Report: Core body temperature sensing on human wrists by JIRS30 heat flux sensor

Abstract

Core Body Temperature (CBT) is one of the most fundamental indicators of human health. Yet, methods to measure CBT remain invasive and often limited to clinical environments. Here, we present JIRS30 heat flux sensor from Jondetech Sensors AB and show how it can realize continuous core body temperature monitoring in a wrist device coupled to an algorithm. By using this system, metrics (amplitude, phase shift) of the circadian rhythm can also be captured. The study included six participants with a combined monitoring time of 282 subject days. Over the human temperature span of 35.5-37.6 °C, the system gives an average bias of less than 0.2 °C and a correlation factor of 0.72 when compared to thermometer pills. The system had a performance which makes it highly relevant for use in continuous core body temperature monitoring on human wrists.

Introduction

Core body temperature (*CBT*) is one of the most fundamental indicators of human health[1]. It reflects what is happening inside the body: metabolism, hormonal changes, immune response, stress and recovery[2].

However, measuring CBT continuously and accurately has always been a challenge[3]. Most existing solutions are invasive, uncomfortable, or too large and power-hungry for everyday use[4]. Mouth and ear thermometers are impractical for long-term monitoring. For measurements on skin (e.g. wrists, forehead, torso), contact thermometers and today's common consumer devices using infrared sensors, fail to accurately measure CBT, since skin temperature alone cannot capture the thermal conditions inside the body[5].

CBT also captures the human circadian rhythm[6]. The circadian rhythm is important because it regulates 24-hour cycles for numerous bodily functions and disruptions of it is linked to health implications.

In this study, the heat flux sensor JIRS30 from Jondetech Sensors AB was integrated into a wrist device to form a wearable system which is typical of clocks and armbands. By the system and a coupled algorithm — CBT can be monitored. In the study, the output of the system was benchmarked against reference methods when worn on humans.

Method

Device description

The hardware consisted of three main blocks. The microcontroller (*MCU*) block (XIAO nRF52840 Sense Plus, Seeed Studio) consisted of an MCU (nRF52840, Nordic) and a rechargeable 3.7 V LiPo battery. The board had an onboard antenna for Bluetooth low energy (*BLE*) communication. The sensor block consisted of JIRS30 that measures heat flux vertically and a temperature sensor (TMP117, Texas Instruments). The sensors were mounted on a printed circuit board (*PCB*). They were sealed and separated by FR4 with low thermal conductivity and aluminum with high thermal conductivity. The chamber of JIRS30 was filled with wax (Bectron MR 3406, Elantas) that had a similar thermal conductivity to the sensor. The chamber of the TMP117 kept air in its chamber. See figure 1 for a cross section of the sensor block. An ADC (MAX31856, Analog Devices) was coupled to JIRS30 to convert and amplify its signal.

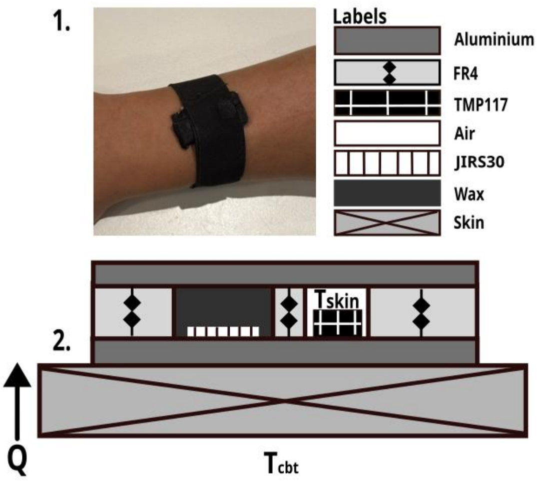

Figure 1. The images illustrate an overview of the hardware configuration for the CBT device. 1. An image of a test subject wearing the device on the wrist 2. Represents a cross section of the sensor block.

Direct model

The fundamental principle to measure the temperature of a body at its center, i.e. its core, T_{cbt}, from a measurement location apart from the center of the body, using heat flux, Q, and surface (i.e. skin) temperature, T_{skin}, follows Fourier's law of heat conduction. It can be stated as,

$$T_{cbt} = T_{skin} + \frac{Q}{U},$$

where U is the thermal conductance of the thermal system formed between the two measurement points. For a thermal body which consists of solid materials with defined dimensions, the thermal conductance is a constant and well-defined parameter. To apply this measurement principle and model on a human body, i.e. to measure the internal human body temperature from a peripheral location such as on a wrist, a more complex relationship is formed between T_{cbt}, Q, and T_{skin}.

Statistical time-dependent model

For measurements of the internal temperature of the human body using sensing of Q and T_{skin}, located on a wrist, the thermal conductance becomes a variable dependent on several external factors. These factors typically are of both of static type (e.g. device configuration, body composition, sex, age) and dynamic type (e.g. contact situation between sensors and skin, environmental effects from the surroundings like wind, and sunshine). With a Q, T_{skin} – sensor duo located on a wrist, it is in an environment that follows the everyday life of its bearer. Typically, Q and T_{skin} were subject to large variations, as shown in figure 2.

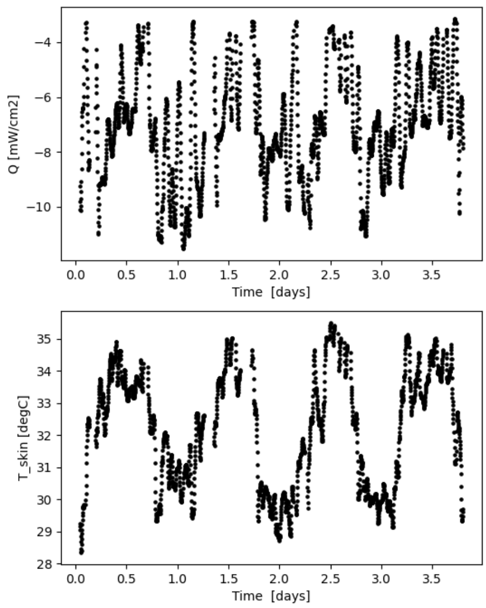

Figure 2. Typical sensor output from the device when worn on a wrist. The outputs of Q and T_{skin} are presented as a function of time.

To handle this complex measurement case, a statistical time-dependent model is instead needed, forming an algorithm (described elsewhere). Briefly, the algorithm utilizes a two-component harmonic function, which has been shown by others to be a good model of the circadian rhythm[7]. In this work, this model uses long-term Q, T_{skin} - data to work out a reliable estimate of T_{cbt}. By use of a rolling data buffer, here set to four days of the latest data points sampled every two minutes, rolling estimates of U can be made, which forms the basis for determining a live value of T_{cbt}. By further analysis of the time-resolved data, relevant human body parameters such as the phase shift of the circadian rhythm and day-to-day T_{cbt} amplitude can be extracted.

Laboratory study

*T*o evaluate the general performance of the devices, a measurement setup was utilized consisting of a temperature climate chamber containing a temperature-controlled plate, i.e. heat stage. The CBT wrist device to be characterized was placed onto the heat stage. The heat stage consisted of a resistive heater, temperature sensor and silicone based thermal insulator, which allowed for a method to experimentally simulate thermal conditions of a human body. The heater of the heat stage was regulated in a feedback control scheme using the thermometer of the stage, allowing for a defined reference temperature, T_{ref}, which could be set and varied in accordance to a typical periodic temperature variation of a human body. For one sub-study, the heat stage was swept from 36 to 39.5 °C to steady state conditions and for another sub-study, the heat stage was set to follow a sine wave (period 24h, amplitude 0.65°C, midpoint 36.8°C) to mimic the temperature of human body. During both sub-studies, the surrounding air temperature in the climate chamber was also swept, which allowed for the device to be characterized in different temperatures. For the first sub-study, the surrounding air temperature was swept between 18.0 °C and 36.0 °C. For the second sub-study, air temperature was set to either 25.0, 32.5, or 35.0 °C.

CBT study on human wrists

A total of six test subjects participated in the study. Each test subject was equipped with a CBT wrist device, a dedicated smart phone for data extraction, and a standard consumer oral thermometer (MT-B127, Geon Corp.) for validation of the algorithm. The CBT wrist devices were in general worn continuously; the participants were instructed to remove the device from the wrists once per day to charge the battery (1h/day). Data from the devices were extracted using BLE to their dedicated smart phones. Oral reference temperature data was taken by each test subject daily, these subjects wore the devices for a total of 282 cumulative days, and thermometer values were gathered for an accumulative period of 97 days during that time. An average of 5.5 thermometer measurements were taken per day. The oral thermometer effectively allowed for reference data to be collected in an evenly distributed manner over the length of the study.

Complementing the thermometer reference method, test subjects was measured using both thermometer pills (e-Celsius capsule, BodyCap) and a high-accuracy thermometer (C405, Terumo), respected in clinical studies[8], in a sub-study. For the thermometer pills, two measurement sessions were conducted, which stretched over 69 hours, i.e. ~3 days, during that time an average of 59 values were registered per hour. The thermometer pills measured the body's internal temperature and gave an accurate depiction of a core value. This reference method was crucial for evaluating the algorithm's ability to find the right phase and amplitude by validation against the pill data.

Results and discussion

Laboratory study

For the first sub-study, where air temperature and T_{ref} were swept to steady state conditions, Q and T_{skin} were measured, and by the direct model, T_{cbt} was calculated, figure 3.

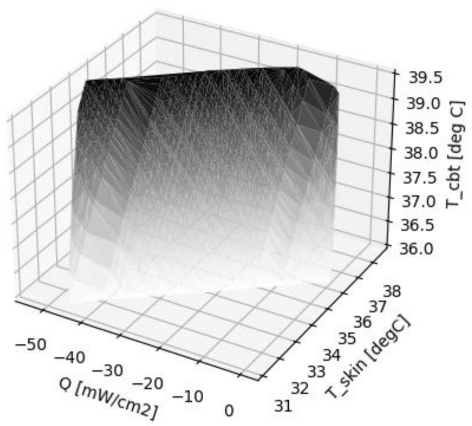

Figure 3. A 3-dimensional graph of T_{cbt} over the measured (T_{skin}, Q) space. at steady state conditions for the air temperature for 18.0 and 36.0 °C.

For the calculation, a global U was determined to be 9.5 mW cm^{-2}°C^{-1} . T_{cbt} correlated strongly with $T_{ref,}$ with a correlation factor of 0.999. For the second sub-study, where a sine wave was applied to mimic the heat output of a human body, figure 4, at different air temperatures, Q and T_{skin} capture the sine wave behavior, but at different nominal levels. When linked by the direct model to give T_{cbt} , they effectively capture the temperature, T_{ref}, of emulated body heat. Notably, this can be done independently of the surrounding air temperature.

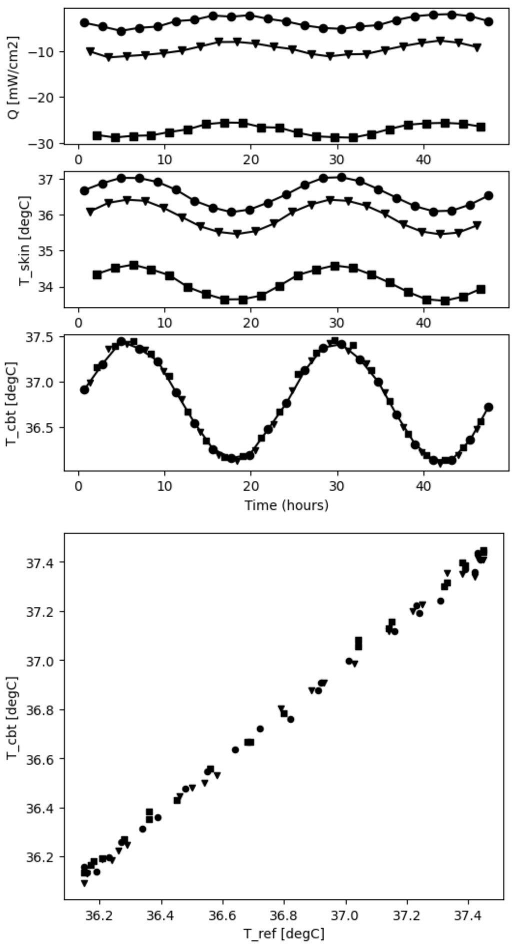

Figure 4. (top) Measured T_{skin}, (second top) Q with the resulting (second bottom) T_{cbt} model as a function of time. (bottom) T_{cbt} as a function of reference temperature. The surrounding air temperature was 25.0 °C (squares), 32.5 °C (triangles), and 35.0 °C (circles).

CBT device evaluation on human wrists

An example of the output from the time-dependent statistical model is shown in figure 5, showing the T_{cbt}, phase shift, and amplitude from test subject 1 followed under a duration of about two months. At the start of the study, the rolling data buffer is empty and needs about four days of measurement to reach stability.

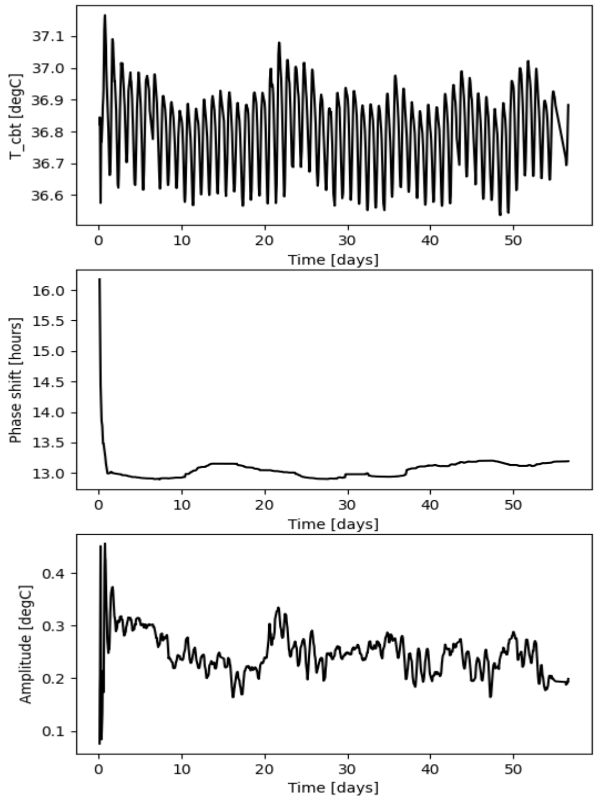

Figure 5. (top) T_{cbt} from test subject 1 using the statistical time-dependent model. (middle) The measured phase shift of the circadian rhythm relative to midnight (00:00 h). (bottom) The measured amplitude of the circadian rhythm. All measured variables are presented as a function of time (days).

After this period, the time-dependent statistical model captures both a day-to-day variation indicative of the circadian rhythm and long-term trends of T_{cbt} in the test subject. Variations and trends in the phase shift and amplitude gave further information about the test subject.

During the study, all test subjects had measured reference temperatures in the normal regime (e.g. no fever or hypothermia, 35.5 to 37.6°C). This was in line with the results of the algorithm (i.e. the time-dependent statistical model) which reported values from 35.8 to 37.6°C.

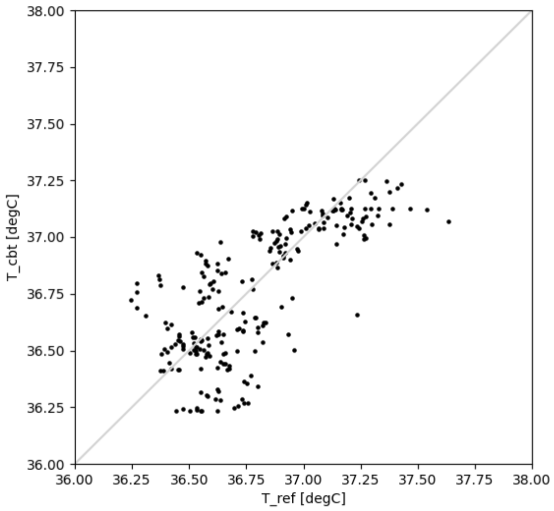

Figure 6. Correlation plot showing T_{cbt} as a function of T_{ref} for test subject 3. The T_{ref} was captured using thermometer pills (e-Celsius capsule, BodyCap). A line (gray) for full correlation is also shown.

To further evaluate the algorithm, test subjects were given thermometer pills to measure the reference of the internal temperature, i.e. the human core temperature. Results from this sub-study are shown in figure 6 as a correlation plot. For the data, the correlation factor, r, was 0.72. The data from the thermometer pills were compared to both the high-accuracy thermometer and the CBT algorithm, figure 7, and, notably, the bias of the CBT algorithm was of similar magnitude to that of the high-accuracy thermometer — both reaching an average bias lower than 0.2 °C.

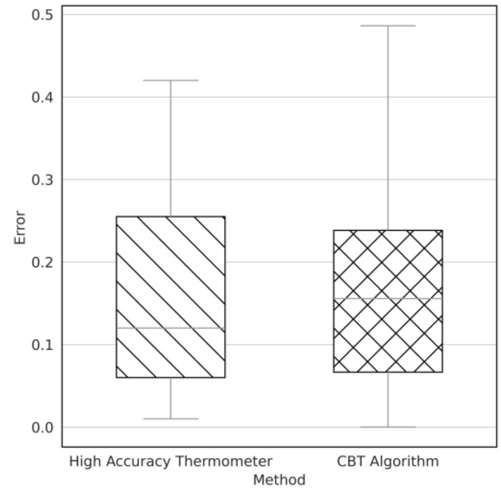

Figure 7. Boxplot showing absolute errors for the high-accuracy oral thermometer (C405, Terumo) and the CBT algorithm, T_{cbt}, compared to thermometer pills (e-Celsius capsule, BodyCap).

In figure 8, T_{ref} and T_{cbt} are presented over the time of day for the three different days of measurement. As seen in the figure, the periodic pattern of T_{cbt} syncs with the circadian rhythm and follows the general trends of T_{ref}. The thermometer pill signal holds more dynamics than the output of the algorithm, but this can be expected as the algorithm is set to only capture the general trends and periodicity of the core temperature. Also, as the measurement locations are different (i.e. wrist and stomach), physiological differences are likely present[9].

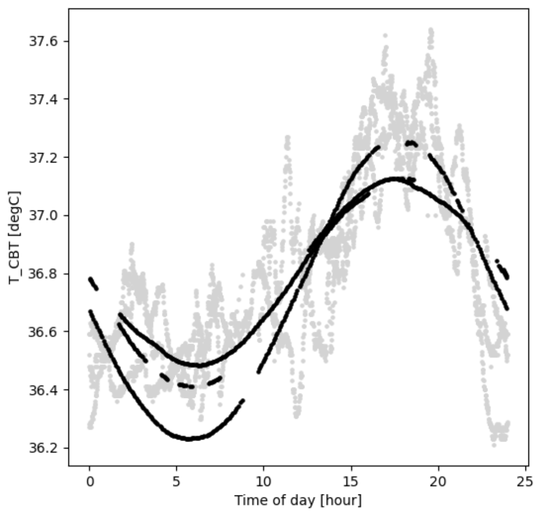

Figure 8. T_{cbt} (black) and T_{ref} (gray) as a function of clock time (time of day i.e. 00:00 to 00:00) for three different days of measurements. The T_{ref} was captured using thermometer pills (e-Celsius capsule, BodyCap).

Conclusion

The JIRS30 heat flux sensor from Jondetech Sensors AB has, as shown in this report, allowed for the realization of continuous core body temperature monitoring by integration of JIRS30 into a wrist device coupled to an algorithm. By use of the system, it has further been demonstrated how metrics of the circadian rhythm can be captured, such as its amplitude and phase. The system had a performance which makes it highly relevant for use in continuous core body temperature monitoring on wrists. The studies show that the system holds, over the human temperature span of 35.5 to 37.6 °C and when compared to thermometer pills, an average bias of less than 0.2 °C and a correlation factor of 0.72.

References

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