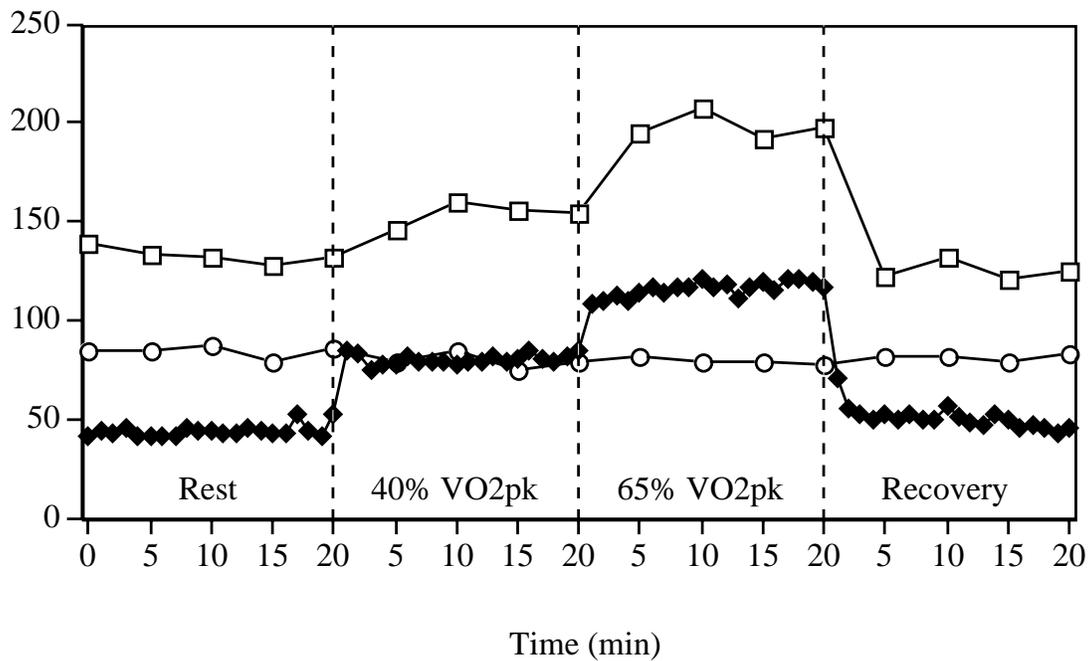
Time	Stage	Esoph.	Rectal	Intestinal	HR	SBP	DBP
0	Rest	37.23	37.18	37.24	43	140	85
1		37.17	37.13	37.25	45		
2		37.23	37.08	37.25	44		
3		37.23	37.08	37.25	46		
4		37.17	37.13	37.26	43		
5		37.17	37.08	37.26	43	134	86
6		37.17	37.13	37.27	42		
7		37.17	37.13	37.27	42		
8		37.23	37.13	37.27	47		
9		37.17	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 <sub>2pk</sub>	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 <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
1	65% VO <sub>2pk</sub>	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



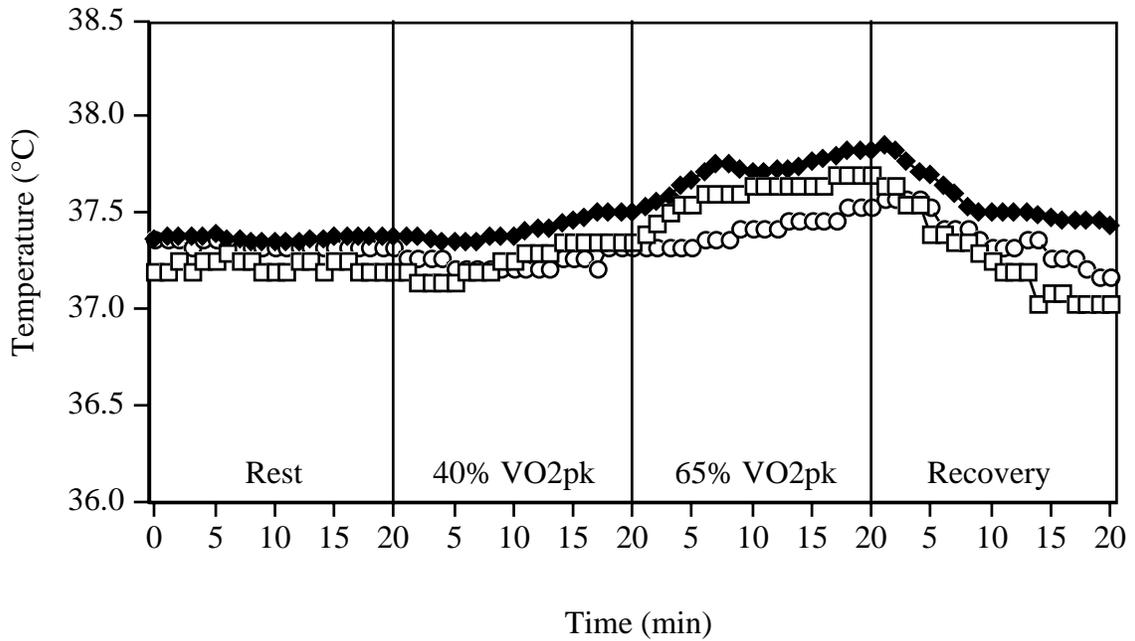
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 5

### Subject 6

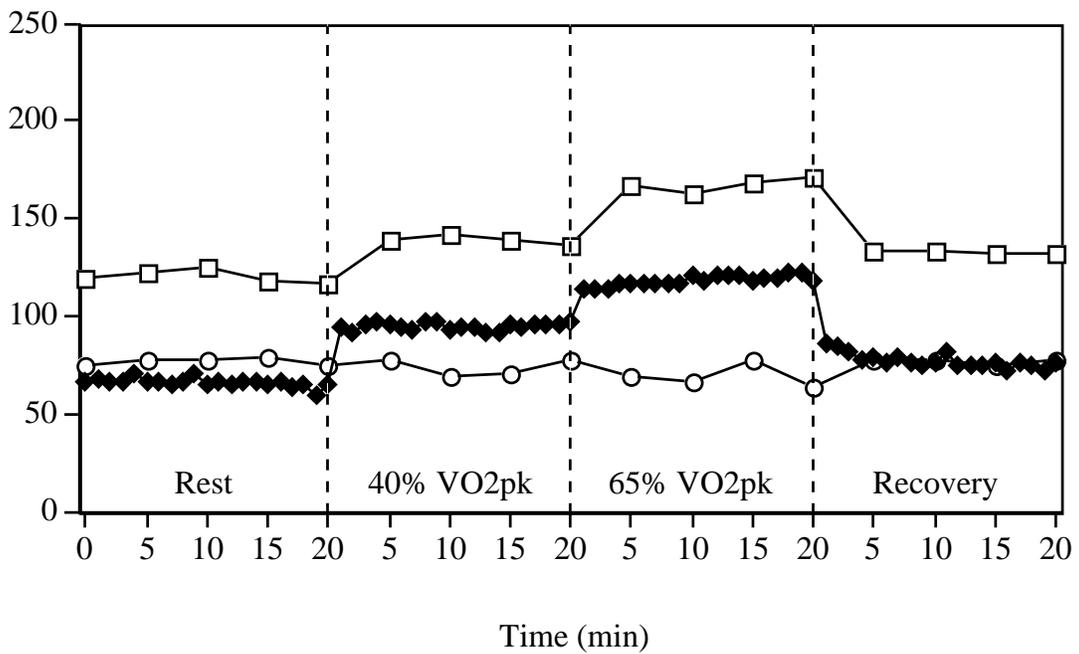
Time	Stage	T <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
0	Rest	37.20	37.37	37.37	68	120	75
1		37.20	37.37	37.38	69		
2		37.25	37.37	37.38	68		
3		37.20	37.32	37.38	67		
4		37.25	37.37	37.38	72		
5		37.25	37.37	37.39	67	123	78
6		37.30	37.32	37.37	67		
7		37.25	37.32	37.37	66		
8		37.25	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 <sub>2pk</sub>	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 <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
1	65% VO <sub>2pk</sub>	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



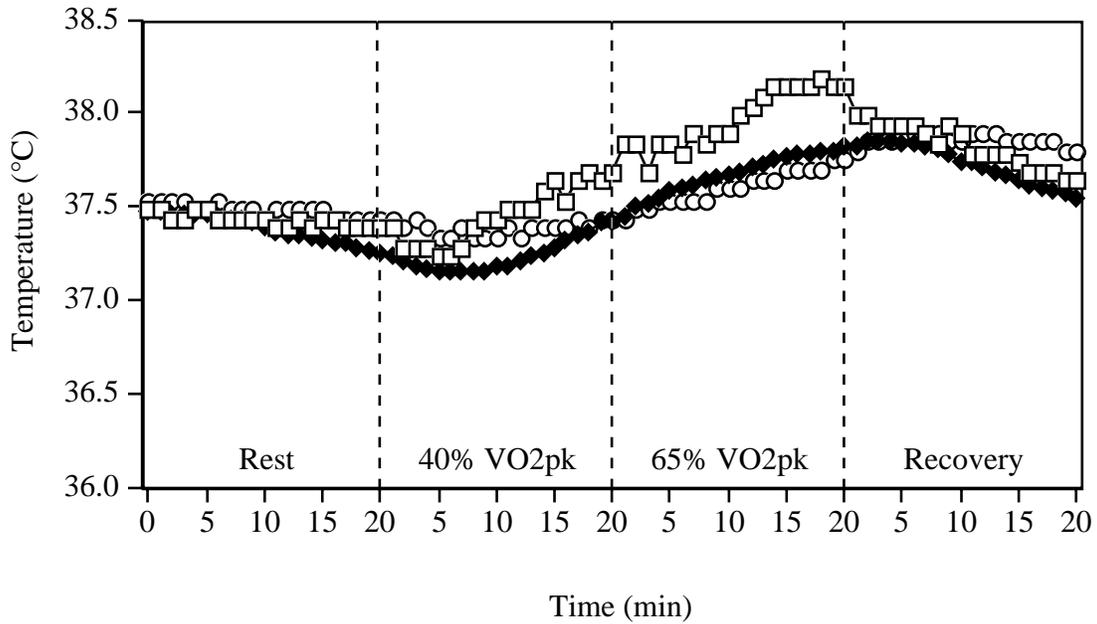
Heart rate (solid diamond), systolic blood pressure (open square), and diastolic blood pressure (open circle) during submaximal exercise in subject 6

### Subject 7

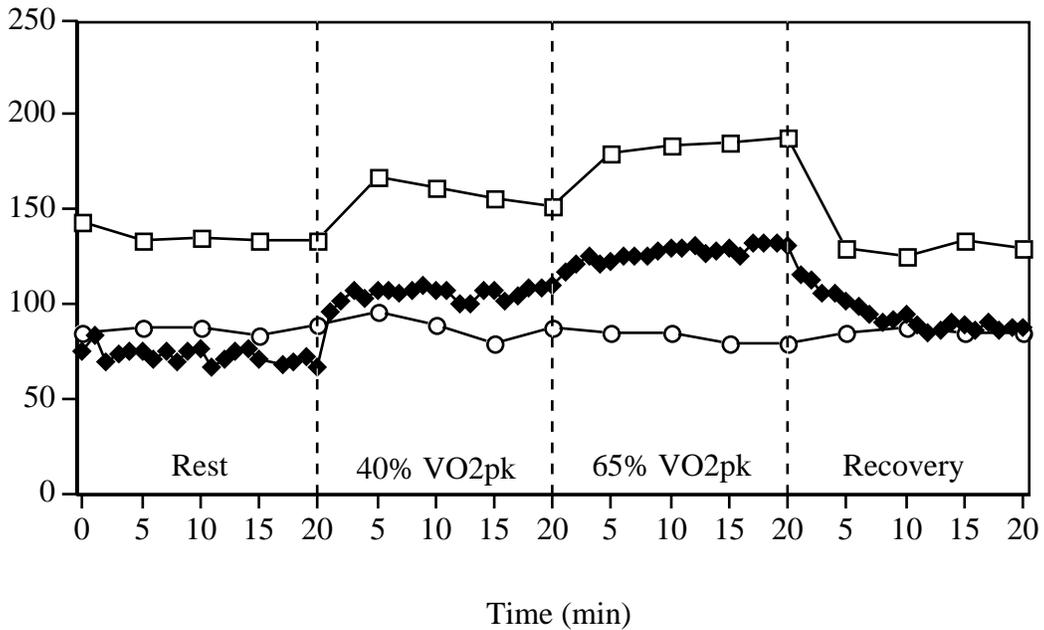
Time	Stage	T <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
0	Rest	37.49	37.54	37.48	75	144	86
1		37.49	37.54	37.48	84		
2		37.44	37.54	37.47	70		
3		37.44	37.54	37.47	74		
4		37.49	37.49	37.47	76		
5		37.49	37.49	37.46	75	134	88
6		37.44	37.54	37.45	72		
7		37.44	37.49	37.44	75		
8		37.44	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 <sub>2pk</sub>	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 <sub>es</sub>	T <sub>rec</sub>	T <sub>in</sub>	HR	SBP	DBP
1	65% VO <sub>2pk</sub>	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



REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE April 2000	3. REPORT TYPE AND DATES COVERED NASA Technical Paper		
4. TITLE AND SUBTITLE Core Temperature Measurement During Submaximal Exercise: Esophageal, Rectal, and Intestinal Temperatures			5. FUNDING NUMBERS	
6. AUTHOR(S) Stuart M.C. Lee*, W. Jon Williams*, Suzanne M. Schneider				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lyndon B. Johnson Space Center Houston, Texas 77058			8. PERFORMING ORGANIZATION REPORT NUMBERS S-859	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER TP-2000-210133	
11. SUPPLEMENTARY NOTES * Wyle Laboratories, Houston, TX 77058-2787				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Available from the NASA Center for AeroSpace Information (CASI) 7121 Standard Hanover, MD 21076-1320			12b. DISTRIBUTION CODE  Subject Category 52	
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.				
14. SUBJECT TERMS life sciences; body measurement; temperature measurement; measurement; bioinstrumentation; bioassay; flight stress; thermoregulation; exercise			15. NUMBER OF PAGES 57	16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	



---