Journal of Exercise Physiologyonline
(JEPonline)

Volume 12 Number 1 February 2009

Official Research Journal of the American Society of Exercise Physiologists (ASEP)

ISSN 1097-9751

Equipment Testing and Validation

UTILITY OF AN INGESTIBLE CAPSULE FOR CORE TEMPERATURE MEASUREMENTS DURING BODY WARMING

HERMANN-J. ENGELS[1], HOSSEIN N. YARANDI[2], JEAN E. DAVIS[2]

[1]Exercise Physiology Lab/ Division of Kinesiology, Health and Sport Studies / College of Education / Wayne State University, Detroit, USA [2,]Center for Health Research / College of Nursing / Wayne State University, Detroit, USA

ABSTRACT

Engels HJ, Yarandi HN, Davis JE. Utility of an ingestible capsule for core temperature measurements during body warming. ***JEP****online* 2009;12(1):1-9. This study compared core temperature (T_c) measurements to active and passive body warming between rectal thermometry and a new ingestible capsule system. Eight healthy adult women participated in two 30-min warming trials consisting of moderate intensity leg cycle ergometry exercise (active body warming, ABW) and a controlled 40°C whole body bath (passive body warming, PBW). Changes in T_c were assessed concurrently using a telemetric, ingestible capsule sensor system (TCS) (Jonah™ capsule, Vitalsense®, Mini Mitter, Bend, OR) and standard rectal thermometry (RTS) (YSI 4600 with YSI 401 rectal probe, YSI, Yellow Springs, OH). A significant difference in T_c recordings between TCS and RTS in ABW and PBW was observed. Significant interactions of subjects' T_c and time indicated that the pattern of change was not the same among subjects. Examination of the plots of T_c vs. time revealed the existence of a proportional bias in all the cases. Regressing T_c on time and comparing the slopes revealed a significant difference in slope coefficients between TCS and RTS for ABW and PBW. However, using the statistical procedures by Bland and Altman (1-3), a good overall agreement between measurement methods was noted. It is concluded that the TCS offers a useful T_c index but is more responsive to active and passive body warming induced rises in T_c than the RTS. Also, cool fluid intake can sometimes produce transient reductions in TCS T_c readings long after initial ingestion. These findings have implications in the context of thermoregulatory status assessments of humans exposed to heat stress.

Keywords: Ingestible Sensor, Heat Stress, Thermoregulation.

INTRODUCTION

It is widely acknowledged that an accurate assessment of human core temperature (T_c) poses numerous challenges. In the past, a number of measurement sites (e.g., rectum, mouth, esophagus, external auditory meatus, and tympanic membrane) have been examined for their potential use but none of them can be regarded as ideal (18,20). While esophageal and rectal T_c measurements are widely considered "gold standard" techniques to monitor and evaluate changes in T_c under many conditions, concerns about their invasive nature, practicality, and lack of acceptability by people in general, often limit their utility (6). There continues to be a need to develop other suitable methodologies that can be used in both the laboratory and field setting to assess human T_c for a wide range of research and clinical applications (6,18).

Historically, one such approach has focused on the development of small-sized, ingestible temperature sensing devices that, once they are swallowed, can telemetrically transmit a temperature signal from inside the body to an external receiving unit for data display or storage. Although a variety of these "ingestible pill" systems have been developed over the years, the utility of only one of them (CorTemp™, HQ Inc, Palmetto, FL) has been studied in depth to date (6). Many experts now consider this emerging technology as the method of choice to monitor human T_c for a wide variety of laboratory and field-based applications (6,9,10,12,14,19).

Recently, as a component of a broader based integrated physiological monitoring system (VitalSense®, Mini Mitter, Bend, OR), a new ingestible T_c capsule sensor called the Jonah™ capsule has been introduced. McKenzie and Osgood (16), in the only published validation study of this system so far, concluded that it is as accurate as rectal T_c measurements for use in normal ambulatory adults. These researchers noted that the mean T_c difference, as assessed simultaneously by the two methods for the duration of the passage of the Jonah™ capsule through their subjects' digestive tract was only 0.04°C (±0.03°C). On the other hand, important differences in T_c readings between methods became evident at times when subjects were engaged in exercise (16). This observation may have important implications for researchers and clinicians interested in using this technology to evaluate human thermoregulatory responses with exercise and other heat stress conditions. Therefore, the present study served to assess the utility of the Jonah™ capsule coupled with the VitalSense® physiological monitoring system for the evaluation of T_c under controlled laboratory conditions of both an endogenously (active body warming, ABW; constant-load cycle exercise at 75% of HR_{max}) and exogenously (passive body warming, PBW; 40°C whole body bath) induced thermal challenge.

METHODS

Subjects

Eight adult women participated in this study. A review of their medical history and health status indicated they were free of history or evidence of cardiovascular disease, stroke, musculoskeletal problems, gastrointestinal disorders, GI surgery, and abnormalities in swallowing. Since the Jonah™ capsule sensor contains ferromagnetic materials that are incompatible with magnetic resonance imaging, subjects agreed not to undergo any MRI procedures throughout the duration of their study participation. The university's institutional review board approved the research and written informed consent was obtained from all participants before they were enrolled in the study.

Procedures

Experimental tests were conducted in the evening under controlled research laboratory conditions. Each session consisted of an initial 10 min quietly seated rest period to establish normothermic

baseline values, which was followed by a 30-min experimental body warming experiment. Active body warming (ABW) consisted of leg cycle (Monark 818, Varberg, Sweden) ergometry exercise at 75% of each subject's age-predicted maximal heart rate (22). Passive body warming (PBW) consisted of a seated whole body bath in a stainless steel, full body hydrotherapy tank (Model T, H.M.100-48; Ille Electric Corp, Williamsport, PA). During each PBW trial, the subject's body stayed submerged in water up to the level of the suprasternal notch. Bath water temperature was set at 40°C and kept within 0.15°C throughout each test using a custom-made, manually controlled, water flow exchange system. Subjects wore shorts, shirt, and aquatic sport sandals in ABW and a one-piece swimming suit in PBW test sessions. Heart rates throughout each trial were monitored continuously using a Polar S810i heart rate monitor and Wearlink transmitter chest strap (Polar Electro Inc, Woodbury, NY). The order of the two body warming trials was randomly assigned and spaced between one to two weeks apart.

Changes in body core temperature under both experimental test conditions were assessed using the following procedures. To measure rectal temperature each subject self-inserted a YSI 401 rectal probe (YSI, Yellow Springs, OH) to a depth of 7 cm beyond the anal sphincter (20), as was indicated by a tape attached to the cable. The rectal probe cable was then secured to the skin on the lower back with medical tape to prevent slippage and connected to a factory calibrated precision thermometer (YSI 4600 Series, YSI, Yellow Springs, OH). This thermometer/probe system has a specified accuracy of ± 0.015°C within the 30-50°C temperature range. Moreover, a RS-232 interface allowed rectal temperature data to be sent to a personal computer using a customized data acquisition software interface (ThermalView, Alpha Technics, Anaheim, CA).

Following the manufacturer's directions (17), the VitalSense® Integrated Physiological Monitoring System was first configured to operate in standard mode and each self-calibrated Jonah™ capsule T_c sensor was activated following an established, brief protocol. Each Jonah™ capsule arrived in an individual, factory-sealed package and is guaranteed by the manufacturer to be accurate within ±0.10°C within the range of 32°C to 42°C as established by a process traceable to the National Institute of Standards and Technology (17). A detailed description of the specifications of the Jonah™ capsule sensor, including key differences to the CorTemp™ capsule system is provided elsewhere (16).

After a telemetric check to confirm that the Jonah™ capsule was transmitting its temperature signal to the VitalSense® telemetric monitor, which for data logging purposes has to be kept within 100 cm of the capsule sensor, each subject swallowed the activated capsule with 250 ml of water. To help assure that the capsule sensor was deeply embedded in the gastrointestinal tract but would not be expelled before completion of data collection (16), it was administered 8 hours before the start of laboratory testing. During this initial time period, the subjects wore the lightweight VitalSense® telemonitor in a waist pouch while pursuing their normal daily activities. Subsequently, during the ABW and PBW laboratory experiments, the monitor was removed from the pouch and affixed to a custom-made, portable small platform kept next to each subject. While study participants were allowed to eat and drink up to 1 hour before the start of an experimental session, they were asked to avoid large-sized meals since it has been shown to reduce a capsule's transit time throughout the body (16). Moreover, since preliminary experiments from this laboratory had revealed T_c readings of the Jonah™ capsule were sometimes affected by cold (5°C) water intake over prolonged time periods after its initial ingestion and assumed exit from the stomach (16), subjects were also not allowed any fluid intake throughout the duration of each laboratory test session. For purpose of this study, the two body core temperature measurement systems were synchronized in time to provide temperature data in consecutive 60-sec sampling intervals throughout each test session.

Statistical Analyses

The Statistical Analysis System (SAS, Version 9.1) was utilized for data analyses. Repeated measures ANOVA was used to examine the change in temperatures within subjects, between TCS and RTS temperatures, and within-subjects-by-between temperatures interaction in active and passive body warming trials. Data from the final minute of the initial quietly seated rest period served to establish each subject's normothermic T_c baseline level. Regression analysis was used to examine the difference in the slopes of the lines representing TCS and RTS temperatures. Since there were replicate measurements by each method on each subject, the procedures described by Bland and Altman (1-3) were used to examine the overall agreement between recorded body core temperatures. These procedures examine the differences between subjects and within subjects variances. All values are reported as means ± standard deviations. A p value of <0.05 was considered statistically significant.

Table 1. Physical characteristics of study participants (mean ± SD).

	Subjects (n=8)
Age (yrs)	55.3±5.9
Stature (cm)	160.4±6.0
Body Mass (kg)	70.8±12.5

RESULTS

The basic physical characteristics of the eight women in this study are shown in Table 1. Mean baseline heart rates at rest were 70.5±5.2 in ABW and 71.1±5.2 in PBW trials (p>0.05). During ABW, heart rates increased gradually over the first 5 minutes of exercise and thereafter remained steady at 126.8 ±7.8 beats/min until the end of the exercise trial. In contrast, during PBW heart rates steadily rose in linear fashion from the first (81.2 ±6.6 beats/min) to the last (109.4±13.0 beats/min) minute of the intervention.

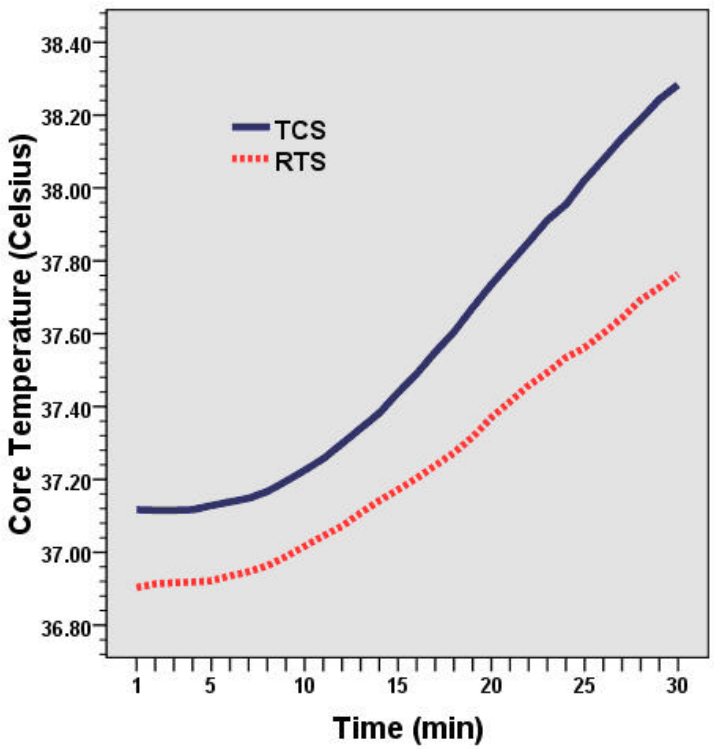

Figure. 1. Mean rectal (RTS) and ingestible capsule (TCS) core temperature recordings during 30-min of active body warming.

Resting normothermic T_c values were similar in ABW (36.91±0.27°C) and PBW (37.02±0.36°C) experiments, but were significantly different between RTS (36.85±0.27°C) and TCS (37.08±0.33°C) T_c measurement methodologies ($p < 0.01$). Similarly, repeated measures ANOVA indicated a significant difference in temperature recordings between TCS and RTS in ABW ($F = 15.29$, $p < 0.01$) and PBW ($F = 57.72$, $p < 0.01$) warming trials. Significant interactions of subjects' temperatures and time indicated that the pattern of change was not the same among the subjects. Examination of the plots of temperatures vs. time revealed the existence of a proportional bias in all the cases (i.e., at lower temperatures, the absolute values of the differences were smaller than the differences in higher temperatures). Regressing the temperatures on time and comparing the slopes revealed a significant difference in slope coefficients between TCS and RTS for ABW ($t = 2.22$, $p =$

0.01) and PBW (t = 5.86, p < 0.01). Average T_c values during ABW rose from 37.03±0.29 °C at rest to 37.71±0.36°C at the end of the trial with the TCS monitoring system (+0.68°C) and from 36.78±0.18°C to 37.23±0.23°C with the RTS method (+0.45°C). During PBW, mean T_c recordings increased from 37.13±0.37°C to 38.31±0.28°C with the TCS method (+1.18°C) and from 36.91±0.33°C to 37.77±0.34°C with the standard RTS technique (+0.86°C). Figures 1 and 2 illustrate the average min-by-min core temperatures obtained by simultaneous RTS and TCS recordings during the 30-min active and passive body warming, respectively.

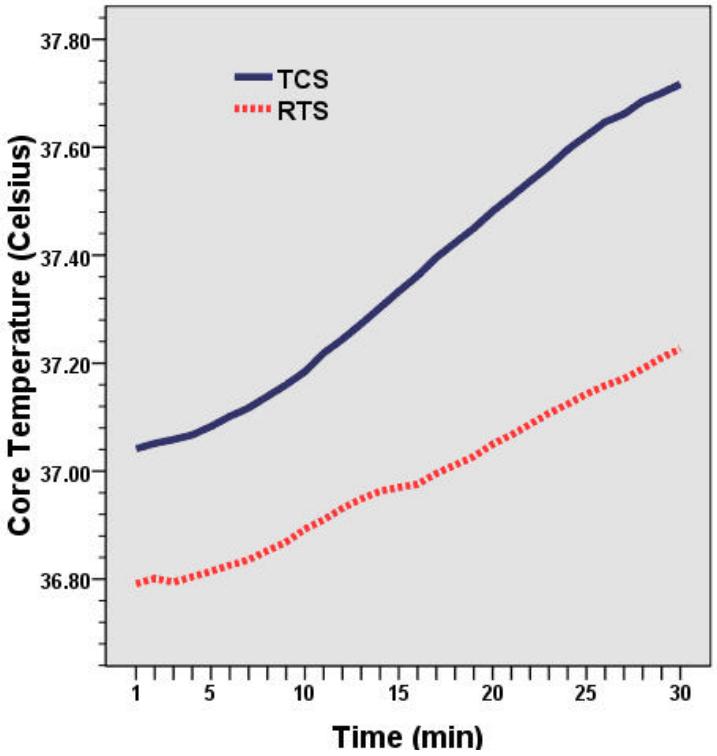

Figure 2. Mean rectal (RTS) and ingestible capsule (TCS) core temperature recordings during 30-min of passive body warming.

Using the procedures described by Bland and Altman (2,3) for determining the agreement between measurement methods with multiple observations per subjects, the 95% limits of agreement between TCS and RTS was estimated to be 0.32±0.58 for ABW and 0.14±0.82 for PBW. As indicated in the difference against average plots shown in Figures 3 and 4, the limits fit the data well. Moreover, high positive correlation coefficients (r) of 0.96 (p < 0.01) for ABW and 0.93 (p < 0.01) for PBW were found for within subjects' body temperatures recorded by TCS and RTS signifying an overall agreement (1).

DISCUSSION

The utility of telemetry-based, small ingestible sensors for the assessment of human body core temperature is of great interest for both research and clinical applications. As in previous validation studies involving the CorTemp™ ingestible capsule system (11-14,21), the present findings revealed a statistically significant bias between RTS derived T_c readings and the new Jonah™ ingestible capsule sensor system. Contrary to Kolka et al. (13) and Sparling et al. (21), who noted higher rectal T_c relative to intestinal T_c values at rest and during exercise, RTS T_c values in the present study were significantly lower than simultaneously determined TCS T_c data at baseline rest and throughout both active and passive body warming interventions. Recent findings by others (11,12,14) using the CorTemp™ capsule system under a variety of different experimental conditions are in general support of the direction of the systematic bias noted in the present study. It remains to be seen whether these differences are accounted for by biological or other variables (6).

McKenzie and Osgood (16) previously reported an excellent overall agreement in T_c measurements between the RTS and Jonah™ capsule method in a study of free-living, normal ambulatory adults who wore both systems from the moment of ingestion of the Jonah™ capsule until its disposal through the feces. These researchers, however, also noted that marked differences in T_c readings between the two techniques became apparent at times when subjects were engaged in strenuous exercise, with the rectal T_c of one subject exceeding intestinal T_c by 1.79°C during exercise in a hot environment. Under the controlled laboratory conditions of this study, involving both an endogenously (exercise metabolism) and exogenously (warm water bath) induced thermal challenge, no such instances of pronounced divergence between T_c measurement methods became apparent. As expected (13,14,19,21), both RTS and TCS T_c values gradually increased throughout the 30-min ABW and PBW test periods and they were significantly higher at the end of the PBW trials compared to ABW experiments. A regression of the T_c recordings on time and comparison of the slopes revealed a significant difference in slope coefficients between TCS and RTS for ABW and PBW. As shown in Figures 1 and 2, during both endogenous and exogenous body warming trials, TCS derived T_c readings overall increased at a faster rate compared to RTS derived T_c values. These findings agree with several earlier studies that employed the CorTemp™ capsule system and noted a slower response of rectal T_c compared to intestinal T_c with exercise (13,21). However, others have recently also reported similar response rates to various active and passive body warming challenges between rectal and CorTemp™ derived intestinal T_c (9,14,19). Further, it is important to note that using the procedures described by Bland and Altman (1-3) for paired data with multiple observations per subject, the present observations indicate overall there was a good agreement between the two core temperature measurement techniques.

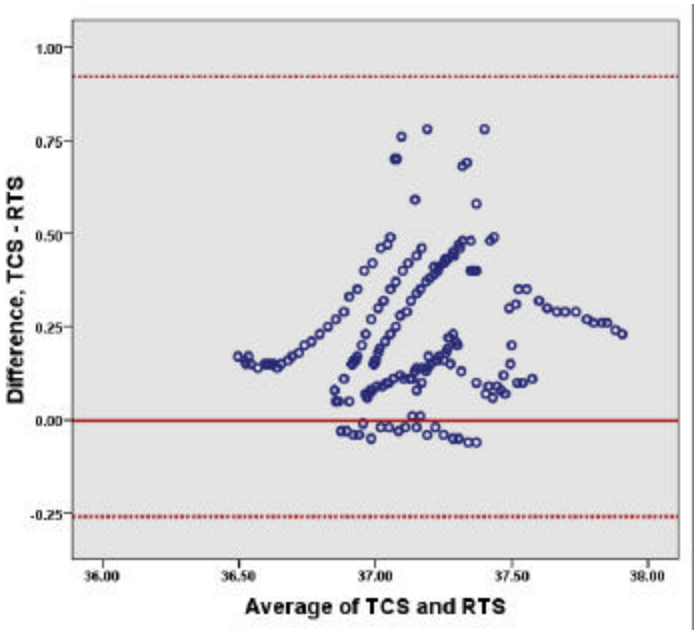

Figure 3. Average and difference in core temperature measurements between TCS and RTS during 30-min of active body warming.

It has been suggested that differences in T_c recordings between RTS and TCS technologies, including the observed variation in response rates to a thermal challenge, may be related to a number of variables, including differences in local tissue temperature, regional blood flow, exercise mode, body position, and posture during exercise (11-14,16,21). Questions remain regarding the possible impact of fluid or food intake, variations in capsule mobility, and the preferred timing of capsule ingestion relative to subsequent data collection (6,16,23). Based on our preliminary work leading up to the present study, the Jonah™

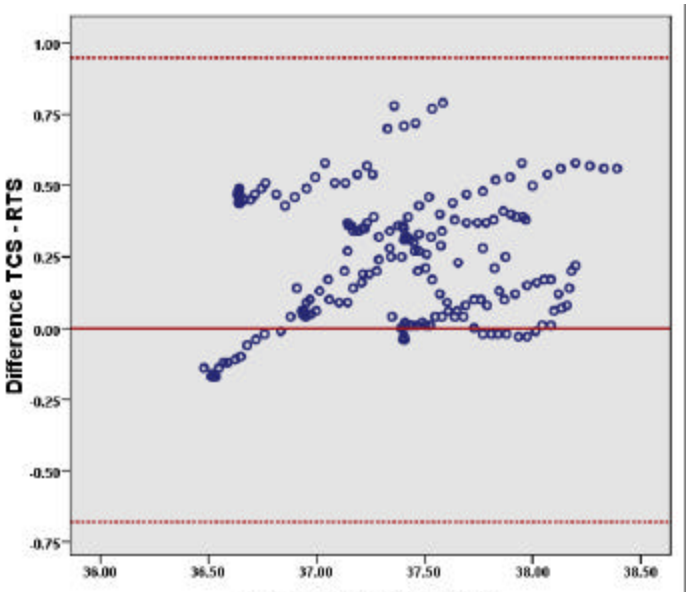

Figure 4. Average and difference in core temperature measurements between TCS and RTS during 30-min of passive body warming.

capsule was administered 8 hrs before testing to allow it to move deep into the gastrointestinal tract and subjects were not permitted the intake of fluids or foods within 1 hour of and throughout each experimental session. Interestingly, in two of the 16 trials underlying this investigation, the provision of 500 ml cool water within minutes of completing the intervention was associated with an abrupt T_c decrease of 3.02°C and 6.25°C, respectively, as measured with TCS, which was followed by a gradual return to normal values over time. Figure 3 illustrates the time course of one such event. These findings support recent observations by others (9,23) utilizing the CorTemp™ capsule system, and show that transient reductions in TCS T_c readings can occur at varying time points long after an ingested capsule has left the stomach and that they do not so in a readily predictable fashion for the same or between different subjects.

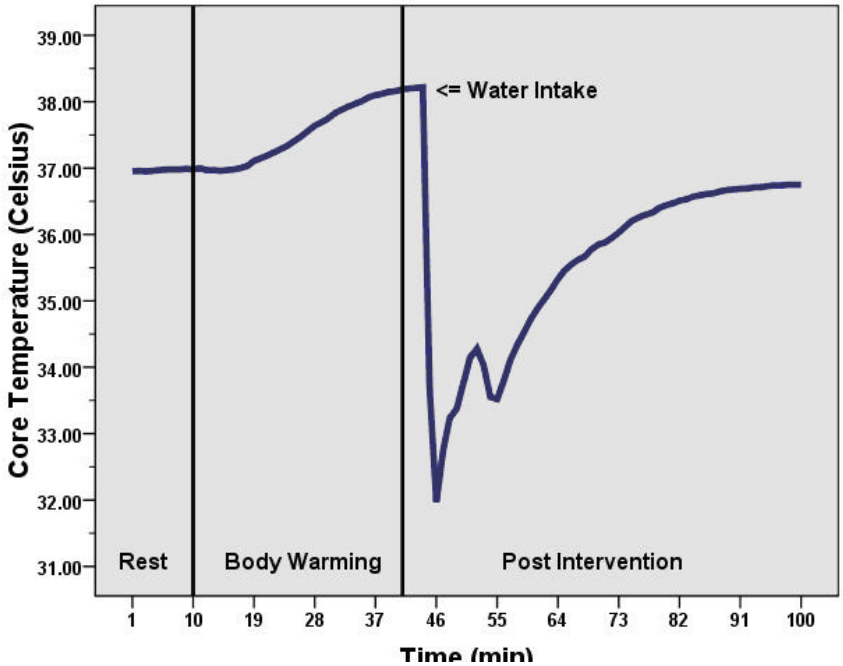

Figure 5. Effect of 500ml cool water intake on TCS temperature recordings in one subject about 9 hours after initial capsule ingestion immediately after completion of an experimental body warming session.

The present study was limited to a direct comparison of RTS and TCS derived measurements of T_c under controlled laboratory conditions involving an initial steady-rate normothermic rest period followed by 30 min of moderate exercise or water bath induced body warming. Similar to earlier studies (12-14,19,21) the ABW and PBW interventions did not approach the level of severe thermal strain that at times may be encountered in some occupational settings (4) or with prolonged exercise in the heat (5). Moreover, in the absence of a leveling-off and achievement of a new T_c plateau toward the end of the 30-min ABW and PBW intervention periods, it is not possible to determine from the present data if the magnitude of the T_c differences between measurement techniques that was noted for normothermic rest (TCS-RTS: 0.24 ± 0.27°C) will be similar at elevated body core temperature levels once the subjects reach a new steady-state T_c. There is a need for empirical research to establish the utility of the Jonah™ capsule system for these conditions.

CONCLUSIONS

The use of ingestible capsule technology is gaining considerable interest for the assessment of body core temperature responses in a wide variety of sport and exercise (5,10), military (7), industrial (4), and medical oriented (8,15) applications. Although the present study in general supports the utility of the new Jonah™ ingestible capsule system for the continuous measurement of T_c (16), findings of a significant positive bias in T_c readings and of differences in response rates to active and passive body warming challenges when compared to traditional "gold standard" rectal thermometry have implications for researchers and clinicians in situations that require a precise assessment of the thermoregulatory status of humans under heat stress conditions. Moreover, it appears that the intake of cool fluids should be avoided or carefully controlled when employing ingestible capsule technology to monitor body core temperature responses.

ACKNOWLEDGEMENTS

Supported by WSU Center for Health Research Collaborating Faculty Scholar Award and NIH/NINR R01 NR008024.

Address for correspondence: Engels HJ, PhD., Division of Kinesiology, Health and Sport Studies, 257 Matthaei Bldg., Wayne State University, Detroit, Michigan, 48202, USA. Phone (313) 577-5896; FAX: (313) 577-9301; Email. Engels@wayne.edu.

REFERENCES

1. Bland JM, Altman DG. Statistics Notes. Calculating correlation coefficients with repeated observations: Part 1 -- correlation within subjects. ***BMJ*** 1995; 310:446.

2. Bland JM, Altman DG. Measuring agreement in method comparison studies. ***Stat Methods Med Res*** 1999; 8:135-160.

3. Bland JM, Altman DG. Agreement between methods of measurement with multiple observations per individual. ***J Biopharm Stat*** 2007; 17:571-582.

4. Brake DJ, Bates GP. Deep body core temperature in industrial workers under thermal stress. ***J Occup Environ Med*** 2002; 44:125-35.

5. Byrne C, Lee JKW, Chew SAN, Lim CL, Tan EYM. Continuous thermoregulatory responses to mass-participation distance running in heat. ***Med Sci Sports Exerc*** 2006; 38:803-810.

6. Byrne C, Lim CL. The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. ***Br J Sports Med*** 2007; 41:126-133.

7. Castellani JW, Delany JP, O'Brien C, Hoyt RW, Santee WR, Young AJ. Energy expenditure in men and women during 54 h of exercise and caloric deprivation. ***Med Sci Sports Exerc*** 2006; 38:894-900.

8. Coyne MD, Kesick CM, Doherty TJ, Kolka MA, Stephenson LA. Circadian rhythm changes in core temperature over the menstrual cycle: method for noninvasive monitoring. ***Am J Physiol Regulatory Integrative Comp Physiol*** 2000; 279:R1316-R1320.

9. Easton C, Fudge BW, Pitsiladis YP. Rectal, telemetry pill and tympanic membrane thermometry during exercise heat stress. ***J Thermal Biol*** 2007; 32:78-86.

10. Edwards AM, Clark NA. Thermoregulatory observations in soccer match play: professional and recreational level applications using an intestinal pill system to measure core temperature. ***Br J Sports Med*** 2006; 40:133-138.

11. Edwards B, Waterhouse J, Reilly T, Atkinson G. A comparison of the suitabilities of rectal, gut and insulated axilla temperatures for measurement of the circadian rhythm of core temperature in field studies. ***Chronobiol Int*** 2002; 19:579-597.

12. Gant N, Atkinson G, Williams C. The validity and reliability of intestinal temperature during intermittent running. ***Med Sci Sports Exerc*** 2006; 38:1926-1931.

13. Kolka MA, Quigley MD, Blanchard LA, Toyota DA, Stephenson LA. Validation of a temperature telemetry system during moderate and strenuous exercise. ***J Thermal Biol*** 1993; 18:203-210.

14. Lee SMC, Williams WJ, Fourtney Schneider SM. Core temperature measurement during supine exercise: esophageal, rectal, and intestinal temperatures. ***Aviat Space Environ Med*** 2000; 71: 939-945.

15. Low DA, Vu A, Brown M, Davis SL, Keller DM, Levine BD, et al. Temporal thermometry fails to track body core temperature during heat stress. ***Med Sci Sports Exerc*** 2007; 39:1029-1035.

16. McKenzie JE, Osgood DW. Validation of a new telemetric core temperature monitor. ***J Thermal Biol*** 2004; 29:605-611.

17. Mini Mitter. ***VitalSense*** *Integrated Physiological Monitoring System Instruction Manual* (Part Number 910-0500-02). Bend, OR: Mini Mitter; 2005.

18. Moran DS, Mendal L. Core temperature measurement: Methods and current insights. ***Sports Med*** 2002; 32: 879-885.

19. O'Brien C, Hoyt RW, Buller MJ, Castellani JW, Young AJ. Telemetry pill measurement of core temperature during active heating and cooling. ***Med Sci Sports Exerc*** 1998; 30:468-472.

20. Sawka MN, Wenger CB. Physiological responses to acute exercise-heat stress. In: Pandolf KB, Sawka MN, Gonzalez RR, eds. ***Human Performance Physiology and Environmental Medicine at Terrestrial Extremes***. Indianapolis: Benchmark Press; 1988; 97-151.

21. Sparling PB, Snow TK, Millard-Stafford ML. Monitoring core temperature during exercise: ingestible sensor vs. rectal thermistor. ***Aviat Space Environ Med*** 1993; 64:760-763.

22. Tanaka H, Monahan KD, Seals DR. Age-predicted maximal heart rate revisited. ***J Am Coll Cardiol*** 2001; 37:153-156.

23. Wilkinson DM, Carter JM, Richmond VL, Blacker SD, Rayson MP. The effect of cool water ingestion on gastrointestinal pill temperature. ***Med Sci Sports Exerc*** 2008; 40:523-528.

Disclaimer