Feasibility of Continuous Monitoring of Core Body Temperature Using Chest-worn Patch Sensor

Paurakh L. Rajbhandary and Gabriel Nallathambi

Abstract— **With rapid advancement in wearable biosensor technology, systems capable of real time, continuous and ambulatory monitoring of vital signs are increasingly emerging and their use can potentially help improve patient outcome. Monitoring continuous body temperature offers insights into its trend, allows early detection of fever and is critical in several diseases and clinical conditions including septicemia, infectious disease and others. There is a complex interaction between physiological and ambient parameters including heart rate, respiratory rate, muscle rigors and shivers, diaphoresis, local humidity, clothing, body, skin and ambient temperatures among others. This article presents feasibility analysis of a wireless biosensor patch device called as VitalPatch in capturing this physio-ambient-thermodynamic interaction to determine core body temperature, and details comparative performance assessments using oral thermometer and ingestible pill as reference devices. Based on a study on a cohort of 30 subjects with reference oral temperature, the proposed method showed a bias of 0.1 ± 0.37 ºC, mean absolute error (MAE) of 0.29 ± 0.25 ºC. Another cohort of 22 subjects with continuous core body temperature pill as reference showed a bias of 0.16 ± 0.38 ºC and MAE of 0.42 ± 0.22 ºC.**

Clinical Relevance— **Non-invasive, continuous and real time body temperature monitoring can lead to earlier fever detection and provides remote patient monitoring that can result in improved patient and clinical outcome.**

I. Introduction

Core temperature is the temperature measured at the deep tissues of the body such as abdominal, thoracic and cranial cavities [1-2]. The hypothalamus is the controlling center for body temperature regulation, and is fed by heat sensing thermoreceptors in different locations in body including skin, cornea, urinary bladder, liver and hypothalamus. Hypothalamus regulates temperature via. mechanisms such as conduction, convection and radiation mechanisms to maintain temperature typically within a narrow margin normally between ~36.5-37.5 ^{o}C [3, 4]. Continuous body temperature is an important parameter for monitoring potential onset and progression of cardiac arrest, head trauma or stroke, infectious and other non-infectious diseases, where an increase in core temperature is often observed [5].

The choice of temperature measurement mode often depends on combination of patient condition, the need to assess rapid change in temperature, invasiveness of the probe, accuracy and comfort of patients. In an ICU setting, body temperature may be monitored by a more invasive mode such as pulmonary (usually considered the gold standard) or urinary catheter, rectal probe, or in some severe cases even using intracerebral probe using trepanation [5, 6]. Although these methods provide a more continuous and accurate body temperature profile, these methods are invasive, often restricts the patient to bedside and requires indication of a more complicated procedure to insert these probes. Ingestible wireless temperature probe capsule has also been used, but it comes with its limitation of high cost, limited duration of operation (12-48 hours) based on gastrointestinal motility, need to wear a receiver vest or unit and sensitivity to local influence including temperature of proximal organ, ingested food and beverage [7, 8].

In a general ward, relatively non-invasive approach for temperature monitoring such as oral, infrared temporal artery, tympanic, or axillary thermometer are more commonly used in a spot check setting and usually does not provide continuous body temperature trend [9-11]. These modes are also prone to human error and due to non-invasive nature of its measurement may be affected by external influences including perspiration, ambient temperature, etc.

Numerous studies have highlighted earlier detection of patient deterioration, lower code blue rates, reduced length of stay, improved patient outcomes and cost effectiveness with continuous non-invasive vital sign monitoring [12, 13]. Towards this goal, we developed a fully disposable wireless patch sensor called as VitalPatch® for continuous remote patient monitoring in hospital and home settings. Based on clinical performance validation in 57 subjects, VitalPatch biosensor demonstrated clinically acceptable accuracies for monitoring of vital signs such as heart rate, breathing rate, and skin temperature, in addition to measures of activity such as measures of activity such as posture detection, pedometer step count, and fall detection [14]. While skin temperature has been studied as a surrogate of patient status in numerous works [15, 16], it may not capture the true dynamics and trends of core temperature. To this end, the next generation of VitalPatch biosensor is enhanced with new sensing functionalities for continuous non-invasive monitoring of core body temperature.

In this article, the performance of continuous core body temperature output of VitalPatch is validated against reference spot check and continuous temperature measurements from oral thermometer and ingestible pill respectively. We demonstrate the potential of the device to continuously

P. L. Rajbhandary is with VitalConnect Inc., San Jose, CA 95110 USA (corresponding author to provide phone: 408-963-4600; e-mail: prajbhandary@vitalconnect.com).

G. Nallathambi is with VitalConnect Inc., San Jose, CA 95110 USA (corresponding author to provide phone: 408-963-4600; e-mail: gnallathambi@vitalconnect.com).

monitor core body temperature, and discuss the clinical implications of the presented work.

II. Materials and Methods

A. Theoretical Background

Complex interaction between physiological and ambient parameters including heart rate and its change, respiratory rate, muscle rigors and shivers, diaphoresis, ambient humidity, clothing, body, skin and ambient temperatures among others have been previously reported. For example, Liebermeister's rule states that for each degree Celsius (ºC) rise in body temperature, there is approximately an eight beats per minute increase in heart rate, although there are exceptions like pulse-temperature dissociation also known as Faget sign in diseases like yellow fever, tularemia and salmonella typhi [17, 18]. Muscle rigors and shivers, diaphoresis can also be caused during fever as mechanism to change core body temperature [19, 20]. Several prior works have attempted to estimate the core body temperature either using just surficial temperatures [15,16], or by utilizing other physiological and environmental parameters [21-26]. Feasibility of a method that utilizes a rich stream of vital signs, activity metrics, ambient information and other physiological parameters measured continuously and wirelessly by VitalPatch along with input (re)calibration temperature to estimate continuous core body temperature is presented and discussed.

B. Experimental set-up and protocol design

A 30 subject cohort study was conducted where subjects wearing the VitalPatch biosensor on the left chest for 3 days continued their activity of daily living with reference oral temperature measured using Welch Allyn SureTemp® Plus 690 hand held oral thermometer 10-16 times a day, each with three independent measurements. Manufacturer's specification states SureTemp® Plus 690 has a calibration accuracy of ±0.1 °C in the ambient operation range of 10-40 °C for body temperature range of 26.07 to 43.3 °C and has a settling time for oral measurement of 4-6 seconds. Subjects are trained and instructed to make the measurements themselves. One of the limitations of this spot check measurements is lack of continuous data and especially when the subject is sleeping or away from the reference device. This poses a challenge to capture the trend and variations that may be caused due to circadian rhythm and other factors.

To overcome the limitation of spot check measurement, a second similar 3-day study with 22 subject cohort is conducted with a continuous reference body temperature captured by ingestible VitalSense core temperature capsule. The VitalSense capsule is a 23 mm long x 8.6 mm diameter biocompatible polycarbonate pill that weights 1.6 gm, has the following manufacturer specification: an accuracy of ± 0.1 °C (32 °C to 42 °C), ± 0.25 °C (25 °C to 32 °C) and ± 0.25 °C (42 °C to 50 °C), data resolution of ± 0.01 °C, sensing range of 25 °C to 50 °C, battery life of up to 240 hours of active transmission with one year of shelf life [7]. VitalSense capsule wirelessly transmits the data to Sensor Electronic Module receiver worn in an Equivital LifeMonitor system vest and provides the core body temperature measurement every 15 seconds. In both studies, subjects were provided with a detailed instruction to annotate their daily activities, food intake, clothing, sleep time, etc., to contextualize any variation of relevant parameters.

C. Performance Metrics

Core body temperature determined using VitalPatch is interpolated with nearest-neighbor scheme to the reference body temperature that is within the window of 15 minutes prior or later to produce time aligned estimated and reference body temperature. This interpolation scheme ensures that the estimated temperature is compared to the reference temperature that is at the farthest 15 minutes apart. The following performance metrics are estimated:

$$b = \frac{1}{n}\sum_{j=1}^{n}\frac{1}{N_j}\sum_{i=1}^{N_j}(t_{b_{i,j}} - \tilde{t}_{b_{i,j}}),$$

$$MAE = \frac{1}{n}\sum_{j=1}^{n}\frac{1}{N_j}\sum_{i=1}^{N_j}\left|t_{b_{i,j}} - \tilde{t}_{b_{i,j}}\right|$$

where b and MAE are the estimated bias and mean absolute error calculated per subject, respectively, n is the total number of subjects, N_j is the total number of sample pairs for the j^{th} subject, $t_{b_{i,j}}$ and $\tilde{t}_{b_{i,j}}$ are the i^{th} sample point of the reference and estimated core body temperature respectively. 95% limits of agreement are also reported.

Based on both cohorts with oral and ingested capsule reference temperature, the bias and MAE are calculated for reference and estimation pair calculated for data collected per subject and an aggregated mean (μ) and standard deviation (σ) statistics is calculated so that contribution from each subject is treated equally by weighting data based on number of samples available for each subject. Analysis is performed for body temperature estimated based on a single initial calibration and on daily recalibration.

III. Results

A. Comparison to Oral Reference Temperature

Figure 1 shows an illustration of a subject's continuous body temperature estimated using VitalPatch over 3-day period along with reference oral temperature measurements. The diurnal circadian rhythm of the body temperature is visible as periodicity in the signal with approximate time period of 24 hours. Reference temperature are not available when the subject is asleep and leads to reference data gap during this time for comparison.

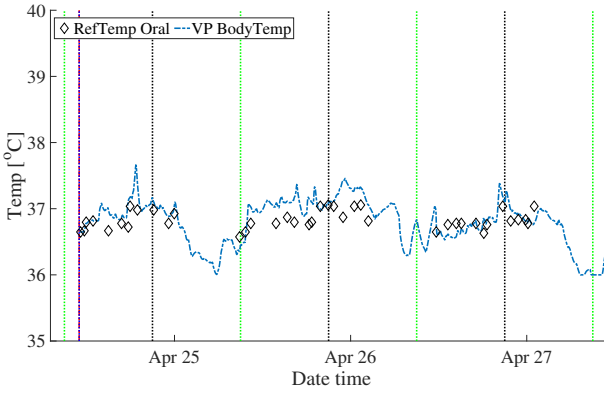

Figure 1. Estimated body temperature with single initial calibration and spot oral reference temperature over multi-day period. Green/black vertical dotted lines are 9 AM/PM. X-axis tick marks show the beginning (00:00 AM) of respective day.

For the cohort of 30 subjects with reference oral temperature, the bias and MAE for single calibration is -0.11 ± 0.28 ºC and 0.29 ± 0.15 ºC, respectively. The 95% limit of agreement with reference oral are (-0.66,0.44) ºC with single calibration. If daily calibration performed, the bias and MAE improves slightly to -0.08 ± 0.27 ºC and 0.27 ± 0.15 ºC, respectively.

TABLE I. PERFORMANCE OF VITALPATCH'S MEASUREMENT OF BODY TEMPERATURE.

Ref Dev	Cal Freq	$\mu_b \pm \sigma_b$ (ºC)	$\mu_{MAE} \pm \sigma_{MAE}$ (ºC)	#Data
Oral	Initial	-0.11 ± 0.28	0.29 ± 0.15	984
	Daily	-0.08 ± 0.27	0.27 ± 0.15	984
Capsule	Initial	0.16 ± 0.38	0.42 ± 0.22	153987
	Daily	0.08 ± 0.24	0.36 ± 0.11	153987

B. Comparison to Ingestible Core Temperature Capsule Reference

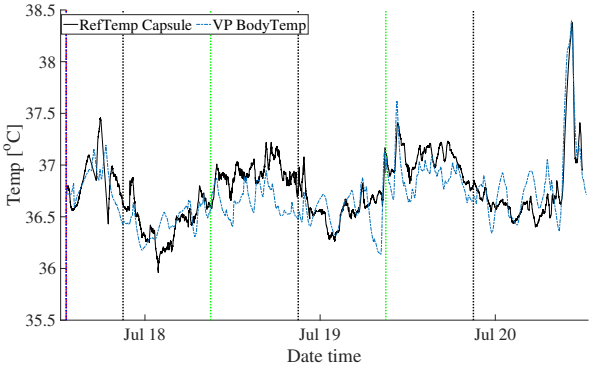

Figure 2. Estimated body temperature with single initial calibration and ingestible capsule reference temperature over multi-day period. Green/black vertical dotted lines are 9 AM/PM. X-axis tick marks show the beginning (00:00 AM) of respective day.

An illustration for a subject's core body temperature based on ingestible capsule and VitalPatch estimated body temperature is shown over multi-day period in Figure 2. The diurnal circadian pattern with approximate periodicity of 24 hours is clearly visible in both profiles. A larger number of reference temperature is available due to higher sampling frequency of the capsule capturing temperature measurement every 15 seconds instead of manual temperature recording performed manually. Over the 22 subjects, the bias and MAE for single calibration is 0.16 ± 0.38 ºC and 0.42 ± 0.22 ºC , respectively. The 95% limit of agreement with ingestible capsule are (-0.59,0.91) C using single calibration. Slight improvement is seen in the metric with daily calibration, yielding bias of 0.08 ± 0.24, MAE of 0.36 ± 0.11and 95% limit of agreement of (-0.39,0.55) ºC. Overall results from both cohort is summarized in Table I.

Continuous core temperature captures not only the trend information that may be missed by manual spot measurements, but also the changes in body temperature due to circadian rhythm during sleep. However, it was observed that the ingestible capsule was susceptible to change in temperature fluctuation due to consumption of cold or warm food and beverage during the early few hours of ingestion of the pill. This resulted in few spikes in the ingested capsule measurement.

C. Effect of calibration

The proposed solution provides a continuous estimation of core body temperature, and when available and provided, it can utilize an independent core body temperature estimate to recalibrate the algorithm and minimize potential errors. This is seen in a slight improvement in performance with the daily calibration process. The bias and MAE for reference oral temperature using daily calibration is -0.08 ± 0.27 ºC and 0.27 ± 0.15 ºC, respectively. The bias and MAE for reference core pill temperature using daily calibration 0.08 ± 0.24 ºC and 0.36 ± 0.11 ºC, respectively. The 95% limit of agreement using daily calibration are (-0.61,0.45) ºC, and (-0.39,0.55) ºC with reference oral and ingestible capsule respectively.

IV. DISCUSSION

Continuous and direct measurement of patient skin temperature is straightforward using thermistor or thermoreceptor elements. Direct skin temperature with added two degrees have also been used as a surrogate of core temperature [27]. However, skin temperature measurement is often contaminated by external sources including ambient temperature, clothing, sun exposure convection of air, etc.

Feasibility study of continuous body temperature-based chest worn biosensor presented highlights the importance of continuous temperature profile in tracking trends, sudden changes and temperature that are not captured by spot check measurements. The study showed that the circadian rhythm that is not captured by spot oral thermometer but captured by ingestible pill is clearly tracked using the evaluated body temperature estimator. These temporal changes can have important clinical implications specifically in cases when acute changes in temperature provides early insight into clinical indication.

Several solutions have proposed utilizing heat flux and isothermal pathway method to continuously assess body temperature in perioperative setting [28]. Despite being continuous methods that offer better accuracy than skin temperature with added approximately +2 C, these methods have fundamental limitation of not being ambulatory. Utilizing additional information including physiological, activity based and ambient measurements that have been shown to be correlated to body temperature may provide additional information to further improve the accuracy of body temperature. In addition, the proposed method is a truly an ambulatory solution which has been tested in the presented study in different daily activities indoors and outdoors.

The validation of the evaluated body temperature measurement shows highly accurate, continuous and ambulatory body temperature monitoring that may be utilized

for improving patient outcome through early detection of changes in body temperature.

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