J. therm. Biol. Vol. 18, No. 4, pp. 203–210, 1993
Printed in Great Britain

0306-4565/93 $6.00 + 0.00
Pergamon Press Ltd

VALIDATION OF A TEMPERATURE TELEMETRY SYSTEM DURING MODERATE AND STRENUOUS EXERCISE

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(Received 1 February 1993; accepted 8 May 1993)

Abstract—1. Esophageal temperature [T_{es} (18.0 ± 6.1 min)] and pill temperature [T_{hti} (25.3 ± 9.1 min)] reached steady state faster ($P < 0.05$) during moderate exercise (40 min at 40% peak $\dot{V}_{O_2}$) than rectal temperature [T_{re} (37.3 ± 4.6 min)] at $T_a = 29°C$, $T_{dp} = 11°C$. Steady-state exercise temperatures were lower for $T_{es} = 37.18 \pm 0.18°C$ and $T_{hti} = 37.20 \pm 0.32°C$ than $T_{re} = 37.46 \pm 0.15°C$ ($P < 0.05$).

2. During moderate exercise the change in core temperature per time (slope) was greater ($P < 0.05$) for T_{es} ($0.050 \pm 0.013°C\ min^{-1}$) than T_{hti} ($0.031 \pm 0.014°C\ min^{-1}$) and T_{re} ($0.018 \pm 0.005°C\ min^{-1}$). During intense exercise the change in T_{es} per minute was twice that for T_{hti} and 5 times that for T_{re}.

3. Overall, T_{hti} tracked dynamic changes in core temperature significantly faster than T_{re}, although T_{hti} did not track dynamic changes as well or as consistently as T_{es}. The concept of using a temperature sensor in a pill may be useful clinically, but mobility of the pill makes this temperature measurement less suitable for research than esophageal or rectal temperature measurements.

Key Word Index: Exercise; telemetry; body temperature; human

INTRODUCTION

The measurement of core temperature for research purposes of clinical safety is generally done using either esophageal or rectal temperature. Both temperatures are reproducible and not biased by environmental temperature (Brengelmann, 1987; Gerbrandy *et al.*, 1954; Mead and Bonmanto, 1949); however, the slow response time of rectal temperature is well documented (Eichna *et al.*, 1951; Gerbrandy *et al.*, 1954; Kolka *et al.*, 1987; Mittleman and Mekjavic, 1988; Molnar and Read, 1974). Telemetry systems offer a means to monitor core temperature using a swallowed "pill" as a sensor which transmits temperature information outside of the body. This technology is useful, especially for monitoring the safety of subjects in situations where, either clothing fully encapsulates the subject, prolonged monitoring is required or hardwiring is not possible (Mackay, 1970; Wolff, 1961). Telemetry technology has been used previously in human subjects to measure core temperature in various experimental protocols (Fox *et al.*, 1961; Gibson *et al.*, 1981; Mittal *et al.*, 1991; Sparling *et al.*, 1992).

Before a telemetry system using a swallowed pill can be judged as an appropriate substitute or replacement for other indices of core temperature, comparisons must be made to acceptable, accurate techniques. Brengelmann (1987) suggested that a measured index of core temperature must: (1) accurately reflect hypothalamic temperature as the hypothalamus is the site of the thermoregulatory controller; (2) the temperature must respond rapidly and accurately to changes in brain temperature; (3) the temperature must not be influenced by changes in environmental temperature; and (4) the measurement should be reliable, easy to use and harmless to the test volunteer.

Eichna *et al.* (1951) reasoned that the temperature of blood in the left ventricle would be the best approximation of what they called "critical deep tissue" temperature, equating this temperature with the temperature of the central thermoreceptors in the brain (Bazett, 1951). It was noted that rectal temperature was not a satisfactory index of rapidly changing internal temperature because changes in T_{re} occurred after heat loss or heat production effectors were activated during body heating or cooling (Eichna *et al.*, 1951). However, rectal temperature was appropriate during "steady state" conditions (Eichna *et al.*, 1951). Both oral and esophageal temperature respond rapidly to changes in body temperature, and both oral and esophageal temperature reflect the temperature at the central thermoreceptors (Gerbrandy *et al.*,

1954). Esophageal temperature is an ideal method for tracking blood temperature in the right heart as it most accurately reflects the integrated temperature of the pre-optic/anterior hypothalamus. Consequently, it responds very quickly to dynamic changes in mean body temperature (Brengelmann, 1987; Gerbrandy *et al.*, 1954; Rowell, 1983; Shiraki *et al.*, 1986, 1988).

The purpose of this study was to compare how well a commercially available temperature telemetry system tracked rapid and absolute changes in core temperature compared with esophageal and rectal temperatures during exercise.

MATERIALS AND METHODS

Eight males volunteered to serve as test subjects after they were informed of the purpose, procedures and known risks of this study. Each signed a consent form describing the study which was approved by appropriate human use review committees. Their mean ($\pm$SD) age was 20 ($\pm$2) years, height was 1.77 ($\pm$0.08) m, mass was 80 ($\pm$2) kg, surface area was 2.00 ($\pm$0.10) m^2, peak $\dot{V}_{O_2}$ was 46 ($\pm$5) ml min^{-1}.

Peak aerobic power (peak $\dot{V}_{O_2}$) was determined for each volunteer (SensorMedics 2900) during continuous resistance work on a cycle ergometer which was modified so that the volunteer pedalled the ergometer as he sat in a chair attached behind the ergometer. The power output was increased approximately 30 W every 2 min until the volunteer could no longer continue pedalling at 60 rpm or when he voluntarily quit pedalling. Peak $\dot{V}_{O_2}$ was designated when oxygen uptake did not change more than 150 ml with increased ergometer resistance. Individual peak $\dot{V}_{O_2}$ was used to calculate the relative work intensity for each experiment.

Three methods were used to measure core temperature: rectal temperature (T_{re}), esophageal temperature (T_{es}) and pill temperature [CorTemp™, Human Technologies, St Petersburg, Fla., ingestible temperature sensor (T_{hti})]. Rectal temperature was measured at a depth of 10 cm past the anal sphincter in the rectum using a calibrated J-type YSI thermistor (Yellow Springs, Ohio). Esophageal temperature was measured at a pre-determined location in the esophagus deemed the "hot spot". The "hot spot" was located by systematically determining temperature in the esophagus beginning at approximately 25% of each volunteer's height until the temperature was at a peak, presumably due to the proximity to the great vessels of the heart. Esophageal temperature was measured using a calibrated 28-gauge copper–constantan thermocouple encased in PE-200 polyethylene tubing (Clay-Adams) which was sealed at one end with dental epoxy. The CorTemp™ telemetry system included an ingestible temperature sensor (2 by 1.3 cm in dia), FM antenna and data recorder system. The calibrated temperature sensor included a silver oxide battery (1.5 V) which provided the power for sensing and transmitting temperature. The components of the sensors were encapsulated in epoxy and covered with silicone rubber. Temperature was transmitted through the body to a double bandoleer-type antenna and recorded by a data logger.

All exercise testing occurred between 0930 and 1200 h. Upon arrival at the laboratory the volunteer swallowed the telemetry pill with water, ate a light breakfast and then inserted the rectal and esophageal temperature probes. Two ($\pm$0.5) hours after swallowing the pills the volunteer was taken to the environmental test chamber to complete the exercise experiment.

The ambient temperature in the environmental test chamber was 29.5 $\pm$ 0.6°C and the dew point temperature was 11.4 $\pm$ 1.0°C. Upon entering the test chamber the volunteer was weighed, the antenna for the telemetry system was attached to his torso, and then he sat in a chair which was positioned behind the cycle ergometer. T_{es}, T_{re} and T_{hti} were measured every 30 s throughout the experiment. Heart rate was measured at 5 min intervals by electrocardiography. A 15 min rest period preceded exercise.

After rest, the volunteer exercised for 40 min at 40% peak $\dot{V}_{O_2}$. When T_{es} stabilized during moderate exercise, the volunteer drank 100 ml of water so that it could be determined whether the pill was still in the stomach. Volunteers A and B were given drinks at ~15 and 30 min of exercise, but the remaining 6 volunteers (C–H) drank only once, at ~20 min of exercise.

Following moderate exercise there was another 15 min rest period. To test whether the telemetry system accurately tracked rapid changes in core temperature, there were three cycles of intense exercise (80% peak $\dot{V}_{O_2}$) for 5 min interspersed with 5 min rest periods. During intense exercise, heart rate was measured every minute. The total length of each experiment was 100 min.

Resting and exercise temperatures, the change in core temperature, the time to steady-state, and the slopes of the individual regression equations (temperature by time) were compared by analysis of variance with repeated measures. When significant differences were identified by analysis of variance ($P < 0.05$), Tukey's test of critical differences was used for *post hoc* comparison.

RESULTS

Figures 1 and 2 show core temperature and heart rate responses. These figures demonstrate the variable temperature response from the swallowed pill in these 2 subjects and represent observations from all 8 subjects. The heart rate responses shown in the bottom panels of Figs 1 and 2 demonstrate the changes in exercise intensity during these experiments. The mean passage time for the telemetry pills was 30.4 ± 8.9 h.

The average resting temperatures were lower for $T_{es} = 36.66 \pm 0.26$°C and $T_{hu} = 36.75 \pm 0.29$°C than $T_{re} = 36.94 \pm 0.22$°C ($P < 0.05$, Table 1). The average steady-state exercise temperatures during moderate exercise were lower for $T_{es} = 37.18 \pm 0.18$°C and $T_{hti} = 37.20 \pm 0.32$°C than $T_{re} = 37.46 \pm 0.15$°C ($P < 0.05$). There was no difference in the change in core temperature from rest to steady-state exercise for the three indices of core temperature. However, the time to reach a steady-state temperature during moderate exercise was faster ($P < 0.05$, Table 2) for T_{es}

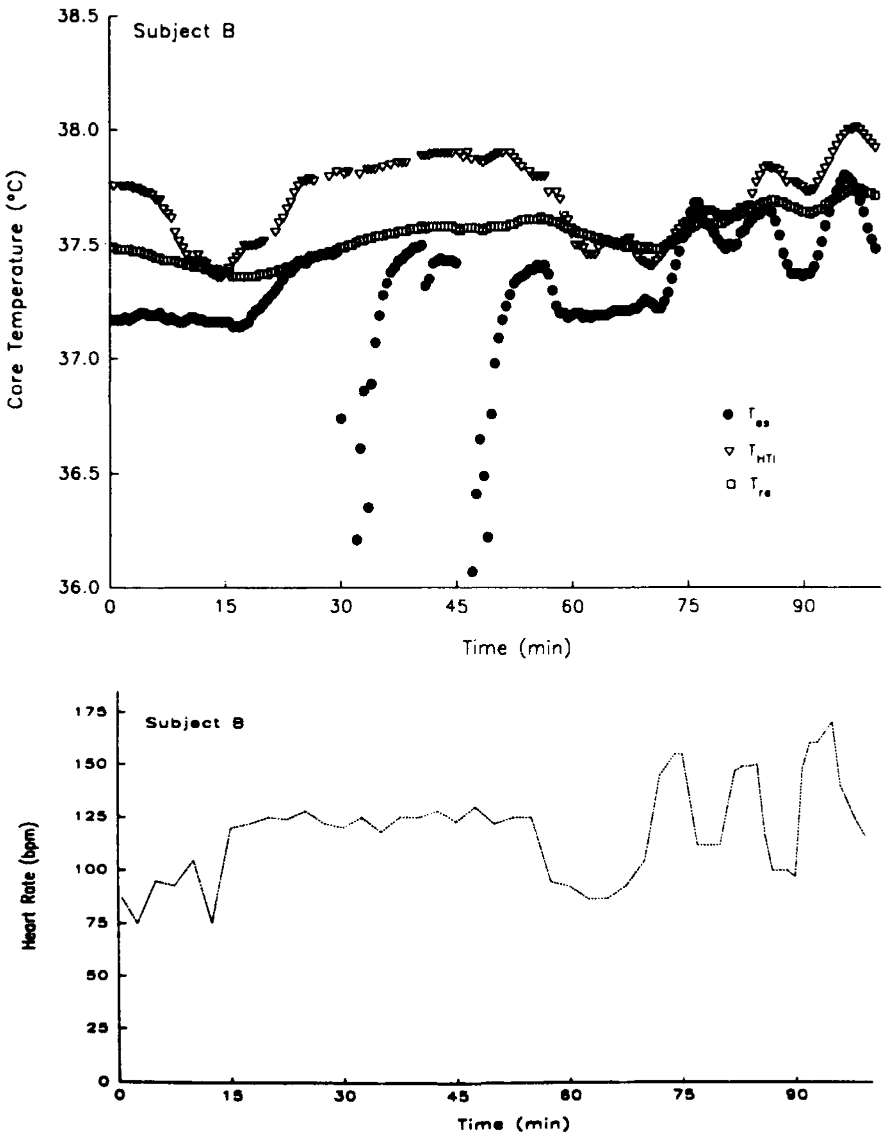

Fig. 1. Esophageal temperature (°C), pill temperature (°C) and rectal temperature (°C) during rest, moderate exercise and intense exercise for a single subject (B) during the 100 min experiment. Moderate exercise started at 15 min, and the heart rate response indicates the cycles of rest and exercise. The times of water ingestion are clearly shown by the decrease in esophageal temperature during moderate exercise.

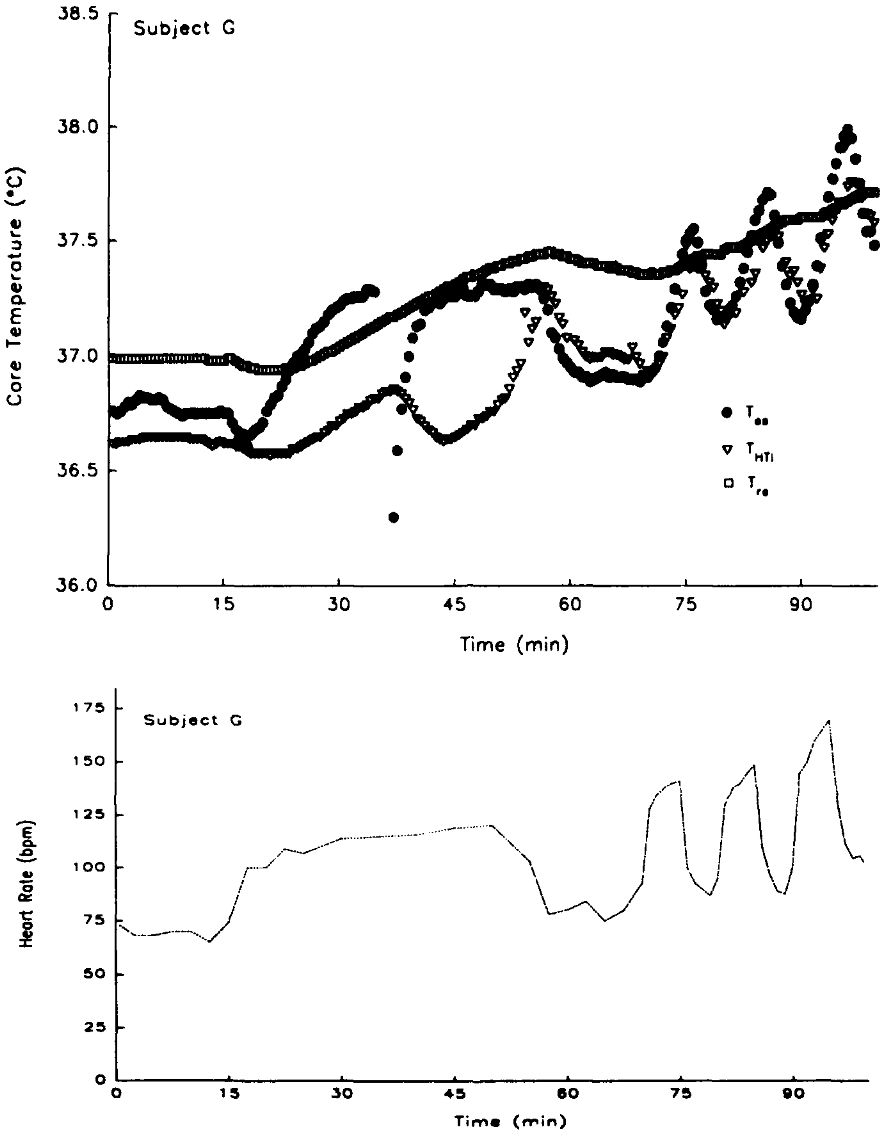

Fig. 2. Esophageal temperature (°C), pill temperature (°C) and rectal temperature (°C) during rest, moderate exercise and intense exercise for a single subject (G) during the 100 min experiment. Moderate exercise started at 15 min, and the heart rate response indicates the cycles of rest and exercise. The time of water ingestion is clearly shown by the decrease in esophageal temperature during moderate exercise.

(18.0 ± 6.1 min) than T_{hti} (25.2 ± 9.1 min) and T_{re} (37.3 ± 4.6 min).

During the third cycle of intense exercise, T_{es} = 37.65 ± 0.23°C, T_{hti} = 37.65 ± 0.31°C and T_{re} = 37.72 ± 0.13°C, however the change in temperature during the entire 100 min experiment was 0.99 ± 0.19°C for T_{es}, 0.91 ± 0.26°C for T_{hti} and 0.78 ± 0.21°C for T_{re}, with T_{es} greater than T_{re} ($P < 0.05$, Table 3). The rate of increase in core temperature (°C min^{-1}) during moderate exercise was higher ($P < 0.05$, Table 4) for T_{es} (0.050 ± 0.013°C min^{-1}) than T_{hti} (0.031 ± 0.014°C min^{-1}) or T_{re} (0.018 ± 0.005°C min^{-1}). During intense exercise T_{es} (0.112 ± 0.028°C min^{-1}) increased faster than T_{hti} (0.066 ± 0.035°C min^{-1}) or T_{re} (0.018 ± 0.009°C min^{-1}) ($P < 0.05$, Table 4).

To more specifically evaluate the response of each of the three temperature indices, the time to observe a 0.1°C change during exercise or rest from exercise was calculated. T_{es} increased 4.4 ± 2.7 min after the start of moderate exercise compared to 7.5 ± 4.8 min for T_{hti} and 12.3 ± 3.0 min for T_{re}

Table 1. Individual core temperatures (°C) during equilibrated rest, steady-state moderate exercise and the third cycle of intense exercise

	Rest			Moderate exercise			Intense exercise		
Ss	T_{es}	T_{hti}	T_{re}	T_{es}	T_{hti}	T_{re}	T_{es}	T_{hti}	T_{re}
A	36.56	36.48	36.81	37.11	36.95	37.44	37.71	37.38	37.78
B	37.16	37.36	37.38	37.46	37.79	37.58	37.79	38.01	37.74
C	36.39	36.77	36.98	37.31	37.30	37.71	37.43	37.31	37.72
D	36.65	36.46	36.88	37.16	37.16	37.42	37.61	37.62	37.71
E	36.62	36.65	36.89	36.91	36.82	37.20	37.44	37.33	37.57
F	36.81	36.96	36.99	37.21	37.32	37.51	37.88	38.08	37.96
G	36.75	36.62	36.98	37.29	36.86	37.43	37.99	37.86	37.71
H	36.32	36.66	36.60	37.00	37.37	37.38	37.36	37.62	37.56

T_{es}, esophageal temperature; T_{hti}, pill temperature; T_{re}, rectal temperature.

($P < 0.05$, Table 5). After 40 min of moderate exercise, a decrease of 0.1°C in core temperature was detected after 2.3 ± 0.5 min for T_{es} compared to 6.5 ± 3.1 min for T_{hti} and 12.2 ± 3.3 min for T_{re} ($P < 0.05$). During the first cycle of intense exercise, a 0.1°C increase occurred by 1.8 ± 0.8 min for T_{es} compared to 3.8 ± 1.5 min for T_{hti} ($P < 0.05$). T_{re} had not changed by the end of 5 min of exercise compared to the rest period between moderate and intense exercise.

DISCUSSION

The primary purpose of this study was to evaluate whether or not the temperature pill telemetry system was a reliable and an accurate index of core temperature. Therefore, pill temperature was extensively compared to esophageal temperature and rectal temperature. At rest, pill temperature was not different from esophageal temperature, but was 0.2°C lower than rectal temperature, a trend which continued during moderate exercise. Esophageal and rectal temperature were measured in this study because esophageal temperature responds rapidly to changes in body temperature (Brengelmann, 1987; Gerbrandy *et al.*, 1954; Rowell, 1983; Shiraki *et al.*, 1986, 1988) and rectal temperature is an adequate index of core temperature during steady-state conditions (Eichna *et al.*, 1951). Tympanic or auditory meatus temperature has been used as an index of internal body temperature in laboratory studies (Baker *et al.*, 1972; Greenleaf and Castle, 1972; Sharkey *et al.*, 1987; Shiraki *et al.*, 1986, 1988). The main detraction for using tympanic temperature and the reason this index was not used in the current study, is that tympanic temperature more reliably tracks skin temperature than core temperature in humans (Greenleaf and Castle, 1972; Sharkey *et al.*, 1987; Shiraki *et al.*, 1986). Initially, tympanic temperature was used because it responded similarly to brain temperature in the monkey and the cat (Baker *et al.*, 1972), and it was proposed that tympanic temperature was the best core temperature index in humans because it more accurately reflects hypothalamic temperature and would also account for selective brain cooling (Brinnel and Cabanac, 1989; Cabanac, 1986; Cabanac and

Table 2. Individual times (minutes from the start of exercise) for core temperatures to equilibrate during steady-state moderate exercise

	Moderate exercise		
Ss	T_{es}	T_{hti}	T_{re}
A	15.5	35.5	40.5
B	12.5	11.0	26.5
C	31.5	32.0	40.0
D	12.0	31.0	37.0
E	18.5	17.0	37.0
F	19.0	19.0	38.5
G	18.5	22.0	39.5
H	16.5	43.0	39.5

T_{es}, esophageal temperature; T_{hti}, pill temperature; T_{re}, rectal temperature.

Table 3. Individual change in core temperature (°C) from rest to the peak temperature observed during intense exercise

Subject	T_{es}	T_{hti}	T_{re}
A	1.15	0.90	0.97
B	0.63	0.65	0.36
C	1.04	0.54	0.74
D	0.96	1.16	0.83
E	0.82	0.68	0.68
F	1.07	1.12	0.97
G	1.24	1.24	0.73
H	1.04	0.96	0.96

T_{es}, esophageal temperature; T_{hti}, pill temperature; T_{re}, rectal temperature.

Table 4. Individual slopes ($^{\circ}C\ min^{-1}$) for core temperatures during steady-state moderate exercise and during the first cycle of intense exercise

	Moderate exercise			Intense exercise		
Ss	T_{es}	T_{hti}	T_{re}	T_{es}	T_{hti}	T_{re}
A	0.053	0.028	0.020	0.049	0.055	0.026
B	0.028	0.037	0.010	0.100	0.038	0.022
C	0.054	0.026	0.025	0.121	0.090	0.000
D	0.050	0.060	0.017	0.107	0.050	0.014
E	0.040	0.018	0.015	0.123	0.049	0.018
F	0.049	0.036	0.016	0.128	0.122	0.022
G	0.052	0.021	0.018	0.130	0.098	0.014
H	0.072	0.019	0.022	0.138	0.015	0.027

T_{es}, esophageal temperature; T_{hti}, pill temperature; T_{re}, rectal temperature.

Caputa, 1979). However, the existence of selective brain cooling in humans has not been proven and remains highly controversial (Cabanac, 1986; Nadel, 1987; Wenger, 1987). In fact, Jessen and Kuhnen (1992) recently reported evidence against selective brain stem cooling in humans.

The only published report (Sparling *et al.*, 1992) comparing this telemetry pill with rectal temperature showed a greater difference between pill temperature and rectal temperature at rest and during exercise compared with the present study (0.4 and 0.8°C, respectively in that study). The differences between reports may be due to differences in experimental design, variation in pill mobility or location, presence of water in the stomach, or meal ingestion. In some of our experiments, pill temperature was abnormally low during moderate exercise (subjects E & G), possibly because there was water in the stomach. However, the pill response improved markedly as the experiment continued, presumably because the pill moved out of the stomach. Also, in one of the experiments, pill temperature was greater than rectal temperature throughout the experiment (subject B). So there was individual variability in pill temperature compared with both rectal temperature and esophageal temperature in these experiments, a condition which would prevent prediction of esophageal or rectal temperature from pill temperature.

In this study, pill temperature was not different than the other core temperature indices during intense exercise, and the total change in pill temperature during the 100 min experiment was not significantly different than esophageal temperature or rectal temperature. However during moderate exercise, although pill temperature reached steady-state faster than rectal temperature, it responded to changes in body temperature significantly slower than esophageal temperature. In addition, during transitions from rest to exercise and back to rest, pill temperature changes faster than rectal temperature, but slower than esophageal temperature. Overall, our analyses indicate that the ingested pill tracked rapid changes in core temperature better than rectal temperature, although not as well or as consistently as esophageal temperature. For example, pill temperature (Fig. 1) decreased during rest, and the responsiveness of the pill differed (Fig. 2) with progressive exercise, both observations due to changing location in the gastrointestinal tract.

Rectal temperature as an index of core temperature, is useful when an individual is in thermal equilibrium (Eichna *et al.*, 1951; Gerbrandy *et al.*, 1954; Kolka *et al.*, 1987; Mittleman and Mekjavic, 1988; Molnar and Read, 1974) and data from the current study indicate that rectal temperature lags behind esophageal temperature by 12–25 min. Even though the moderate exercise period was 40 min, it often took this entire exercise period for rectal

Table 5. Time (min) to observe a 0.1°C increase or decrease in core temperature during 40 min of steady-state moderate exercise, 15 min of rest following moderate exercise and 5 min of intense exercise

	Moderate exercise			Rest			Intense exercise		
Ss	T_{es}	T_{hti}	T_{re}	T_{es}	T_{hti}	T_{re}	T_{es}	T_{hti}	T_{re}
A	9.0	0.5	12.5	3.0	11.0	15.0	2.0	4.0	5.0
B	5.5	2.5	13.5	3.0	3.5	11.0	3.5	3.0	5.0
C	2.0	13.0	13.0	2.0	3.0	15.0	1.0	2.5	5.0
D	3.0	6.0	11.0	2.5	6.5	11.0	1.0	4.0	5.0
E	4.0	8.5	15.0	2.0	10.5	15.0	2.0	4.0	5.0
F	1.5	7.0	10.0	2.0	3.5	9.0	2.0	3.0	5.0
G	7.5	15.0	16.5	2.0	6.5	15.0	2.0	2.5	5.0
H	3.0	7.5	7.0	2.0	7.5	6.5	1.0	7.0	5.0

T_{es}, esophageal temperature; T_{hti}, pill temperature; T_{re}, rectal temperature. If the temperature did not change by the end of the appropriate period, the time for the entire exercise or rest period was entered.

temperature to equilibrate. However, the mean change in core temperature during moderate exercise was measured as effectively by rectal temperature as by either other core temperature index. On the other hand, these experiments show that rectal temperature was often changing in an opposite direction from esophageal temperature during transitions from exercise to rest and back to exercise. These are not new findings, and we emphasize that during exercise in a hot environment, a delay in detecting a substantial increase in core temperature by using rectal temperature might contribute to heat injury.

In conclusion, the telemetry system as a core temperature data acquisition system was reliable provided that preliminary screening by water bath calibration eliminated those sensors (pills) which measured temperature inaccurately. For the most part, the telemetry system accurately measured core temperature with the drawback that mobility of the pill in the GI tract caused changes in both the absolute temperature and the temperature response characteristics which made pill temperature less reliable than either rectal or esophageal temperature.

The concept of using a temperature sensor in a pill (Wolff, 1961) may be useful clinically, but mobility of the pill makes this temperature measurement less suitable for research than either esophageal or rectal temperature measurements. Based on 8 experiments (100 min), changing anatomical location of the pill resulted in an inappropriate change of 0.2–0.3°C in at least 2 experiments. Temperature pills should not be used for research from which decisions will be made regarding heat storage differences between conditions because an inappropriate change in core temperature of 0.2–0.3°C could confound findings.

Acknowledgements—The authors are indebted to the volunteers who performed in these experiments. We gratefully acknowledge the technical support provided by Ms P. Burgoon, Mr B. Cadarette, Ms L. Levine, SGT W. Latzka, SSG P. Gutierrez, Ms D. Cohen, Ms A. Tarentino and Ms G. Carrubba. We also thank the medical monitors, CPT J. Cook, MAJ M. Reardon and LTC W. Curtis. The views, opinions and/or findings contained in this report are those of the authors and should not be construed as official Department of the Army position, policy or decision, unless so designated by other Official documentation. Human subjects participated in these studies after giving their free and informed consent. Investigators adhered to Army Regulation 70-25 and United States Army Medical Research and Development Command Regulation 70-25 on the Use of Volunteers in Research. Approved for public release; distribution unlimited. Funding for this study was provided, in part, by the Joint Working Group of the Physiological and Psychological Effects of the NBC Environment and Sustained Operations on Systems in Combat (P^2NBC^2) program of the U.S. Army Chemical School. The temperature telemetry system was supplied by COL D. Redmond, Chief, Special Studies Branch, Department of Behavioral Psychology, WRAIR, in support of the funding agency, P^2NBC^2.

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