Estimation of body temperature rhythm based on heart activity parameters in daily life

Sooyoung Sim, Heenam Yoon, Hosuk Ryou and Kwangsuk Park

Abstract— **Body temperature contains valuable health related information such as circadian rhythm and menstruation cycle. Also, it was discovered from previous studies that body temperature rhythm in daily life is related with sleep disorders and cognitive performances. However, monitoring body temperature with existing devices during daily life is not easy because they are invasive, intrusive, or expensive. Therefore, the technology which can accurately and nonintrusively monitor body temperature is required. In this study, we developed body temperature estimation model based on heart rate and heart rate variability parameters. Although this work was inspired by previous research, we originally identified that the model can be applied to body temperature monitoring in daily life. Also, we could find out that normalized Mean heart rate (nMHR) and frequency domain parameters of heart rate variability showed better performance than other parameters. Although we should validate the model with more number of subjects and consider additional algorithms to decrease the accumulated estimation error, we could verify the usefulness of this approach. Through this study, we expect that we would be able to monitor core body temperature and circadian rhythm from simple heart rate monitor. Then, we can obtain various health related information derived from daily body temperature rhythm.**

I. INTRODUCTION

Body temperature is one of the physiological signals which reflect individual biological clock. There are several reliable markers of biological clock, such as plasma melatonin and plasma cortisol. However, as body temperature is relatively easy to observe, it is often monitored to examine biological clock or circadian rhythm [1].

Body temperature rhythm and circadian rhythm, which can be extracted from body temperature monitoring, are associated with various health conditions of a body. M.H. Vitaterna, *et al.* mentioned that disruption of circadian rhythmicity within the body is relevant with health problems like altered hormonal function, mental problems, and gastrointestinal complaints [2]. Also, body temperature rhythm can be used for diagnosing and treating the sleep disorders. According to L.C. Lack's research, there was an abnormality of body temperature rhythm in patients with sleep onset insomnia, early morning awakening insomnia, or sleep maintenance insomnia [3]. And researchers tried to treat insomnia by adjusting the phase of body temperature rhythm using light [4]. In addition, changes in body temperature rhythm depending on menstruation cycle were observed from several studies [5, 6]. Therefore, body temperature rhythm has a potential as a gynecological indicator for examining the abnormality of menstruation cycle and predicting the next menstruation. Finally, Kenneth P. Wright *et al.*, identified that there is a correlation between body temperature and human's cognitive function. Specifically, the higher body temperature became, the better cognitive performance was [7].

Although body temperature rhythm is an effect physiological marker for understanding various health conditions as mentioned above, the existing techniques for monitoring body temperature are not suitable for being applied to daily life. Rectal thermometer or oesophageal thermometer can continuously and accurately monitor body temperature. However, they are too invasive to be used in daily life. Meanwhile, it is very easy and convenient to measure body temperature with axillary thermometer or infrared ear thermometer. However, they are not appropriate for continuous monitoring of body temperature because both methods restrict body movements. To accurately monitor body temperature from axillary, users are instructed to fix their upper arm close to torso. Also, long-term tympanic membrane temperature monitoring seems impractical because one of the ears should be plugged. Recently, ingestible temperature capsule was invented to ameliorate the disadvantages of previous devices. And it has been proved that the capsule can be usefully applied to various fields of study [8-10]. However, it is not an economical method as the capsule can no longer monitor body temperature after excretion.

To measure body temperature continuously, noninvasively, and efficiently, many researchers proposed various ideas [11-13]. Especially, M.J.Buller *et al.* suggested a brilliant idea to estimate body temperature based on heart rate monitoring [14]. However, they verified the availability of the method only for the hyperthermia status caused from exercise. In this study, we tried to examine the capability of the method in estimating the body temperature rhythm during daily life. Moreover, we investigated on the usefulness of heart rate variability indices in estimating body temperature. Through this preliminary study, we expect to develop a noninvasive and nonintrusive method to monitor body temperature as well as circadian rhythm in daily life.

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II. Materials and Methods

A. Physiological signals monitoring

Ten young, healthy subjects (8 males and 2 females, Age: 26.6±1.8 years old) were participated in this study. The experimental protocol was designed following the Helsinki Declaration of 1975. Body temperature was measured with ingestible temperature capsule (Philips/Respironics, USA). We validated the accuracy of ingestible temperature sensor with stirred water bath. Then, subject was instructed to swallow the temperature capsule at 9 p.m. After ingesting the temperature capsule, fluids or foods intake was prohibited. To monitor heart rate and heart rate variability, Ag/AgCl gel electrodes were attached on the chest at 10:30 p.m. Subjects were advised to go to bed and wake up according to self-selected sleep-wake schedule. Also, most daily indoor and outdoor activities including rest, study, sleep, and walk were allowed. However, intense exercise was forbidden. To develop and validate the body temperature estimation model, data from 11 p.m. to 10 a. m. were analyzed.

B. Body temperature estimation model

In the study [14], M.J.Buller *et al*. concentrated on the relationship between heart rate and body temperature during exercise. During physical work, body temperature is increased from metabolic heat production. Then, the heart beats faster because blood flow to skin increases and right atrial pressure and filling decreases. As a result, heart rate and body temperature shows positive correlation during exercise. We hypothesized that the relationship between two physiological signals - heart rate and body temperature - would be maintained during daily life. Specifically, as body temperature increases in the morning and decreases at night, we expected that the heart rate would fluctuate depending on body temperature to keep the thermal homeostasis of a body. In addition, as thermoregulation process mentioned above is based on the activity of autonomic nervous system and heart rate variability parameters reflect the activity of autonomic nervous system, we investigated if body temperature can be estimated based on heart rate variability indices.

All of the physiological data were smoothed with Savitzky-Golay filter. Then, mean heart rate (MHR) and normalized mean heart rate (nMHR) were calculated. Also, to find out other valuable parameters in body temperature estimation, we analyzed 10 heart rate variability indices – SDNN, RMSSD, pNN50, LF, HF, TF, VLF, nLF, nHF, and LFHF ratio [15]. Each parameter was computed every 5 min.

To estimate body temperature based on heart activity observations, we introduced extended Kalman filter [16]. Temperature estimation model based on Kalman filter is composed of 'time update model' and 'observation model'. Basically, we applied the same models as those in [14]. However, as shown in Figure 1, we considered various orders of 'observation models' to improve the accuracy of body temperature estimation. Detailed explanation of estimation process is expressed in [14]. Data from 6 randomly selected subjects were used as training data and data from the rest 4 subjects were used as test data.

- Time update model

$$CT_t = a_1 CT_{t-1} + a_0 + f \ \ where\ f \sim N(0,\gamma)$$

- Observation model

$$MHR_t = b_1 CT_t + b_0 + g_1 \ \ where\ g_1 \sim N(0,\sigma_1)$$

$$MHR_t = b_2 CT_t^2 + b_1 CT_t + b_0 + g_2 \ \ where\ g_2 \sim N(0,\sigma_2)$$

$$MHR_t = b_3 CT_t^3 + b_2 CT_t^2 + b_1 CT_t + b_0 + g_3 \ \ where\ g_3 \sim N(0,\sigma_3)$$

Figure 1. Example of body temperature estimation model based on heart activity parameter - mean heart rate (MHR) (CT: core body temperature, t: time point, a_i: time update model coefficients, f: noise, γ: Standard deviation of the discrete probability distribution of ΔCT, b_i: observation model coefficients, g: noise, σ_i: Mean of the standard deviations of heart-related parameter values binned by CT at 0.1˚C interval)

III. Results

To figure out which heart activity related parameter shows strong correlation with body temperature, we calculated Spearman rank correlation coefficient. As a result, 5 parameters had relatively strong correlation with body temperature (Figure 2). Then, we set up temperature estimation models using training data. In total, one time update model and 15 observation models (three models from each heart activity parameter) were verified to estimate body temperature rhythm.

Finally, we verified the performance of temperature estimation models using test data. As a result, we confirmed that most of the 5 heart activity related parameters could be utilized for body temperature estimation (Figure 3). And as shown in Table Ⅰ, we calculated RMSE (root mean square error) and bias to evaluate and compare the performance of each model.

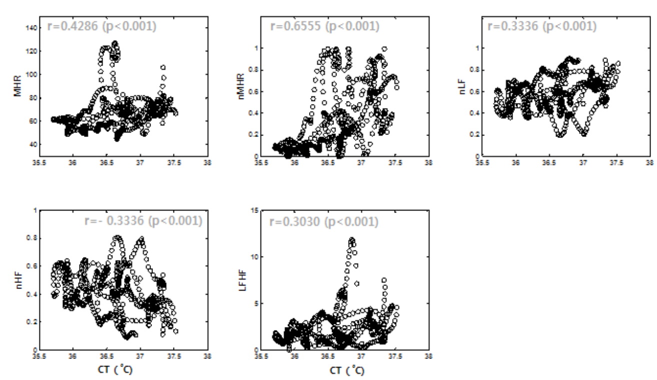

Figure 2. Five heart activity related parameters which showed relatively strong correlation with body temperature (r: Spearman rank correlation coefficient)

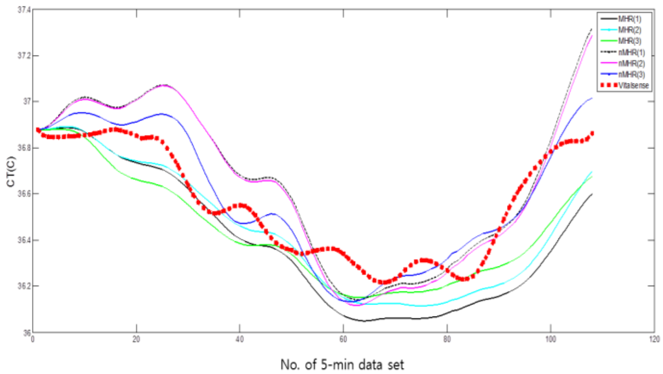

Figure 3. Example of body temperature estimation from heart activity related parameters - MHR and nMHR – in one subject. The red dotted line shows measured body temperature rhythm with ingestible temperature capsule.

TABLE I. BODY TEMPERATURE ESTIMATION RESULTS USING VALIDATION DATA (4 SUBJECTS)

Heart related parameters	Order of observation model	RMSE (˚C)	Bias (˚C)
MHR	1	0.62	0.13
	2	0.95	-0.32
	3	0.53	0.02
nMHR	1	0.38	-0.01
	2	0.37	0.00
	3	0.35	-0.00
nLF	1	0.42	-0.11
	2	0.39	-0.16
	3	0.45	-0.29
nHF	1	0.42	-0.11
	2	0.39	-0.16
	3	0.45	-0.29
LFHF	1	0.39	-0.07
	2	0.43	-0.12
	3	0.75	-0.21

IV. DISCUSSION AND CONCLUSION

We established the body temperature estimation model based on characteristics of heart activity. And this approach was inspired from the research of M.J.Bullers *et al* [14]. Even though the model of both studies is based on extended Kalman filter method, we applied novel parameters to estimate body temperature. Also, we verified the capability of this model for accurately monitoring body temperature in daily life. Among various heart related parameters, nMHR, nLF, nHF, and LFHF ratio could estimate body temperature with RMSE no more than 0.40˚C (Table Ⅰ). Normalized MHR showed better performance than MHR because baseline heart rate is different from individual to individual. Standardized spectral compounds (nLF and nHF) with quadratic observation model could accurately estimate the body temperature rhythm. Also, LF/HF ratio which reflects sympathovagal balance seemed to be useful to estimate body temperature which is the result of balance between sympathetic and parasympathetic activities. However, we can't estimate body temperature in real time when using normalized MHR. Therefore, we concluded that frequency domain parameters of heart rate variability such as nLF, nHF, and LFHF seems most useful because it can accurately estimate body temperature as well as require less delay – about 5 minutes - than normalized MHR.

Although we could acquire promising results, there are still some challenges that we have to consider. First of all, to improve the reliability of this method, we should include more subjects. Also, it seems that the estimation error gets bigger as time passes. And this is because the errors are accumulated. To accurately estimate body temperature for longer than 24 hour and acquire circadian rhythm, we should consider additional approaches to reduce the estimation error.

In conclusion, we confirmed the possibility that we can estimate body temperature rhythm from heart activity monitoring. And the technology validated in this study offered a potential to replace the previous invasive or intrusive thermometers. We expect that this method can provide great applicability in various fields such as chronobiological study, sleep disorders treatment, and gynecologic research. In future study, we will consider other useful algorithms to develop more accurate body temperature estimation models and validate its performance with subjects from diverse groups. Also, we would apply this method to long-term data to verify its performance for measuring circadian rhythm.

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