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Auditory canal temperature measurement using a wearable device during sleep: Comparisons with rectal temperatures at 6, 10, and 14 cm depths

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ABSTRACT

Monthly rhythms in the body core temperature of women during sleep can provide significant information concerning hormonal fluctuations. The purpose of the present study was to examine and evaluate auditory canal temperature ($T_{auditory}$), measured with a newly-developed wearable and wireless device, as a practical index to estimate body core temperature variations during a 7-h sleep period. Comparisons with rectal temperature (T_{re}) at different depths were conducted. Nine young females slept in a climate chamber at an air temperature of 27 °C with 50% relative humidity. Rectal temperatures at 6, 10 and 14 cm depths, as well as partially insulated $T_{auditory}$ were simultaneously measured every 5 s during sleep. The results showed that $T_{auditory}$ was, on average, 0.32 °C lower than T_{re} at 14 cm depth ($P = 0.010$), while significant relationships between $T_{auditory}$ and T_{re} at 10 cm ($r^2 = 0.634$, $P = 0.010$), and at 14 cm depths were also found ($r^2 = 0.826$, $P = 0.001$). Rectal temperatures at 6 cm and 10 cm depths fell between those of $T_{auditory}$ and T_{re} at 14 cm. We concluded that $T_{auditory}$, as measured using the newly-developed wearable device, can be a reliable, practical and continuous estimate of body core temperature during sleep.

1. Introduction

Body core temperature follows a circadian rhythm over 24 h, displaying different patterns between periods of waking and sleeping. The most common observation in body core temperature during sleep is a progressive decrease after sleep onset (Barrett et al., 1993), which has been associated with heat redistribution from the core to the peripheral tissues (Kräuchi et al., 1999; VanSomeren, 2000), and a reduction in whole body and cerebral metabolic heat production (Buchsbaum et al., 1989; Kreider et al., 1958). The significance of this reduction in core temperature during sleep has been highlighted by several studies, which have focused on the relevance of body core temperature to such issues as sleep disturbance (Watanabe et al., 2003), affective disorders (Daimon et al., 1992), and menstrual functions (Baker and Driver, 2007).

In order to understand sleep-related thermoregulatory responses and associated conditions, continuous monitoring of body core temperature using valid and reliable indicators is needed. Rectal temperature (T_{re}) is one of the most commonly used measurements for estimating body core temperature, and it is known to be reliable and stable, as well as being less affected by external changes (Åstrand et al., 2003; Saltin and Hermansen, 1966). Despite that, two issues are often raised: insertion depth with regard to a thermal gradient in the rectum and the difficulty of continuous and tethered monitoring during daily lives. Firstly, T_{re} was measured at various depths, from 4 to 27 cm (Lee et al., 2010), with 10 cm being the most common depth reported in the literature and recommended by ISO 9886 (1992). However, a 10 cm depth is not an absolute standard for T_{re}, as there have been several studies that measured it at a shallower depth (Smitz et al., 2009) and at deeper depths of 15–16 cm (Lee et al., 2010; Miller et al., 2017). Second, T_{re} is often less preferred as it is uncomfortably invasive (Lee et al., 2011), especially for continuous sampling over long periods (Areas et al., 2006).

With regard to the second issue, less invasive and easier to measure alternatives are preferred. The temperature of auditory canal ($T_{auditory}$) can be an acceptable surrogate of core temperature (Cooper et al., 1964; Hansen et al., 1996; Keatinge et al., 19). This measure is taken deep in the auditory canal near the tympanum, anatomically close to the brain arteries and veins (Fraden and Lackey, 1991), and thus it is considered appropriate for tracking blood temperature of

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hypothalamus (Taylor et al., 2014; Todd et al., 2014). As the inside of the auditory canal makes a blackbody-like cavity it is an optimal emitter of electromagnetic radiation (Fraden and Lackey, 1991). In this way, $T_{auditory}$ can be obtained by measuring skin-emanated natural electromagnetic radiation (Wise, 1991), which is strongly influenced by carotid blood flow (Cooper et al., 1964). Since being proposed by Williams and Thompson (1948), $T_{auditory}$ has been an acceptable surrogate of body core temperature, albeit there still exist polarizing views on its validity (Cooper et al., 1964; Greenleaf and Castle, 1972). The major advantages of this index include its non-invasiveness, ease of use and its rapid and dynamic response to thermal transitions (Lee et al., 2011). However, the auditory canal is easily affected by ambient temperature changes, which result in a thermal gradient along the skin and within the auditory canal (Taylor et al., 2014). Therefore, minimizing those effects by insulating the ear is an important issue.

At present, basal body core temperature monitoring for women in their childbearing years is considered as an important measure to recognize significant changes in the levels of oestrogen and leuteinizing hormone. Previous studies which examined the possibility of $T_{auditory}$ as a proxy index for body core temperature mainly focused on the awakened state (Roth et al., 1996; Lee et al., 2011). The non-invasive nature of $T_{auditory}$ could be of particular value in sleep studies, because it is more comfortable and will be associated with less interruptions of sleep. A reliable measurement of $T_{auditory}$ during sleep, using a home-applicable wireless device, can help women in their childbearing years to check their ovulatory phase (Coyne et al., 2000). In addition, it will allow parents to precisely check, in real-time, and quantify fever-related hyperthermia (Brennan et al., 1995; Van Staaij et al., 2003). $T_{auditory}$ may be superior to temperatures obtained using gastrointestinal pills, a similarly non-invasive measure, especially during sleep. However, as pointed out by Taylor et al. (2014), the within-sensor average temperature, as pills transverse the gastrointestinal tract, is about 0.5 °C when measured overnight. Given that the circadian and menstrual variations in body core temperature are of the same magnitude, this challenges the utility of that index.

Measurement technologies of $T_{auditory}$ have gradually developed. Such improvements include continuous measurement using a wireless, wearable device with real-time monitoring. The mobile application was a particular interest of the present study. However, whether or not $T_{auditory}$ can provide a reasonable index of body core temperature during sleep still needed to be investigated. Therefore, the present study aimed to evaluate that possibility, as measured using a newly developed wireless device during 7-h sleep. Those data were compared with simultaneously measures of rectal temperature. As measurement depth in the rectum is crucial when absolute temperature is important (Taylor et al., 2014), comparisons were made between $T_{auditory}$ and T_{re} at three different rectal depths. The three insertion depths were determined based on the most adopted depth of 10 cm: at 6, 10, and 14 cm depth. We hypothesized that $T_{auditory}$ would show similar increasing or decreasing tendencies to those observed at the rectum, but would be of a lower value.

2. Methods

2.1. Subjects

Nine young, female Koreans, participated in this present study ([Mean ± SD]24 ± 3 y, 163.6 ± 4.6 cm, 52.6 ± 8.3 kg, 19.6 ± 2.4 kg m^{-2} body mass index and 1.59 ± 0.13 m^2 body surface area). We recruited female because, in their childbearing years, they are often interested in monitoring their basal body temperature. Volunteers having symptoms of sleep disturbance, sleep disorder, irregular sleep patterns or taking female sex hormone drugs were excluded through pre-screening. All subjects had regular sleep schedules (6–8 h of sleep per night). They were all non-smokers and were instructed to keep their daily activity routines before every trial. Subjects were also required to refrain from strenuous exercise and alcohol 24 h before arriving, and from eating food, including stimulating or caffeinated drinks, for 3 h before arriving. Each trial was scheduled according to self-reported menstrual cycles. They were tested during the 10 days before and after their ovulation day, and did not take part during their menstrual cycles. Five subjects were in the follicular phase and four were in the luteal phase according to the self-reported cycles. Full explanations of the aims, procedures, discomforts and risks of the study were provided in detail to each subject, who then gave her informed consent in writing prior to participation. The procedures and protocols of this study were approved by the Institute Review Board of Seoul National University (IRB No. 1810/001-008).

2.2. Experimental procedures

All trials were conducted in a climatic chamber maintained at an air temperature of 27 °C and 50% relative humidity (RH). These are the conditions typically encountered with in Korean bedrooms, where sleepers are lightly clothed. Subjects were required to visit the laboratory, and sleep in the climatic chamber twice. The first trial was conducted to make them comfortable in the new sleeping environment. After the first trial (48 h), subjects participated in the experimental trial. The sleep protocol was based on our previous work (Ko and Lee, 2018), with two to three subjects undertaking their sleep trial simultaneously. On each experimental day they entered the bedroom together at 11:30 p.m. and lay down. Upon arriving at the laboratory at 10:00 p.m., subjects changed into identical short-sleeve T-shirts and half-length trousers (all 100% cotton, 309 g in weight, 0.3 estimated clo) wearing their own underwear. Subjects took sufficient rest after instrumentation, and became comfortable with one another before starting the experiments.

Before leaving the preparation room at 11:25 p.m. to move into the bedroom, they went to the bathroom if needed. Subjects were not allowed to bring electrical devices into the bedroom. Single bedding for summer, including a sponge mattress (polyester 100%, 5 cm thickness) and its sheet (polyester 100%, 110 cm × 200 cm), a blanket without padding (polyester 100%, 155 cm × 200 cm, 1 cm thickness), and a pillow (cover: polyester 100%, 40 cm × 60 cm; padding: polyester 100%, 6 cm thickness) were assigned to each person. Subjects covered themselves with a blanket resting their heads on a pillow, and were instructed not to fall asleep until 00:00 a.m. At 00:00 a.m., the light was turned off and subjects started sleeping in a supine position wearing an earplug in the left ear, to minimize the effects of unnecessary noise during sleep. Subjects were encouraged to leave the bedroom immediately and let the experimenters know in case of any emergency during the experiments. At least one experimenter stayed awake in the bedroom sitting in a chair and monitored the experiments for safety. At 07:00 a.m., the light was turned on and subjects were woken up. Subjects completed a sleep quality questionnaire about the previous night, while still lying down on the mattress, they then left the bedroom and the experimental clothing and sensors were removed. No subjects came out of the bedroom or went to bathroom during the sleep phase.

2.3. Measurements and calculations

Auditory canal temperature was measured every 5 s using an infrared (IR) sensing thermometer worn in the right ear. The wearable auditory canal device consisted of an IR sensor (Ear sensor, LG Electronics, Korea) and a plastic body surrounded by a silicone body molded to fit within the external auditory meatus, which also contributed to providing a partial insulation (Fig. 1). Additional insulation, however, was not applied to reflect a realistic setting for utilizing the home-applicable device. In every trial, each subject was assigned a new pre-calibrated device. Auditory canal temperature data were transmitted via Bluetooth and automatically recorded in real time using a smart phone application (WTW-500; LG electronics, Korea).

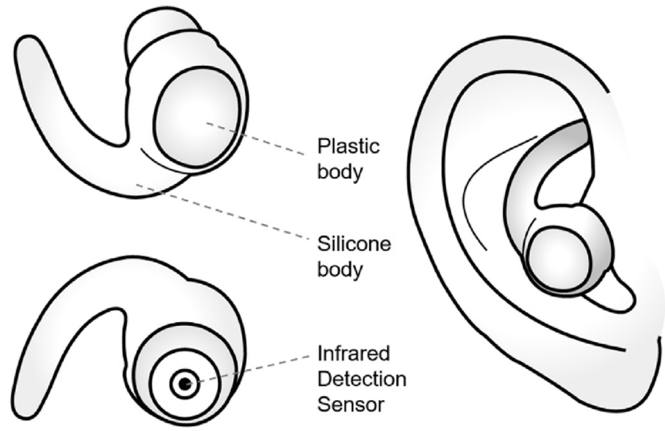

Fig. 1. Illustration of the wireless wearable device for auditory canal temperature measurement.

Rectal temperature was measured at depths of 6, 10, and 14 cm from the anal sphincter every 5 s, using a newly developed 3-point rectal thermistor probe (LT-ST08-11, Gram Corp., Japan). The three points of the rectal probe were secured at their assigned depths using medical tape (Micropore; 3M, United States) so as not to move out of position. Subjects were instructed to insert the rectal probe 14 cm beyond the anal sphincter, and to affix the sensor with medical tape on three skin sites: 1–1.5 cm next to the anus, on the middle of the right buttock, and on the right side of the waist. Rectal temperature was automatically recorded using a data logger (LT-8A; Gram Corporation, Japan).

Heart rate was monitored every 5 s throughout the sleep period using a chest-belted sensor and receiver watch (RC3 GPS; Polar Electro, Finland). Body mass loss during sleep was derived from the change in body mass before and after sleep (ID2, Mettler-Toledo, Germany). These mass changes were assumed to represent body fluid losses.

For the first night of adaptation sleep, a wrist-worn actigraph was worn on the non-dominant side of each subject to attain objective sleep variables, such as sleep-onset latency, sleep efficiency, number of awakenings and average awakening length, as described in our previous study (Ko and Lee, 2018). Three sleep fragmentation indices representing the non-relaxed period were calculated in the software: movement index, fragmentation index and sleep fragmentation index. Greater values in these indices indicate that the sleep period was more disrupted. Subjective evaluation of the night's sleep was obtained in the morning using the sleep quality questionnaire.

2.4. Data analyses

Data were analyzed using SPSS statistics 21.0 at a significance level of 0.05. First, a Shapiro-Wilk test was undertaken to test normality. Differences between the body core temperature measurements from the rectum at three depths and the auditory canal were determined using a repeated measure ANOVA. The pair-wise comparison with False Discovery Rate (FDR) correction was used as a post-hoc test. To determine agreement between $T_{auditory}$ and rectal temperature measurements at different depths, individual data over time were plotted using the Bland-Altman method (Bland and Altman, 2007). The limits of agreement were defined as the upper and lower 95% confidence intervals. As the pairs of the measurements were not independent one another, the "multiple observations per individual" method (Bland and Altman, 2007) was applied in the Bland-Altman plots using MedCalc. Sleep variable analyses from actigraphy were performed with Actilife 6 using the Sadeh algorithm (Sadeh et al., 1994). Rectal temperatures at 6, 10, 14 cm depth, $T_{auditory}$, and heart rate data were averaged over 15 min for analytical and graphical purposes. A paired *t*-test for parametric data and a Wilcoxon signed-rank test for non-parametric data were conducted to compare the objective and subjective evaluation of sleep quality between the adaptation sleep trial and the main sleep trial. All data except the anthropometric data, were expressed as mean ± SE.

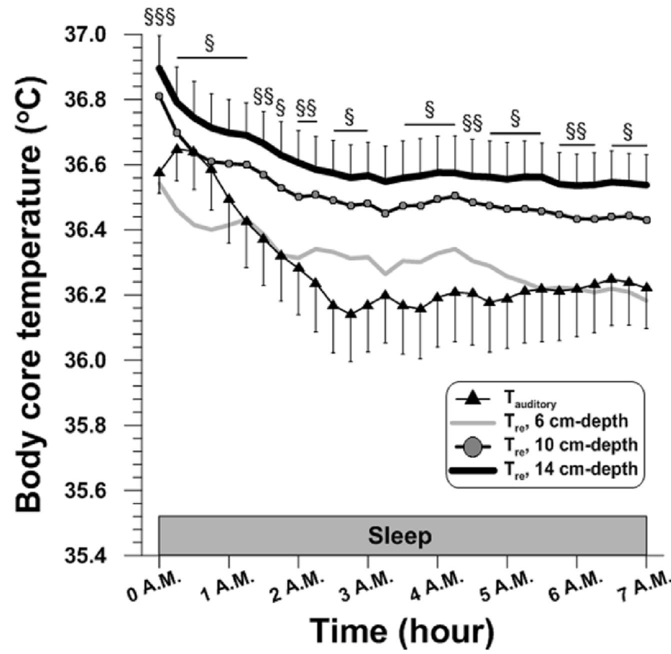

Fig. 2. Time courses of auditory canal temperature and rectal temperatures at 6, 10 and 14 cm depth during 7-h sleep. $T_{auditory}$: auditory canal temperature; T_{re}: rectal temperature ($^{§}P < 0.05$, $^{§§}P < 0.01$, and $^{§§§}P < 0.001$).

3. Results

3.1. Time courses of auditory canal and rectal temperatures at 6, 10, 14 cm depth during sleep

Body core temperatures all decreased during the sleep (Fig. 2). Among those indices, T_{re} at 14 cm depth tended to be the most stable and highest throughout sleep (Fig. 2). Auditory canal temperature, and T_{re} at 6 cm depth, had a steeper decrease during sleep, while the values for T_{re} at 14 cm and 10 cm depth showed a steadier decline or plateau (Fig. 2). Significant differences between the body core temperature values appeared throughout the sleep period ($P < 0.05$ between the sites) (Fig. 2). Pairwise comparisons with FDR correction revealed that T_{re} at 6 cm depth intermittently displayed lower values than those of T_{re} at 10 cm depth (at 0.00, 0.30, from 1.30 to 2.15, at 2.45, 4.30, from 5.50 to 6.15 and 6.45 h) and those of T_{re} at 14 cm depth (at 0.00, 0.30, from 1.30 to 2.15, at 4.30, from 5.30 to 6.30 h) ($P < 0.05$) (Fig. 2).

Auditory canal temperatures were significantly lower than T_{re} at 14 cm depth at 0.00 h and from 1.30 h to the end of the experiment ($P < 0.05$) (Fig. 2). Compared to T_{re} at 10 cm depth, $T_{auditory}$ also displayed significantly lower values at 0.00 and 3.00 h, as well as from 3.30 to 6.00 h ($P < 0.05$) (Fig. 2). No significant differences were found between $T_{auditory}$ and T_{re} at 6 cm depth throughout sleep (Fig. 2). For the first 3 h of sleep, $T_{auditory}$ decreased a significantly greater amount than T_{re} at all depths ($P = 0.002$ between the sites) (Fig. 3A). The decreasing magnitudes for the last 3 h of sleep were 0.14 ± 0.08 °C, 0.06 ± 0.06 °C, and 0.04 ± 0.06 °C for T_{re} at 6 cm, 10 cm, and 14 cm depth, respectively. Auditory canal temperature for the last 4 h, on the contrary, slightly increased by 0.03 ± 0.06 °C showing a significant difference between body core temperature measurements ($P = 0.028$ between the sites). Changes in of $T_{auditory}$ during the entire sleep was the highest and T_{re} at 14 cm depth was the lowest

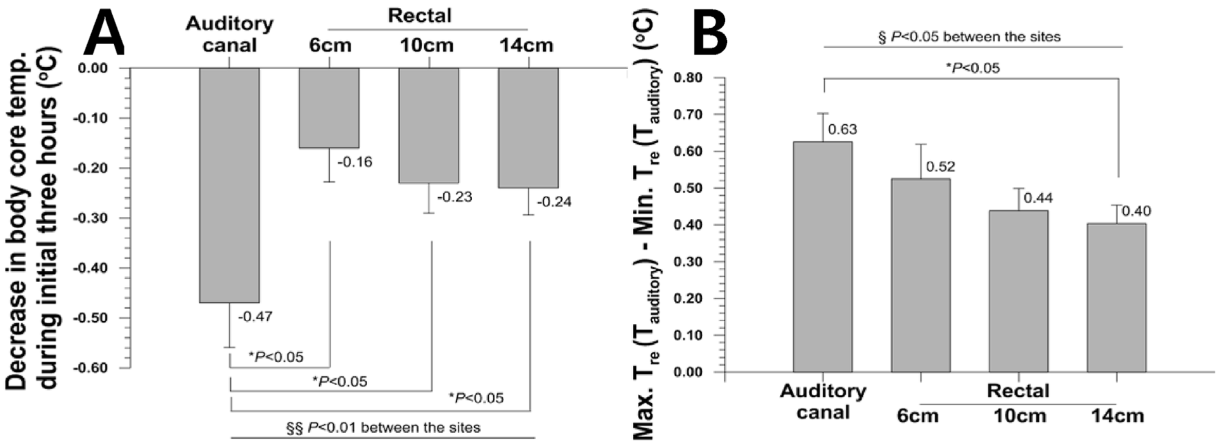

Fig. 3. Decreases in body core temperatures for the first 3 h of sleep (A) and range of body core temperatures during sleep (B).

with significant differences between the sites (P = 0.040) (Fig. 3B).

3.2. Agreement between auditory canal temperature and rectal temperatures at 6, 10, 14 cm depth during sleep

Bland-Altman plots with multiple observations per individual between $T_{auditory}$ and T_{re} at the three depths exhibited no increasing nor decreasing trend, which was demonstrated by no significance of regression analyses (P = 0.659, P = 0.277 and P = 0.084 for Fig. 4–C, respectively). The variability also tended to be evenly distributed across the plot (Fig. 4A–C). The deeper the depth of T_{re} compared to $T_{auditory}$, the greater the magnitude of the bias appeared. Limits of agreement (LOA), on the contrary, were the narrowest in the plot of $T_{auditory}$ and T_{re} at 14 cm depth and the widest in the comparison of $T_{auditory}$ to T_{re} at 6 cm depth (Fig. 4A–C).

3.3. Heart rate, body mass loss, sleep variables and sleep quality questionnaire

Heart rate tended to decline as sleep progressed within a normal range, with an average of 63 ± 1 bpm during the 7-h sleep. Body mass loss during sleep was 34.5 ± 3.2 $g\,h^{-1}$ (21.4 ± 1.5 $g\,h^{-1}.m^{-2}$ per body surface area). There were no differences in the actigraphy variables between the adaptation sleep (1st sleep) and the main experiment (2nd sleep) (Table 1). The sleeps of both trials were evaluated as being normal, according to the sleep variables. Responses in sleep quality questionnaire showed no statistical differences between the two nights except for the following question: How hot was the room you slept in? (P = 0.027, Table 1). The significant difference might be assumed to be due to adaptation to, and feeling more thermally neutral in, the new slightly warm sleeping environment during the second sleep.

4. Discussion

The current study compared auditory canal temperature measured by an infrared wearable device to rectal temperatures at the three rectum depths in 7-h comfort sleep to assess its applicability as a body core temperature estimation during sleep. The body mass loss of 21.4 $g\,h^{-1}.m^{-2}$ was comparable to the previously reported value of 23 $g\,h^{-1}.m^{-2}$ in a normal healthy resting adult in a comfortable environment with no sensible sweating (Kuno, 1956), and thermoneutral sleep environment in the present study was supported by the subjective responses of sleep quality. Those results imply the thermal neutrality of the conditions chosen in the current study. The following two issues will be discussed: First, how much discrepancy is present in T_{re} during sleep according to the insertion depths? Second, to what extent IR $T_{auditory}$ is similar or dissimilar to the T_{re} at different depths during sleep?

4.1. Differences between rectal temperatures at the depths of 6, 10 and 14 cm during sleep

To assess reliability of $T_{auditory}$ to estimate body core temperature during sleep, as compared to T_{re}, it would be meaningful to first address longitudinal temperature differences in the rectum, because T_{re} at the three depths exhibited different tendencies from one anotherTo begin with, T_{re} at 6 cm depth during sleep had a propensity to fluctuate more than T_{re} at 10 cm and 14 cm depths did. Miller et al. (2017) suggested a

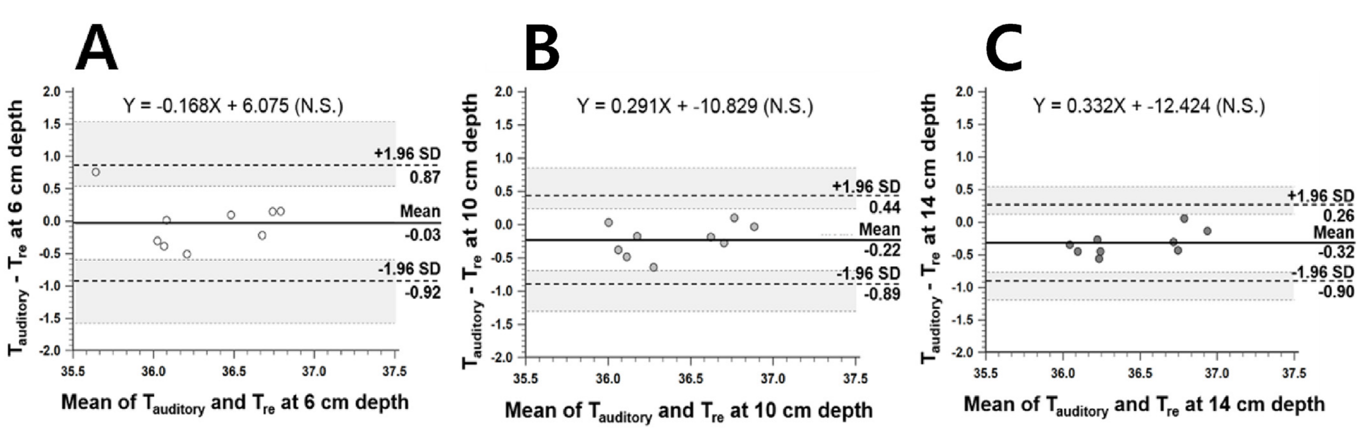

Fig. 4. Bland-Altman plots of auditory canal temperatures and rectal temperatures at 6 cm (A), 10 cm (B) and 14 cm (C) during sleep. Shaded areas show 95% confidence interval for limits of agreement. $T_{auditory}$: auditory canal temperature; T_{re}: rectal temperature.

Table 1
Sleep variables and sleep quality questionnaire for 1st and 2nd sleep.

Sleep variables	1st sleep	2nd sleep	P value
Sleep-onset latency [min]	6.2 ± 2.3	3.8 ± 1.3	N.S.
Sleep efficiency [%]	83.7 ± 3.6	81.1 ± 4.3	N.S.
Number of awakenings [times]	20 ± 2	21 ± 1	N.S.
Average awakening length [min]	2.9 ± 0.5	3.5 ± 0.7	N.S.
Movement index (MI)[a] [%]	12.6 ± 1.9	14.4 ± 2.5	N.S.
Fragmentation index (FI)[b] [%]	15.2 ± 3.1	12.2 ± 3.0	N.S.
Sleep fragmentation index (SFI)[c] [%]	27.8 ± 4.2	26.7 ± 4.5	N.S.
Questionnaire questions[d]			
1. Estimate of the amount of movement during sleep	1.4 ± 0.3	1.4 ± 0.3	N.S.
2. Estimate of depth	2.0 ± 0.4	2.2 ± 0.3	N.S.
3. Estimate of how rested you are upon awakening	2.0 ± 0.2	2.4 ± 0.2	N.S.
4. Spontaneity with which you awoke in morning	1.4 ± 0.4	1.4 ± 0.5	N.S.
5. Estimate of sleep according to dimensions of satisfaction, quality, and disturbance	2.0 ± 0.3	2.4 ± 0.3	N.S.
6. How hot was the room you slept in	1.3 ± 0.4	−0.1 ± 0.4	0.027
7. How humid was the room you slept in	0.3 ± 0.3	−0.1 ± 0.3	N.S.
8. How thermally comfortable was the room you slept in	0.8 ± 0.5	0.4 ± 0.3	N.S.

All data were expressed as mean ± SE (N = 9).
Q.1.0 Tossed all night, 1 Tossed frequently, 2 Neutral, 3 Hardly tossed, 4 Did not toss at all.
Q.2.0 Slept lightly, 1 Slept somewhat lightly, 2 Neutral, 3 Slept somewhat deeply, 4 Slept deeply; Q.3.0 Awoke exhausted, 1 Awoke somewhat exhausted, 2 Neutral, 3 Awoke somewhat refreshed, 4 Awoke refreshed.
Q.4.0 Awoke abruptly, 1 Awoke somewhat abruptly, 2 Neutral, 3 Awoke somewhat spontaneously, 4 Awoke spontaneously.
Q.5.0 Bad night, 1 Somewhat bad night, 2 Neutral, 3 Somewhat good night, 4 Good night.
Q.6. −4 Very cold, −3 Cold, −2 Cool, −1 Slightly cool, 0 Neutral, 1 Slightly warm, 2 Warm, 3 Hot, 4 Very hot.
Q.7. −3 Very dry, −2 Dry, −1 A little dry, 0 Neutral, 1 A little wet, 2 Wet, 3 Very wet.
Q.8. −3 Very uncomfortable, −2 Uncomfortable, −1 A little uncomfortable, 0 Neutral, 1 A little comfortable, 2 Comfortable, 3 Very comfortable.
[a] MI = the percentage of periods with positive value on the Y-axis counts during sleep period.
[b] FI = the percentage of 1 min periods of sleep versus the whole periods of sleep.
[c] SFI = the sum of MI and SFI.
[d] Responses in questionnaire questions were obtained using the following scales.

possible reason for those differences, with probes at deeper depths being enclosed by heavier organs, resulting in steadier values, whereas T_{re} at 4 cm depth reflects temperatures of anal cavity, which is surrounded by only the anal sphincter.

Furthermore, T_{re} at 6 cm depth showed lower values than those measured at the deeper depths by 0.25 °C (vs. 10 cm) and 0.34 °C (vs. 14 cm) on average. The difference of 0.25 °C (6 cm vs. 10 cm depth) is comparable to the decrease of 0.23 °C in T_{re} at 10 cm depth during the first 3 h of sleep; the 0.34 °C difference (6 cm vs. 14 cm depth) can be matched to 0.35 °C difference of T_{re} at 14 cm depth during the whole sleep. In other words, the initial insertion-depth-related temperature gradients correspond to the differences resulting from three or 7 h of heat dissipation or reduced heat production observed during sleep.

The final point to consider when comparing the auditory canal measurement to T_{re} is that the T_{re} gradient found was not linear with changes in measurement depths during sleep. Despite the equal 4 cm gap, differences in the T_{re} between at 6 cm and 10 cm depth were 0.19 °C on average during sleep, which is almost the twice the value between at 10 cm and 14 cm depth (0.10 °C). Similar results showing these gradients at certain depths in the rectum were already suggested by Lee et al. (2010) and Buono et al. (2014) for exercising and resting individuals; they did not find systemic differences between T_{re} measured deeper than 10 cm and 7 cm depth, respectively.

4.2. Comparison between auditory canal and rectal temperatures during sleep

One interesting observation in the present study was that $T_{auditory}$ declined significantly faster during the first 3 h of sleep than the rectal measurements. That difference may be attributed to the two factors: susceptibility of $T_{auditory}$ to ambient temperatures, which is the major limitation of this index, and thermal inertia of the rectum. Indeed, previous studies which compared tympanic membrane temperature and T_{re} (Hashizume, 1997), or which monitored brain and peritoneal cavity temperatures in rats (Alföldi et al., 1990), did not find differences in the temperature decrease between those temperatures during initial sleep. Taylor et al. (2014) reported that an insulated auditory canal temperature can track variations in deep body temperatures and non-insulated auditory canal temperature is easily influenced by ambient temperature. Some might suggest that this mechanism can explain conflicting results between the present study and the aforementioned studies. The fact that the silicone body of the wearable device used in the present study is likely to partially, but not fully, isolate the measurement site from the environment which had an air temperature of 27 °C renders this interpretation more reasonable.

However, apart from the external effects, it is also known that T_{re} shows much slower responses to changes in deep body temperature than $T_{auditory}$ (Lee et al., 2011; Nadel and Horvath, 1970). Therefore, it is probable that the $T_{auditory}$ decrease were faster than T_{re} during initial sleep, because it is a more sensitive index, and it rapidly responds to reduced metabolic heat production and increased heat dissipation to the environment after sleep onset. The more rapid decrease in $T_{auditory}$ contributed to the mean difference of 0.32 °C between $T_{auditory}$ and T_{re} at 14 cm depth during sleep, which seemingly corroborates changes previously reported. For example, Taylor et al. (2014) reviewed that $T_{auditory}$ was lower than T_{re} by approximately 0.4–0.6 °C at rest and during exercise. The magnitude of that difference reported for 'awake' individuals was greater than found in the present study. Direct comparisons between the values observed in waking and sleeping, however, may not be the most appropriate.

Auditory canal temperature measured using the wearable device had similar absolute values to T_{re} at 6 cm depth during sleep with the mean difference of −0.03 °C. However, it is our view that measures at that depth are too variable, and should be discontinued. Moreover, the widest limits of agreement shown by the Bland-Altman plot, and of the most pronounced fluctuation of T_{re} at 6 cm depth during sleep, are probably due to its relatively greater susceptibility to the ambient temperature than the other deeper measurement sites. Therefore, we suggest consideration of T_{re} at 10 or 14 cm depth as a more appropriate reference.

5. Conclusions

We examined $T_{auditory}$ continuously measured using a partially insulated, infrared wearable device during sleep, through the direct comparisons with T_{re} at three different depths. The time courses of $T_{auditory}$ were compared to $T_{auditory}$ to T_{re} at the 6, 10 and 14 cm rectum depths during the entire sleep period. While $T_{auditory}$ was on average 0.32 °C lower than T_{re} at 14 cm depths, limits of agreement were the narrowest in the plot of $T_{auditory}$ and T_{re} at 14 cm depth. We concluded that $T_{auditory}$, measured using the newly-developed wireless device with its silicone head cover, can be a reliable continuous estimate of the changes in body core temperature during sleep, but they are not absolute body core temperature estimations. Last but not least, measuring $T_{auditory}$ is more practical and convenient than measuring T_{re} during sleep. In this regard, $T_{auditory}$ can be used in sleep environments and may be utilized to monitor monthly changes in body core temperature to predict the stage of ovulation for females.

Conflicts of interest

There are no conflicts of interest.

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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.2019.102410.

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