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Wireless measurement of rectal temperature during exercise: Comparing an ingestible thermometric telemetric pill used as a suppository against a conventional rectal probe

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ABSTRACT

Wireless measurement of rectal temperature during exercise may circumvent some limitations associated with the use of a conventional wired probe. We determined, for the first time, whether temperatures provided *in vivo* by wireless ingestible thermometric telemetric pills and a rectal probe compare favorably under conditions producing slow and rapid increases and decreases in rectal temperature. While wearing a rectal probe linked to a wireless ingestible thermometric telemetric pill, 13 participants completed the following phases: 1) 30 min sitting; 2) 45 min passive heat exposure (40–42 °C); 3) 45 min sitting while ingesting 7.5 g of ice slurry · kg body mass^{-1}; 4) running exercise (38 °C) at 68% $\dot{V}O_{2max}$ until a 39.5 °C increase in rectal probe temperature and; 5) cold-water (10 °C) immersion until a 1.5 °C decrease in rectal probe temperature. Acceptable differences between devices were taken as ≤ 0.3 °C. Mean differences within phases were all < 0.3 °C, whereas 95% limits of agreement ranged from ± 0.2 °C to ± 0.4 °C, coefficient of variations from ± 0.3% to ± 0.6% and typical error of measurements from ± 0.1 °C to ± 0.2°. Of the 14881 rectal temperature values measured over the experiment with the wireless ingestible thermometric telemetric pills and rectal probe, 91% of the differences between devices were found to be ≤ 0.3 °C. Results suggest that rectal temperatures provided by a wireless ingestible thermometric telemetric pill used as a suppository agree with those of a conventional wired probe. Hence, rectal temperature can reliably be measured using a wireless ingestible thermometric telemetric pill as a suppository.

1. Introduction

In exercise physiology research, the continuous measurement of core body temperature is fundamental to study and understand how the thermoregulatory control operates during situations generating gains or losses of low, moderate or significant body heat (Lim et al., 2008; Taylor et al., 2014). Body temperature can be measured at different sites, however many of them, such as the mouth, aural canal, armpit and forehead have demonstrated validity problems (Casa et al., 2007). Conversely, other sites such as the pulmonary artery and oesophagus have been shown to provide valid data of core body temperature, however they are difficult to implement, require trained medical personnel and are inconvenient for subjects (Savoie et al., 2015). Gastrointestinal temperature measured with a wireless ingestible telemetric pill has been demonstrated to provide reliable measurement of core body temperature (Byrne and Lim, 2007). However, this technique has limitations since the pill may be contaminated by food or fluid ingestion (Roxane et al., 2018) and it is impossible to determine its exact position within the gastrointestinal tract. This is not irrelevant, given that it has been reported that temperature is not constant along the gastrointestinal tract, which may contribute in confounding body temperature measurements (Byrne and Lim, 2007). The rectum, on the other hand, is a valid, easily accessible and commonly used anatomical site for measuring core body temperature (Casa et al., 2007). Moreover, rectal

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temperature is the preferred and recommended method of the National Athletic Trainers' Association (NATA) for assessing core body temperature (Casa et al., 2015).

Rectal temperature is typically measured using a probe connected to a non-portable data recorder. The rectal probe needs to be maintained at a desired depth within the rectum using either tape or a harness. Despite its widespread use, this technique is not without limitations. In fact, it can hardly be used outside laboratory conditions, or outside a confined space within a laboratory, let alone in an aquatic environment, at least under non-static conditions. Despite careful securing, slipping of the rectal probe outside the rectum is never totally preventable, which may contribute to invalidate or impede parts of an experiment. Prolonged sitting while wearing a rectal probe may be uncomfortable for volunteers. Finally, in order to maintain proper securing of the rectal probe volunteers may need to limit their movement amplitude at the hip level, which sometimes may limit research possibilities.

We believe that using a small, wireless ingestible thermometric telemetric pill as a suppository could potentially solve many of the technical limitations associated with measuring rectal temperature with a conventional wired rectal probe. A wireless ingestible thermometric telemetric pill has already been used to assess rectal temperature during exercise (Adams et al., 1975; Byrne and Lim, 2007; Cheuvront et al., 2009; Ely et al., 2010; Kenefick et al., 2009; Xu et al., 2013). However, whether this measurement technique provides measurements that mirror those provided by a conventional wired rectal probe has yet to be confirmed.

Fig. 1 presents results from a pilot study we performed in a circulating water bath where temperatures deriving from a wireless ingestible thermometric telemetric pill and a rectal probe were compared during a change in water temperature from 37.1 °C to 39.5 °C over a 24 min time-period. Three experiments were conducted in this pilot study: 1) the wireless ingestible thermometric telemetric pill and rectal probe were linked together by a connector (Illustration 1) and introduced in the water bath; 2) the wireless ingestible thermometric telemetric pill and rectal probe were linked together by a connector and placed in the middle of a condom filled with human feces, which was then introduced in the water bath; 3) the wireless ingestible thermometric telemetric pill and rectal probe were placed beside each other in the middle of a condom filled with human feces, which was then introduced in the water bath. Results illustrate that when tested in water the differences in temperatures between the wireless ingestible thermometric telemetric pill and rectal probe remain within the measurement error of both devices (± 0.1 °C); however, when tested in human feces, independent of the presence of the connector, the differences in temperatures between the wireless ingestible thermometric telemetric pill and rectal probe reached more than 0.3 °C at some point, which is higher than the sum of the measurement error of both devices. These findings warrant the conduct of an *in vivo* study comparing the changes in temperatures between a wireless ingestible thermometric telemetric pill and a conventional rectal probe.

Therefore, the purpose of this study was to compare measurements of rectal temperatures deriving from a commercially-available wireless ingestible thermometric telemetric pill to those of a conventional rectal probe during slow and rapid increases and decreases in core temperature induced by periods of passive cooling, passive heating, active heating and active cooling. We hypothesized that the differences in temperatures between the wireless ingestible thermometric telemetric pill and rectal probe would be lower under conditions of passive cooling and heating than active cooling and heating.

2. Methods

2.1. Subjects

Thirteen (10 males and 3 females) healthy and physically active volunteers (31 ± 9 yrs; 174 ± 9 cm; 72 ± 10 kg; body mass index: 23.8 ± 3.4 m^2; body surface area (BSA): 1.86 ± 0.16 m^2; ratio BSA to body mass: 261 ± 21 $cm^2\,kg^{-1}$; maximal oxygen consumption ($\dot{V}O_{2max}$): 53 ± 7 mL kg body $mass^{-1} \cdot min^{-1}$) participated in this study. Prior to obtaining their informed written consent, each participant received explanations of the study protocol and its associated risks and benefits. The University of Sherbrooke Institutional Review Board approved all protocol procedures.

2.2. Experimental approach to the problem

Following a preliminary visit where baseline measurements were taken, volunteers underwent a research protocol during which continuous and simultaneous measurements of rectal temperature with a wireless ingestible thermometric telemetric pill and rectal probe were made. Assessment of rectal temperature was made during conditions eliciting slow and modest increases (passive sitting under hot ambient temperatures) and decreases (passive sitting under temperate temperatures with ice slurry ingestion) in rectal temperatures as well as rapid and significant increases (running exercise in a hot ambient temperature) and decreases (cold-water immersion) in rectal temperatures.

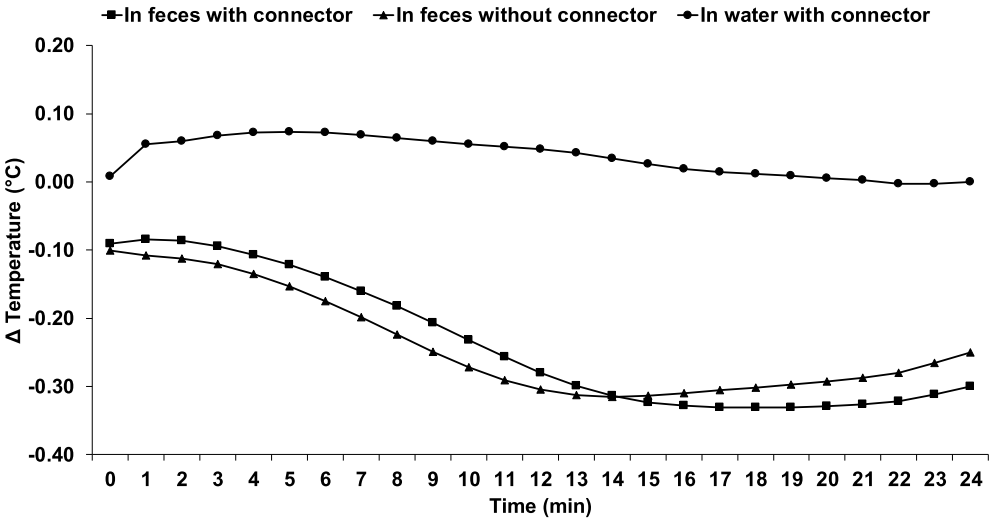

Fig. 1. Differences in temperatures between a wireless ingestible thermometric telemetric pill and rectal probe while tested in a water bath under three conditions: 1) in water only with the wireless ingestible thermometric telemetric pill and rectal probe linked by a connector; 2) in a condom filled with feces introduced in the middle of the water bath with the wireless ingestible thermometric telemetric pill and rectal probe linked by a connector placed in the center of the condom; 3) in a condom filled with feces introduced in the middle of the water bath with the wireless ingestible thermometric telemetric pill and rectal probe placed in the center of the condom, without the connector.

2.3. Preliminary visit

During the preliminary visit, volunteers underwent measurements of body mass, height, resting heart rate, blood pressure and $\dot{V}O_{2max}$. Nude, post-void body mass was measured with a high precision digital scale (Bx-300 +, Atron Systems, USA), height with a wall stadiometer and heart rate and blood pressure after a 3-min seated period with a digital sphygmomanometer (Welch Allyn 420 series, USA). Maximal oxygen consumption was measured on a motorized treadmill (TMX 22, Trackmaster, USA) using an expired gas analysis system (Cosmed Quark CPET, Cosmed, USA) that had been calibrated with gases of known concentration. After volunteers had warmed-up for 5 min while running at 6 km h^{-1} and 1% gradient, treadmill speed then increased to 8 km h^{-1} with further speed increments of 1 km h^{-1} every minute until volitional exhaustion of volunteers. Using the linear relationship between running speed and $\dot{V}O_2$, individual running speeds corresponding to 68% $\dot{V}O_{2max}$ were determined.

2.4. Pre-experimental protocol

Volunteers were asked to report to the laboratory in a well-fed and rested state. Additionally, they were required to drink 250 mL of tap water 60 min prior to arriving at the laboratory and then to remain fasted.

2.5. Experimental protocol

A schematic representation of the research protocol is provided in Fig. 2. Following body mass measurement, participants put on their running clothing (shorts, socks and T-shirt) and were instrumented with a chest electrode to measure heart rate, a conventional wired rectal probe linked to a wireless ingestible thermometric telemetric pill by a custom-made silicon connector (Illustration 1), and four epidermal probes affixed above the left pectoral muscle, left forearm, left thigh and left calf muscle. The passive heat exposure period was completed inside a 115 × 65 × 80 cm head-out, infrared-heated portable environmental chamber (ProHealth Sauna, CAN), whereas the cold-water immersion period inside a 135 cm × 78 cm x 64 cm, 379-L circulating water bath. Transition times were not standardized between phases or individuals, but were performed as rapidly as possible. Other than ingesting ice slurry and having access to cold water (~4 °C) during the running exercise that they could pour on their body or rinse their mouth with, volunteers could not consume fluids during the experiment. Prior to immersion, volunteers removed the data recorder, their socks and their running shoes, but were free to remove or keep their T-shirts on. Volunteers were asked to immerse themselves up to the neck and keep all other body parts under water for the entire duration of the immersion period.

2.6. Measurements and procedures

2.6.1. Heart rate

Heart rate was measured with a T-31 Polar electrode linked to a Vantage NV Polar heart rate monitor (Polar USA, USA).

2.6.2. Rectal temperatures

A single, reusable, NIST traceable and calibrated YSI 401 wired rectal probe (Yellow Springs Instrument, USA) inserted 15 cm beyond the anal sphincter was used as the conventional rectal probe. The rectal probe was securely held in place with the aid of a lightweight harness. An ingestible thermometric telemetric pill sold to measure gastrointestinal temperature was used to assess rectal temperature wirelessly (CorTemp HQ Inc., USA). The CorTemp HQ pills are interchangeable to within ± 0.1 °C at temperatures between 30 °C and 45 °C (HQ Inc).

Rectal temperatures were measured continuously every 10 s. The rectal probe was connected to a high precision digital thermometer (Traceable 4005, Control Company, USA), whereas signals emitted by the wireless ingestible thermometric telemetric pill were captured with a single CorTemp Data Recorder (HQ Inc, Palmetto, FL) securely held in place at the volunteers' lower back and base of the gluteal muscles. The rectal probe and a wireless ingestible thermometric telemetric pill were linked together by a medical-grade silicone connector (Illustration 1) designed and developed by our laboratory. The tip of the rectal probe was slid ~1 cm into the connector until it reached two holes made on each side of the connector, which allowed the tip to be exposed to ambient conditions. The wireless ingestible thermometric telemetric pill was also slid ~1 cm inside the connector until it touched the tip of the rectal probe. The connectors were designed such that the temperature sensing crystals of the wireless ingestible thermometric telemetric pills, which are centrally located, were exposed to ambient conditions. As demonstrated in Fig. 1, pilot studies performed in a water bath show that the connector is not significantly impacting the temperatures provided by the rectal probe and wireless ingestible thermometric telemetric pill.

Prior to the start of the experiment, the rectal probe and each of the 13 wireless ingestible thermometric telemetric pills were calibrated against a high precision, partial immersion, non-mercury glass thermometer (Thermo Scientific Ertco, USA) in a water bath (Precision 281,

Arrival at laboratory			Phases	1	2	3	4	5	Post immersion		
1	2	3		Rest ↓	Passive heating ↓	Ice slurry ingestion ↓	Exercise ↓	Immersion	1	2	3
Void of the bladder	Urine sample + urine specific gravity	Nude body mass	Goal	Equilibrium period	Produce a slow and small increase in core temperature	Produce a slow and small decrease in core temperature	Produce a rapid and important increase in core temperature	Produce a rapid and important decrease in core temperature	Void of the bladder	Urine sample + urine specific gravity	Nude body mass
			Duration (min)	30	45	45	Variable	Variable			
			Conditions	Passive seating	Passive seating	Passive seating + Ingestion of 2.5 g of ice slurry · kg body mass^{-1} · 10 min^{-1} for the first 30 min	Treadmill running exercise at 68% $\dot{V}O_{2max}$ until a rectal probe temperature of 39.5°C	Immersion in a circulating water bath until a rectal probe decrease in temperature of 1.5°C			
			T (°C)/ RH (%)	23/37	40-42/40	23/37	38/25	10-11.5			

Fig. 2. Schematic representation of the experimental protocol. **RH**: Relative humidity. **T**: Temperature.

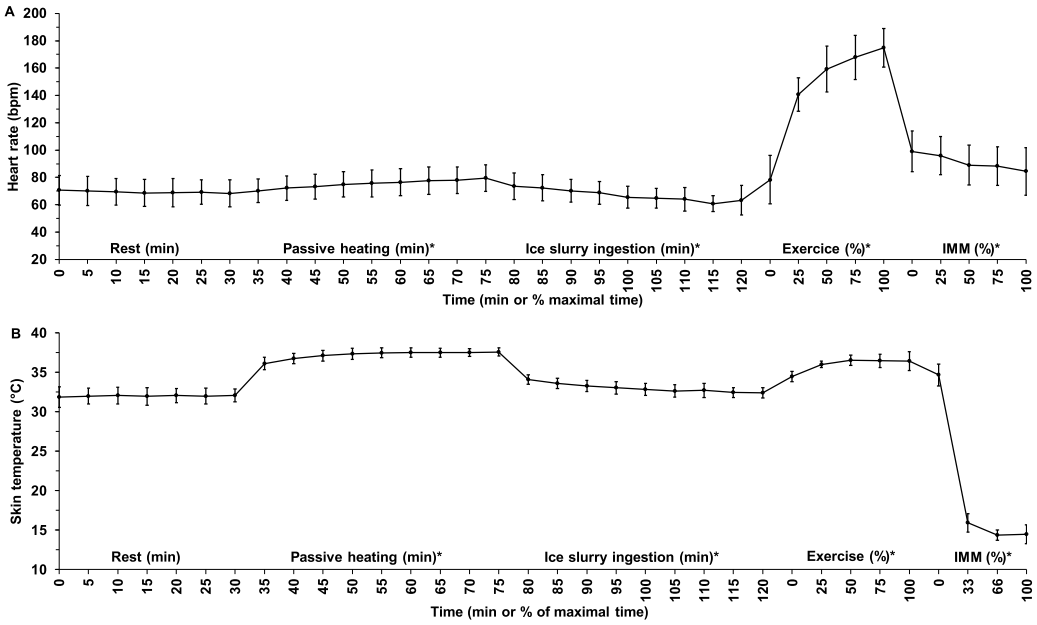

Fig. 3. Changes in heart rate (a) and skin temperature (b) across time for all five phases. **IMM**: Cold-water immersion. *: significant time effect within phase.

Thermo Scientific, USA) at 4 different temperatures: 37 °C, 38 °C, 39 °C and 40 °C. Wireless ingestible thermometric telemetric pill and rectal probe temperatures were then predicted using a 4-point regression line constructed for each of them (Challis and Kolb, 2010).

2.6.3. Skin temperatures

Skin temperature was measured every 5 min throughout the experiment with YSI 409 B (Yellow Springs Instrument, USA) probes held in place with Transpore tape (3 M, USA). The skin probes were connected to a switch box linked to a high precision digital thermometer (Traceable 4005, Control Company, USA). Mean skin (Ramanathan, 1964) temperatures was computed using the following equations:

$$\text{Mean skin temperature} = (0.3 \times T_{pectoral}) + (0.3 \times T_{arm}) + (0.2 \times T_{thigh}) + (0.2 \times T_{calf});$$

where T is temperature in °C.

2.6.4. Hydration variables

Urine specific gravity was assessed with a digital refractometer (PAL-10S, Atago, USA). Sweat loss was estimated using the change in body mass from the pre-to post-experiment period, corrected for ice slurry intake and urine losses. Percent body mass loss was calculated using the following formula:

$$\%\ body\ mass\ loss : \frac{Pre - experiment\ body\ mass - post - experiment\ body\ mass}{Pre - experiment\ body\ mass} x\ 100$$

2.6.5. Ice slurry

Cubes of ice were first shaved with a commercially available instrument (Hamilton Beach, USA). The ice flakes were then mixed with water (4 °C) in a 64:36% ice-to-water ratio to create ice slurry. For palatability and provision of energy, orange or raspberry glucose-fructose syrup (~22 g) was added to the ice slurry. The ice slurry was then transferred to a beaker which was immersed in an ice-filled cooler placed in the lower back of a refrigerator maintained at 2–4 °C.

2.6.6. Statistical analysis

Acceptable difference between devices was taken as ≤ 0.3 °C (Casa et al., 2007). A one-way repeated measures analysis of variance (ANOVA) or Friedman analysis was utilized to determine the significance of the changes in heart rate and mean skin temperature across time among the different phases. Linear mixed-effects modeling was used to analyze data with missing cases (e.g., urine specific gravity). Relative validity was assessed with the Pearson product-moment correlation coefficient (*r*) (Atkinson and Nevill, 1998). Absolute validity was determined with the computation of the typical error of measurement (TEM), coefficient of variation (CV) and the Bland-Altman 95% limits of agreement (LoA) (Atkinson and Nevill, 1998). Heteroscedasticity was tested using a linear regression model (Atkinson and Nevill, 1998). For all 5 phases, a statistically significant relationship was observed between the magnitude of the changes in rectal temperature and differences between devices. However, no corrections were made given that this relationship explained less than 2.5% and 11% of the variability between differences for phases 1 to 4 and phase 5, respectively. Because exercise and cold-water immersion times varied between individuals, results for those phases are reported based on a percentage of maximal time. Statistics were performed with the 2016 Microsoft Office Excel (Microsoft, USA) and IBM SPSS Statistics (version 21, USA) softwares. Results were considered significant at $p < 0.05$. Otherwise stated, data are reported as means ± SD.

3. Results

3.1. Fluid balance

Subjects were adequately hydrated before the start of the experiment, as supported by a urine specific gravity of 1.013 ± 0.009 g mL^{-1} and an associated urine color of 3.7 ± 2.5 arbitrary units. At the end of the experiment, urine specific gravity increased to 1.017 ± 0.01 g mL^{-1} ($p < 0.01$) and urine color to 5.1 ± 1.2 arbitrary units ($p < 0.01$). Mean participants' ice slurry intake was 541 ± 81 g. Urine production during the experiment reached 322 ± 231 mL. Total sweat loss, sweat rate and dehydration level measured at the end of the experiment were 1176 ± 513 mL, 362 ± 150 mL h^{-1} and 1.3 ± 0.4% of body mass, respectively.

3.2. Heart rate

Fig. 3a depicts the changes in heart rate across time for all five phases. Average heart rate during the baseline, passive heating and ice

slurry ingestion phases was relatively stable and similar across time. A time effect was observed for heart rate during phases 2 and 3 (both < 0.01), but not during phase 1 ($p = 0.52$). Heart rate increased over time ($p < 0.01$) during the running phase. Following exercise, heart rate dropped sharply and rapidly during the transition period and reached 101 ± 15 bpm immediately prior to the cold-water immersion period. Following entry into the bath, heart rate continued to slowly decrease ($p < 0.01$).

3.3. Mean skin temperature

Fig. 3b illustrates the changes in mean skin temperature across time for all five phases. During phases 1 and 3, where volunteers were passively seated and exposed to laboratory ambient temperature, mean skin temperature was relatively similar between conditions. Independent of whether heat stress was induced passively or actively, the pattern of changes in mean skin temperature during phases 2 and 4 was similar. The most significant change in mean skin temperature across a single phase occurred during the immersion period. In fact, from the pre- to post-cold-water immersion period mean skin temperature decreased by 20.2 ± 1.2 °C ($p < 0.01$). Except for phase 1 ($p = 0.59$), a significant time effect was observed for the changes in mean skin temperature across time.

3.4. Rectal probe and wireless ingestible thermometric telemetric pill temperatures

Fig. 4a (phases 1 to 3) and 4b (phases 4 and 5) depict the changes in rectal temperatures across time for both devices. Table 1 reports the statistical comparisons associated with the changes in rectal probe and wireless ingestible thermometric telemetric pill temperatures. Across all phases rectal probe temperatures were greater than the wireless ingestible thermometric telemetric pill temperatures. However, in none of the phases was the mean difference or TEM between devices greater than the delimitation criterion of ≤ 0.3 °C. Pearson product-moment correlation coefficients show that for all 5 phases temperature between devices were highly correlated. Interestingly, uncorrected data show that mean differences between devices were above the ≤ 0.3 °C threshold for all 5 phases.

The LoAs were relatively similar over the 5 phases, and 95% of the results obtained with the rectal probe ranged from 0.5 °C to −0.2 °C (phase 1), 0.4 °C to −0.1 °C (phase 2), 0.4 °C to −0.1 °C (phase 3), 0.6 °C to −0.1 °C (phase 4) and 0.7 °C to −0.2 °C (phase 5) of the values obtained with the wireless ingestible thermometric telemetric pill.

During the exercise and cold-water immersion periods, rectal probe and wireless ingestible thermometric telemetric pill temperatures respectively increased and decreased as a fraction of percentage of time. The time to reach a 1 °C increase in rectal temperature during exercise was respectively of 1162 ± 125 s and 1109 ± 216 s for the wireless ingestible thermometric telemetric pill and rectal probe ($p = 0.40$). On the other hand, the time to reach a 1 °C decrease in rectal temperature during the cold-water immersion period was respectively of 587 ± 394 s and 688 ± 572 s for the wireless ingestible thermometric telemetric pill and rectal probe ($p = 0.27$). The rate of change in rectal temperatures within all phases were not statistically different between devices.

4. Discussion

The objective of this study was to determine whether the use of a wireless ingestible thermometric telemetric pill as a suppository provides measures of rectal temperatures that compare favorably well with those of a conventional wired rectal probe under conditions of passive heating, ice-slurry ingestion, running exercise and cold-water immersion. *A priori* established acceptable level of difference between devices was set at ≤ 0.3 °C (Casa et al., 2007). In none of the 5 phases was the criterion threshold crossed; we therefore interpret this observation to suggest that values of rectal temperature deriving from a wireless ingestible thermometric telemetric pill and conventional wired rectal probe agree with each other. Results from the current study highlight for the first time the possibility that a commercially-available wireless ingestible thermometric telemetric pill can reliably be used to measure rectal temperature under various conditions.

The mean difference in temperature between devices varied from 0.1 to 0.2 °C across all phases, with rectal probe temperatures being systematically higher than those from the wireless ingestible thermometric telemetric pill throughout the experiment. The range of differences in temperatures between devices was within the sum (± 0.2 °C) of the measurement error of each device (± 0.1 °C) and, therefore, is tenable from a technological standpoint. Moreover, these *in vivo* findings are in line with those of our *ex vivo* studies conducted with human feces. Indeed, the latter pointed out that a difference of ~0.1 °C between devices was to be expected during situations incurring no or modest changes in rectal temperatures, whereas one up to ~0.3 °C was possible during situations of rapid changes in rectal temperature. Our results are also congruent with those of Kenefick et al. (2009) who reported in an unpublished pilot study a mean difference in rectal temperature of 0.1 °C between a rectal probe and a wireless ingestible thermometric telemetric pill, with some individual differences reaching up to 0.2 °C. Interestingly, our results show that the differences in temperatures between devices is relatively stable across a spectrum of rectal temperatures varying from ~37.0 °C to 39.8 °C, suggesting that the wireless ingestible thermometric telemetric pill can be used as a suppository across a wide range of thermal stresses.

Despite that a systematic difference in temperature was observed between devices, the mean rate of change in rectal temperature was, however, shown not to significantly differ between devices in all five conditions studied. During exercise, for example, mean rates of increase in rectal temperature of 0.055 ± 0.007 °C/min and 0.058 ± 0.009 °C/min were observed for the wireless ingestible thermometric telemetric pill and rectal probe, respectively. These figures indicate that the different devices would reach an increase in rectal temperature of 1 °C within a time difference of less than 60 s, which is acceptable from a clinical standpoint given that the measurement error of those devices is 0.1 °C. Proulx et al. (2003) have observed a similar rate of increase in rectal temperature measured with a wired rectal probe during running exercise at 38.8 °C and 65% $\dot{V}O_{2max}$. During cold-water immersion, mean rates of decrease in rectal temperature were of the order of 0.093 ± 0.047 °C/min for the wireless ingestible thermometric telemetric pill and of 0.097 ± 0.067 °C/min for the wired rectal probe. These rates of change in rectal temperature measured with a rectal probe were either similar, lower or higher than what has been found by others with whole body or up to the sternum/clavicles immersion level in 10 °C–15 °C water (Zhang et al., 2015). Disparity between findings could be related to water temperature, gender, speed of water circulation inside the bath, immersion level, pre-immersion rectal temperature, clothing worn and subjects' anthropometry. Altogether, our results show that wireless ingestible thermometric telemetric pills are able to capture slow and rapid increases and decreases in rectal temperature.

There are several circumstances under which it may be useful to use a wireless ingestible thermometric telemetric pill as a suppository. First, when continuous, uninterrupted monitoring of rectal temperature is critically important for the success of a study. In fact, unlike the use of a wired rectal probe, a wireless ingestible thermometric telemetric pill used as a suppository is unlikely to come out of the rectum. Second, under research circumstances where either it would be impossible or not practical to measure rectal temperature with a conventional wired rectal probe or that researchers rule out the possibility of providing the wireless ingestible thermometric telemetric pill orally to ensure that it would not be excreted prior to beginning the study or getting contaminated by fluid or food consumption during exercise. Third, when a measure of rectal temperature is needed, and the study is being

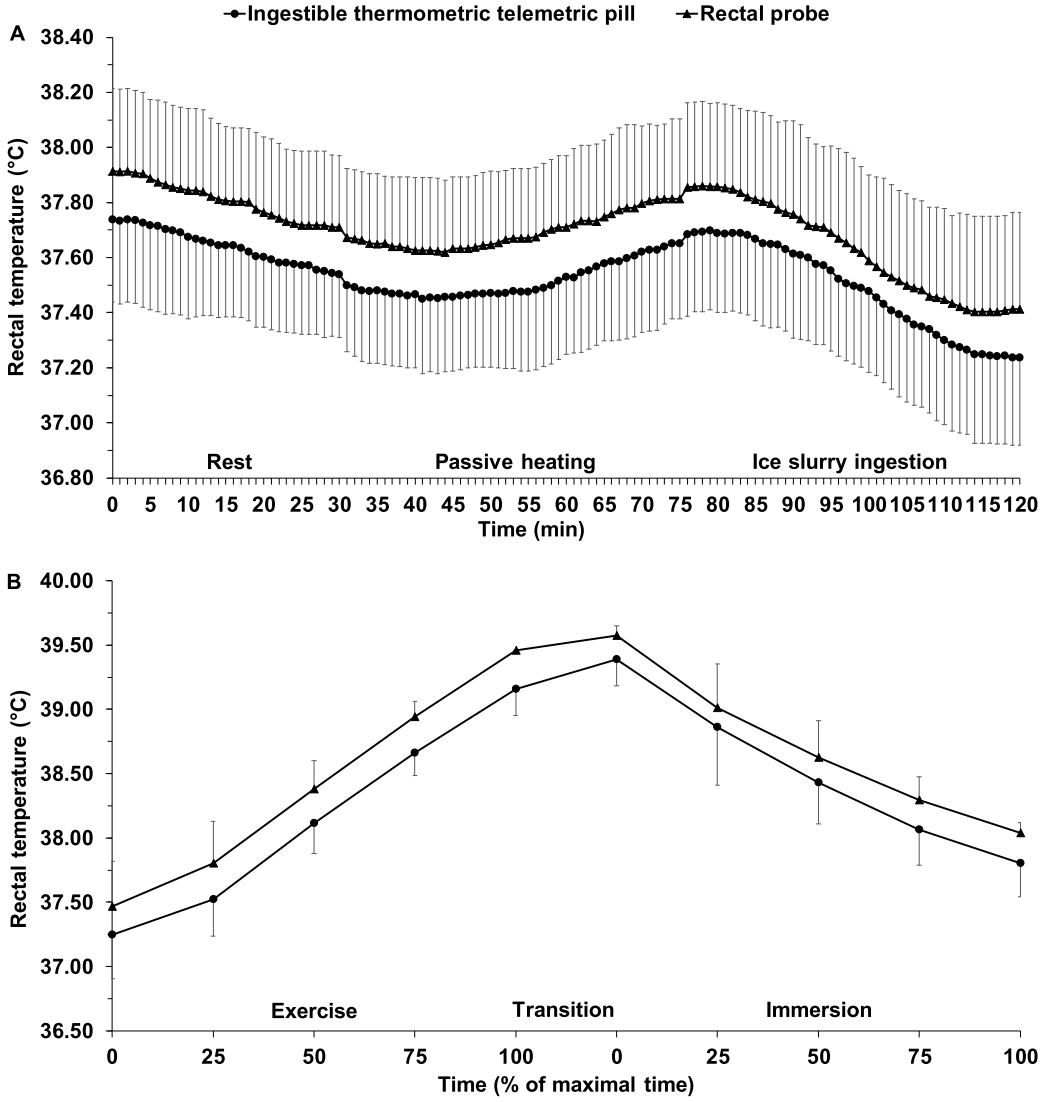

Fig. 4. Changes in wireless ingestible thermometric telemetric pill and rectal probe temperatures during rest, passive heating and ice slurry ingestion (a) and exercise and cold-water immersion (b) across time during the experiment.

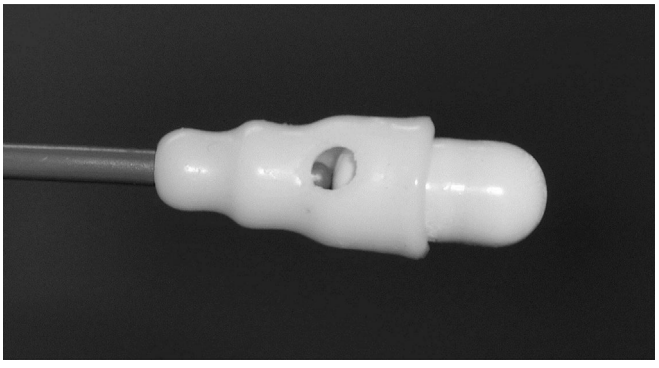

Illustration 1. Illustration showing the connection between the rectal probe and wireless ingestible thermometric telemetric pill.

performed outside laboratory settings or under field conditions. Fourth, when the monitoring of core temperature needs to be made within a short time window in a group of research participants or athletes during a practice or a game. Finally, for coaches who would like to monitor the heat acclimatization process of their athletes. It has been suggested that a progressive overload approach (e.g., controlled hyperthermia to a core temperature of 38.5 °C) induces a more complete adaptation to the heat than the traditional repeated exposure to a constant work rate regimen (Periard et al., 2015). Given our results showing that the wireless ingestible thermometric telemetric pill is unlikely to underestimate rectal temperature during exercise by more than 0.6 °C (95% LoAs), then using this device as a suppository within this context should remain a safe strategy.

Results of this study must be interpreted with the following limitations in mind. First, both devices were linked together with a medical-grade silicone connector which, potentially, may have contributed to some measurement differences between devices. However, pilot studies conducted in human feces revealed that the connector is unlikely to have contaminated temperature measurements deriving from both devices by more than ~0.05 °C, which is lower than the measurement error of both devices. Second, wireless ingestible thermometric telemetric pills' effectiveness was not assessed during steady-state exercise conditions. Nonetheless, we have no reason to believe that under this specific condition differences between devices should diverge from those observed during the non-steady state exercise condition. Finally, our results only apply to the use of the HQ CorTemp wireless ingestible thermometric telemetric pill.

Table 1
Statistical comparisons between the rectal probe and wireless ingestible thermometric telemetric pills.

Periods	N (Total:14881[&])	Δ (°C)	≤ 0.3 °C (%)	TEM (°C)	LoA (°C)	CV (%)	r	Rate of change in temperature (°C)/min	
								RP	WITTP
Rest	2364	0.1*	94	± 0.2	± 0.3	± 0.4	0.83	−0.007 ± 0.006	−0.007 ± 0.003
Passive heating	3557	0.2*	98	± 0.1	± 0.2	± 0.3	0.91	0.003 ± 0.005	0.003 ± 0.004
Ice slurry ingestion	3396	0.1*	99	± 0.1	± 0.2	± 0.3	0.93	−0.011 ± 0.004	−0.011 ± 0.002
Exercise	2752	0.2*	76	± 0.2	± 0.4	± 0.5	0.97	0.058 ± 0.009	0.055 ± 0.007
Immersion	1657	0.2*	77	± 0.2	± 0.4	± 0.6	0.92	−0.097 ± 0.067	−0.093 ± 0.047
Global mean	–	0.2*	91	± 0.2	± 0.3	± 0.4	0.96	–	

Δ: rectal probe-wireless ingestible thermometric telemetric pill; **CV**: coefficient of variation; **LoA**: 95% limits of agreement; **r**: Pearson product-moment correlation coefficient; **RP**: rectal probe**; TEM**: typical error of measurement; **WITTP**: wireless ingestible thermometric telemetric pill; &: difference between total and sum of data from each phase represents data from the transition periods; *: systematic bias.

In summary, mean differences between devices were below the criterion threshold of 0.3 °C under all conditions. Hence, the use of wireless ingestible thermometric telemetric pills as suppositories appropriately tracks changes in rectal temperature under conditions including modest and rapid changes in rectal temperature.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2019.05.010.

Declarations of interest

None.

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