Non-invasive Core Body Temperature Sensor for Continuous Monitoring

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***Abstract*—Lab-on-skin technology is one of the wearable devices that have been massively developed in recent years for continuous remote monitoring of health performance including core body temperature (CBT). The needs in supervising the CBT is crucial for medical purposes and athletes and army to avoid heat stroke due to high external temperature and physical exertion. The most accurate measurement of CBT is rectal or oesophagus temperature, but this invasive method is not applicable and comfortable for continuous monitoring. Thus, this research proposes a new development of the wearable temperature sensor by using single-heat-flux concept with integration of wireless transceiver module that can transmit data wirelessly to other devices. This paper provides CBT sensor device development and experimental results of the sensor on several parts of the body. Experiment reveals that CBT estimation on the forehead is the most reliable as it gives smallest mean difference between CBT device and a commercial clinical thermometer, 0.05°C whereas behind ear and wrist gives 0.15°C and 0.37°C.**

***Keywords*—wearable, core body temperature, single-heat-flux**

I. Introduction

Keeping body temperature at normal boundaries is very important as the irregular ranges can cause to ill conditions. Physiologically, the human body has thermoregulation process where it normally keeps regulating body temperature to normal boundaries despite changes in the environment. With the protection of the skin and antibody somehow there is a possibility when the body can no longer maintain the temperature at the regular range due to extremely hot or cold environment and infection. This condition will trigger the thermoregulatory responses where the body reacts according to the situation. Hypothermia is defined as a condition of human when it already reaches cold temperature while hyperthermia is a human body response when it reaches higher temperature. Hypothermia most likely happens to firefighters, soldiers and athletes who perform heavy training or labourer who work outside the building under extreme exposure of heat [1]–[3].

Hyperthermia and hypothermia conditions may not possibly happen normally unless a proper action is taken care quickly, for example covers with adequate layers of clothes or blankets and drinks a lot of water. However, fever is a body condition that normally happens, and it is one of the earliest symptoms to a potentially life-threatening infection and even seizures. Therefore, monitoring temperature continuously is important so that fever can be detected as quickly as possible and immediate treatment from the doctor can be done.

This paper covers CBT sensor device based on single-heat-flux concept which is suitable for wearable and continuous monitoring of CBT. The device is integrated with a wireless module for remote and continuous monitoring. A validation on the reliability of the CBT device is performed by comparing measurements from developed CBT device and a commercial infra-red contact thermometer.

II. Related works

Temperature is one of the ancient yet a vital indicator to designate a certain condition especially for the human body system. The simplest method to diagnose fever is by placing hands on the forehead or any part of the skin to feel the heat, however it is not accurate. The first technology to measure temperature that was invented was in 1592 which is the air thermometer by Galileo [4]. The thermometry device was then innovated as the decades went by to different kinds of forms from bulky mercury thermometer to digital thermometer. Up until recently, researcher is still studying on developing and improving temperature sensor especially on measuring core body temperature. Based on Intensive Care Unit (ICU) standard, the most accurate CBT reading is from internal temperatures such as rectal, pulmonary and esophageal temperature, however the measuring approach is invasive which causes uneasiness to the patient thus it is not suitable for continuous monitoring [5], [6]. Therefore, non-invasive approaches include microwave radiometry [7], [8], zero-heat-flux (ZHF) [5], single-heat-flux (SHF) [9], [10] and dual-heat-flux (DHF) [3], [11]–[13] are introduced.

Microwave radiometric thermometer focuses on deep tissue temperature monitoring to assist speedy recovery from hypothermia that occurs during perioperative care. Several works on near-field radiometry for wearable purpose has been developed [7], [8]. Even though miniaturization on this approach is feasible, the bulky size of the antenna along with the radiometer device is still not suitable for wearable concept in general application of CBT monitoring by general users, not only in the hospital.

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R. Fox first has designed the "zero heat flux" concept [14] where the device consists of a heater outside the device supplies maximum heat to the skin and the sensor creates a perfect insulation zone to trap heat from loss to the environment. Thus, the skin temperature (T_{skin}) that is measured by the sensor is assumed to equal to the CBT (T_{core}). Popular ZHF commercial sensor is SpotOn by 3M where it is applied in many hospitals for preoperative and postoperative care [5], [15]. However, the continuous heating element is not applicable for wearable purpose.

For SHF and DHF case, the usage of a heater is eliminated by taking other additional parameter into account which is device temperature (T_{device}). SHF uses single temperature sensor for each T_{skin} and T_{device} meanwhile DHF applies two sensors for each parameter. Gunga *et al.* [10] introduced SHF to study relationship between CBT and heat strain in human according to various surrounding temperature. Then, they extended the research on their headband-SHF device to study human CBT in earth and space [16].

In comparison to SHF, more parameters in term of temperature are considered in DHF, which this method is applicable for a device that has an asymmetrical thickness between two measuring points. In 2009, Kitamura *et al.* introduced a new DHF device to estimate core body temperature without the need for a heater. Its thermometer probe looks similar to stethoscope probe-shape that is covered with urethane sponge to insulate from heat loss. This research had been improved by many works, including Tamura *et al.* [3] and Song *et al.* [13].

III. System Description

This section discusses on formation of SHF equation for the CBT device and details on construction of CBT device system and hardware.

A. Core Body Temperature Derivation

Single-heat-flux system that is implemented in this CBT sensor device is conceptualized in Fig. 1. This concept shows heat flow from two layers which are the core body and the CBT device. The CBT device has two thermistors that are placed on different locations; outward to the skin (T_{skin}) and top of the device (T_{device}). The estimation of CBT is based on linear heat flow in sensors during equilibrium only, not covering during cooling down or heating up process.

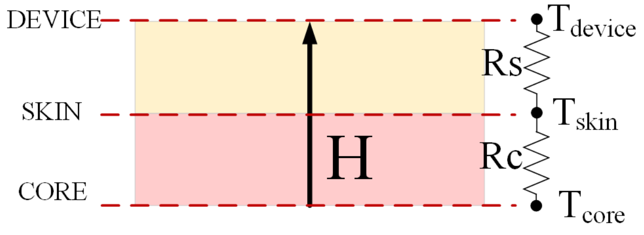

Fig. 1. Heat flow concept across core body part to outer of the device.

Equation (1) can be simply derived based on Fig. 1. where R_s is defined as thermal resistance of the device (between two sensors) while R_c is thermal resistance of the core body (area under bottom sensor).

$$T_{core} = T_{skin} + \frac{R_c}{R_s}(T_{skin} - T_{device}) \tag{1}$$

R_s and R_c from (1) are determined from thermal conductivity, k of respective material where in this case referring to Fig. 1, the materials are human skin and the device cover which is Ethylene-vinyl Acetate foam (EVA foam). Thermal conductivity of human skin is 0.37W/mK whereas EVA foam has lower thermal conductivity values 0.038W/mK.

B. System Overview

Wireless CBT measurement system can be categorized into two parts which are transceiver (CBT device) and receiver (laptop). The configuration of the hardware system of CBT measurement is shown in the block diagram, Fig. 2. The CBT device is controlled by ATMega328, 8MHz chip which is embedded on the Arduino Pro-Mini. Two Beatherm NTC thermistors act as input for the device meanwhile two NRF24L01 2.4GHz wireless modules are used as transmitter and receiver in the system. The CBT device is powered by a 3.7V Li-Po battery.

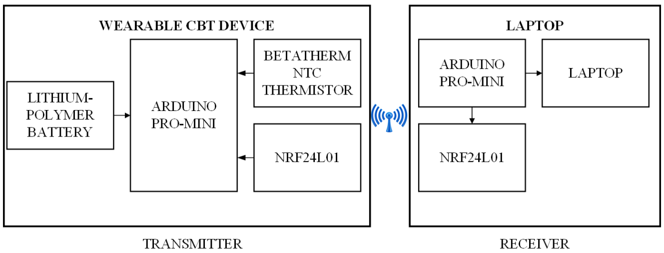

Fig. 2. Block Diagram of Wearable CBT Sensor Wireless System.

When powered up the CBT device, thermistors will take reading of respective temperature and directly send arrays of data to the receiver while receiver will store the data in the Excel file.

C. Hardware

Developed CBT sensor device aims to be applicable for remote monitoring and most importantly is convenient to all different users regardless their gender and age. By implementing the system, Arduino Pro-mini, NRF24L01 and the thermistors are combined as shown in Part A in Fig. 3.

EVA Foam is used as the protective layer to cover the CBT device because of it has low thermal conductivity is good to isolate the ambient temperature to interrupt temperature value in the device. Before the device is encapsulated with the foam, the circuit modules are covered so that each thermistor can be placed on top and bottom of circuit modules. Part B in Fig. 3 shows a thermistor placed on top of covered circuit modules. The top thermistor is placed upward to measure T_{device} while the bottom thermistor's disc which is applied

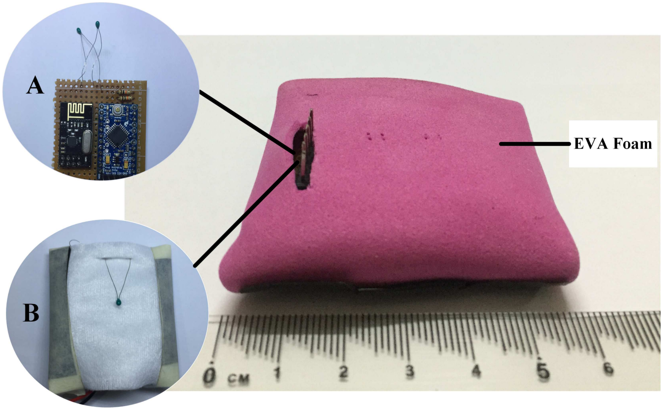

Fig. 3. Developed CBT sensor device with main controller, temperature sensors and a wireless module.

to measure T_{skin} is exposed outside the device so that the disk surface will touch the skin.

IV. Experiment

The main purposes of the experiment are to verify the reliability of the CBT sensor device and to confirm that different parts of human body has different body temperature. The experiment is conducted on five volunteered participants in a room with average ambient temperature, T_a=31.5±0.62 °C and average humidity, H=52.39±1.15%.

Each participant is seated while the temperature is taken. Body temperature reading is measured on several places on the body which are forehead, behind ear, and wrist. The developed sensor device is used to take real measurement of temperature for all specified sites whereas HuBDIC Dotory Contact Forehead thermometer, FS-201 is used to take temperature, T_{ref} at the same sites as a reference. This thermometer is specialised to take forehead, behind ear and surface temperature thus the reading is promising for any contact parts of the body. FS-201 thermometer is also used to keep taking T_a and H value to monitor the control variable of the experiment.

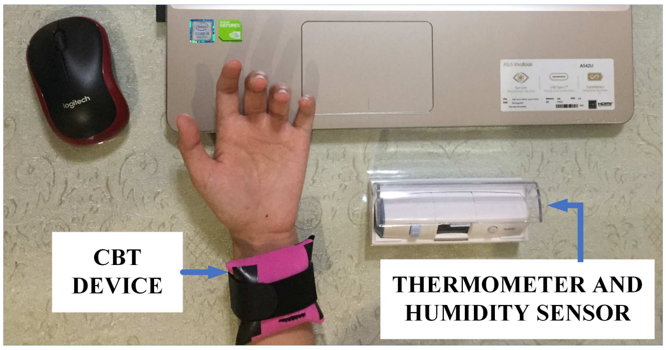

Fig. 4. User study setup of CBT measurement on wrist.

For forehead and behind ear measurement, participant wore headband that attached the sensor device under it while the device is place and tighten on the wrist by using an action camera wrist strap. Temperature is taken on each site for five times with 2-minute interval for the sensor to cool down. Fig. 4 shows the experimental setup where it shows participant's hand with the CBT sensor device placed on the wrist is resting on the table.

V. Results

The results are based on the experiment that was conducted under controlled ambient temperature on five participants. The results that were measured by the CBT device is then recorded into (1) to calculate estimation of T_{core}.

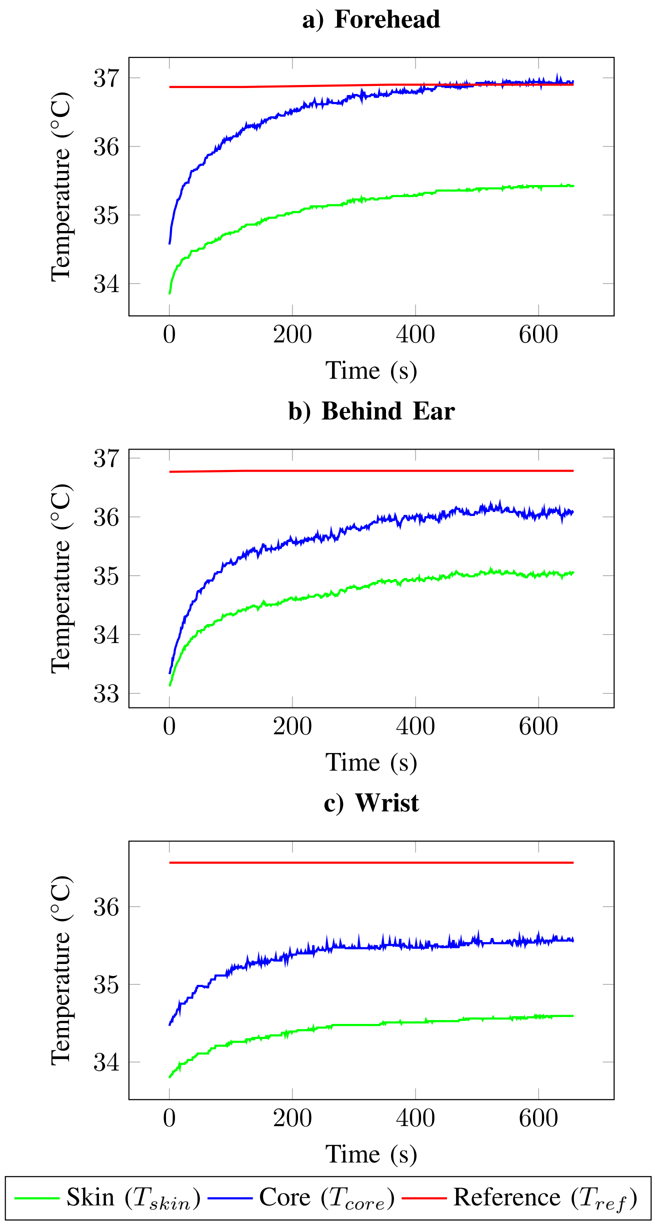

Fig. 5. Average temperature of measured skin temperature, reference temperature and estimated core temperature at a) forehead, b) behind ear and c) wrist.

The average of the measured T_{skin}, T_{ref} and estimated Tcore for all participants is demonstrated graphically in Fig. 5. From Fig. 5, it can be seen that the hotter site takes time for the sensor to settle before it reaches its equilibrium state compared to the less hot site. The CBT sensor device takes 550 seconds (9.17 minutes) to reach steady-state on forehead whereas it takes 499.8 seconds (8.33minutes) for behind ear measurement. Wrist temperature measurement is the fastest compared to the other sites as it only takes 300 seconds (5 minutes) to settle.

To sum up based on reading after it reaches equilibrium, the mean difference between estimated T_{core} for forehead and measured T_{ref} on the forehead is $0.05\,°C$ while the mean difference of T_{core} and T_{ref} for behind ear measurement is $0.15\,°C$ and last but not least, the mean difference of T_{core} and T_{ref} on the wrist gives $0.37\,°C$. Comparison between each estimated core temperature is shown in Fig. 6.

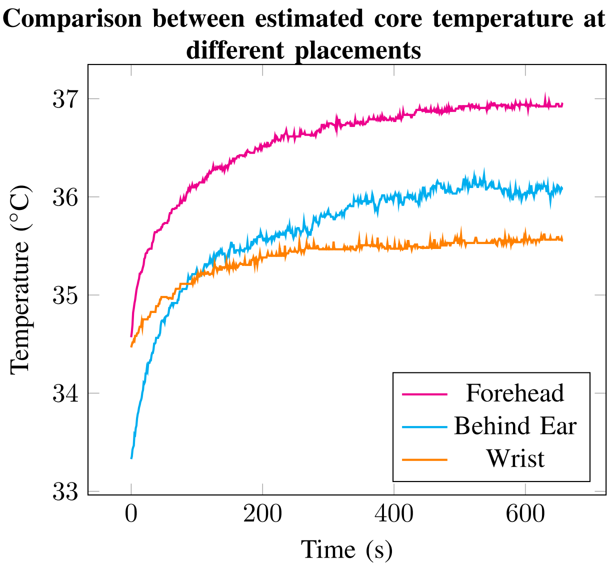

Fig. 6. Body temperature measurements at forehead, behind ear and wrist.

VI. Conclusion

Based on the experiment, it can be concluded that CBT temperature on the forehead is the highest compared to other placements. CBT measurement on forehead is more promising than the other areas as its difference from reference temperature is very small which is $0.05\,°C$. The results on behind-ear temperature measurement should give higher reading than this obtained result as biologically, behind ear is one of the most heated part of the body. However, the estimated core temperature on behind-ear is less than expected due to the sensor placement as it is contacted on the skin by hanging it on under the headband and it is easily moved so the sensor might be partially contacted with the skin.

To prove more promising measurement, a study of larger group must be conducted with a variety of age and physiological in the future. This study has only shown data of core body temperature during resting but at the same time this case can be implemented to get basal body temperature for learning circadian rhythm. Moreover, the device should also be tested on different range of temperature to give more sets of data to validate.

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