Evaluation of conventional invasive measurements and examination of non-invasive measurement technique on human body core temperature

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Abstract
It is important in many cases to measure and monitor, human body core temperatures, to prevent the likes of heat stroke and hypothermia. Measuring core body temperatures is also important for example, in relation to the basal body temperatures of women, and for improving the quality of life for vulnerable people such as infants, and those with cervical spine injuries. In doing so, thermal environmental changes can be monitored. However, todays conventional measuring method is apparently invasive because a temperature sensor has to be inserted into the body, from the outside. Characteristics of the body parts measured were considered by the subject experiments. There was a difference in core temperatures, depending on the measurement body parts, and it was found that the temperature decreased in the order of rectum, sublingual, and tympanic during normal times. It was confirmed that the tympanic temperature showed the most significant increase in core temperature, with running and the sublingual temperature the best in responsiveness. As a non-invasive core temperature measurement method, the basic characteristics were examined by the heat transfer experiment for the dual-heat-flux method. Thus, it was clarified that adequate temperature accuracy can be guaranteed if appropriate materials, thicknesses, and sizes are selected and the adiabatic condition for the peripheral part is fulfilled.

Keywords: Core temperature, Invasive and non-invasive measurements, Subject measurement, Body part, Heat transfer

1. Introduction
The human body core temperature is a physiologically important numerical value in clinical management of patients, modeling of thermoregulatory mechanism, and evaluation of thermal load on the human body. It is necessary to monitor the core temperature for preventing heat stroke and hypothermia [1-2]. Conventional core temperature measurement is invasive and exhibits different behavior depending on the body part measured [3-6]. In this study, the measurements were made in the
tymanic, sublingual, and rectum by subject experiments. We compared the core temperatures of different body parts and considered their characteristics. On the other hand, the practical application of a non-invasive core temperature measurement method with a few measurement restrictions is desired. The zero-heat-flow [7-10] and the dual-heat-flux methods [11-14] have been proposed as non-invasive core temperature measurement methods. In the zero-heat-flow method, the core temperature is obtained by achieving thermal equilibrium on the skin surface using a thermal insulating material and a heater. It is already commercialized and applied to manage the body temperature during surgery [8], however, its application under the non-restricted conditions of daily life is difficult. The dual-heat-flux method is one of the deflection measurement methods not requiring a heater, thus, may have a wider application range. Although the basic principle is explained, there are multiple issues for practical use, and quantitative evaluation cannot be adequate. In this study, in consideration of future developments in daily life, a basic study was conducted by the heat transfer method [11], which simulated human skin.

2. Subject experiment of invasive human body core temperature

2.1 Measurement items and subjects
Measured environmental factors were air temperature, relative humidity, and solar radiation (outdoor only), and physiological factors measured were skin temperature at four sites (chest, upper arm, thigh, and lower leg), core temperature at three sites (sublingual, ear cavity (tympanic), and rectum), blood pressure, heart rate, expiratory metabolism, and perspiration. The core temperature was measured every 10 s using an infrared sensor inside the ear and thermistors for other parts. The subjects were six healthy male students aged 22-24 years. The subjects initiated the experiment after resting for 30 min in a room at 26°C. They performed the exercise by running on a treadmill.

2.2 Experimental method

2.2.1 Outdoor exercise load experiment
The subject experiment was carried out on the wood deck of a building courtyard at the Nakamozu Campus of Osaka Prefecture University. To examine the effect of solar radiation on the core temperature, the experiments were conducted using the protocol shown in Figure 1, and the exercise was performed in the sunny area.

![Figure 1. Protocol of subject experiment 1.](image)

2.2.2 Indoor exercise load experiment
The subject experiment was carried out at a room (air conditioning and cooling 26°C setting) in a building at the Nakamozu Campus of Osaka Prefecture University. To examine the influence of body posture and exercise on core temperature, the experiments were conducted using the protocols shown in Figures 2 and 3.

![Figure 2. Protocol of subject experiment 2.](image)
2.3 Experimental results and discussion

Figure 4 shows a comparison of the indoor and outdoor core temperatures (rectal and sublingual) similar for the same subject and at 23°C. The moving average value for 1 minute is displayed. The same was applied below. Although, the outdoor experiment was expected to have a higher core temperature than the indoor experiment due to the effects of solar radiation, the core temperature of the indoor experiment was slightly higher. Therefore, the effect of solar radiation on the core temperature was lesser than the effects of posture, exercise, and physical condition of the subject.

Figures 5 and 6 show the measurement results of experiments 2 and 3 (rectal, sublingual, and tympanic). In all cases, the number of subjects with no missing measurement data was five, the curve represents the average value, and the error bar represents the standard deviation at the switching time of posture and exercise. The mouth was sometimes opened during the exercise, and a decrease in sublingual temperature was observed. Variations in tympanic temperature were observed due to changes in posture and body movements during exercise.
Figure 7 shows a comparison of each core temperature in the sitting position before exercise. Each core temperature varied depending on the measured body part, and the average value decreased in the order of rectum, sublingual, and tympanic. The rectal temperature was highest [3-5]. Similar results were obtained over the entire experiment time in Figures 4-6. Significant differences in measured temperature were confirmed between the rectum and sublingual, and rectum and tympanic.

Figure 8 shows the changes in each core temperature during the exercise period. Although there was no significant difference between the regions at a running speed of 4 km/h, a significant difference was observed at a traveling speed of 7 km/h. The tympanic was significantly changed compared with the rectum and sublingual, with a greater change in the rectum than in the sublingual. The tympanic is closely associated with the behavior of the brain temperature in the hypothalamus, which controls the amount of sweating [4].

Regarding the responsiveness of the core temperature, Figure 9 shows the time from the start of exercise (running speed 4 km/h) until the rise of the core temperature. There was a significant difference between the sublingual and the other responses, with a shorter sublingual response time than that of the rectum and tympanic. The responsiveness of pulmonary arterial blood temperature, significantly affecting changes in body temperature, is close to sublingual temperature [4]. As shown in Figures 5 and 6, the decrease in rectal temperature was lesser than that in the tympanic and sublingual after the exercise.
3. Examination of measurement method of non-invasive core temperature

3.1 Measurement principle
The dual-heat-flux method [11] was adopted for measuring the non-invasive human body core temperature. It is assumed that one-dimensional heat is transferred from the core part of the body to the skin and two types of flat plate materials (insulation materials) with different thicknesses cover the skin, and thermal equilibrium. This is a method to calculate the heat flux passing through each thermal insulating material from the temperature at both ends of the thermal insulating material and obtain the core temperature \( T_{core} \) without using the thermal resistance value \( R_{sk} \) of the skin tissue. Figure 10 shows the concept related to the measurement principle. The temperatures at both ends of the insulation are \( T_1 \) to \( T_4 \), and the thermal resistance of the insulation is \( R_1 \) and \( R_2 \). The core temperature obtained from each measured temperature is shown in Equations (1) and (2).

\[
T_{core} = T_1 + \frac{(T_1 - T_3)R_{sk}}{R_1} \quad (1)
\]

\[
T_{core} = T_2 + \frac{(T_2 - T_4)R_{sk}}{R_2} \quad (2)
\]

The thermal resistance value \( R_{sk} \) of the skin tissue is deleted from both equations, and the deep temperature \( T_{core} \) is obtained.

\[
T_{core} = T_1 + \frac{(T_1 - T_2)(T_1 - T_3)}{K(T_2 - T_4) - (T_1 - T_3)} \quad (3)
\]

Where, \( K=R_1/R_2 \). When the contact thermal resistance value \( R_t \) between the skin and the thermal insulating material is considered, the deep temperature \( T_{core} \) is shown in Equation (4).

\[
T_{core} = T_1 + \frac{(T_1 - T_2)(T_1 - T_3)}{S(T_2 - T_4) - (T_1 - T_3)} \quad (4)
\]

Where, \( S=R_1(R_2+R_{sk})/R_2(R_1+R_{sk}) \). When \( R_{dt}, R_2 << R_{sk}, S=\text{const} \), and the core temperature can be calculated considering the contact thermal resistance. It is desirable to minimize the contact thermal resistance.

3.2 Heat transfer experiment simulating biological tissue
A simulation experiment was performed controlling the core temperature. The temperatures were measured based on the dual-heat-flux method, and the measurement of core temperature accurately from the viewpoint of accuracy and responsiveness was verified. Figure 11 shows the measurement setup. The measurement items were air temperature (5 mm directly above the thermal insulating material and room temperature), temperatures at the top and bottom edges of the thermal insulating material (\( T_1, T_2, T_3, T_4 \)), side temperature of the thermal insulating material, core (agar bottom) temperature, and water.
The temperature. Agar simulating biological tissue (agar powder: water = 7 g: 100 mL, thickness 15 mm) was used to make a petri dish with an outer diameter of 125 mm, and the temperature was controlled in a constant temperature bath. The air temperatures were measured with a thermocouple and the others were measured with a thermistor every 10 s. To reduce the contact thermal resistance, an aluminum sheet of 0.3 mm thickness was inserted between the heat insulating material and agar, and the heat insulating material (50 x 50 mm) was fixed with tape. The material of the heat insulating material was polystyrene foam which was easy to process.

Figure 11. Experimental apparatus.

Figure 12 shows the time variations of the upper and lower end temperatures of the thermal insulating material, the core part (agar bottom part) temperature, and the estimated core part temperature by the dual-heat-flux method. The air temperature was 31°C. About 30 min after the start of the experiment, a temperature close to the measured data of the core temperature was obtained by the dual-heat-flux method. Table 1 shows the measurement accuracy of the core temperature when the thickness of the thermal insulating material was different. The measurement accuracy was the worst when the thickness of the insulation was 5 mm and 9 mm. This was related to the surface roughness when the thermal insulating material was cut. Sufficient measurement accuracy was confirmed for the other two cases.

Figure 12. Steady-state experiment result for 5 mm and 9 mm in thermal insulation thickness.
An experiment was conducted in which the temperature was kept constant for 60 min from the initiation of measurement, and then the set temperature of the thermostatic chamber was increased by 0.3°C. The temperature was 32-33°C. Table 2 shows the response time when the thickness of the thermal insulating material was different, and the measurement accuracy of the core temperature after changing the set temperature. The response time was about 20 min. In case of a combination of 6 mm and 12 mm thick insulation, the temperature difference was large and the accuracy was not good. The smaller the thickness, the smaller the temperature difference, and the better the measurement accuracy. This is due to the small heat loss from the side surface of the thermal insulating material, which meets the one-dimensional heat conduction assumption more strictly.

**Table 1.** Comparison of measured and estimated core temperature for steady-state experiment.

| Thermal insulation | 6 mm/12 mm | 5 mm/10 mm | 5 mm/9 mm |
|--------------------|------------|------------|-----------|
| Measured $T_{\text{core}}$ [°C] | 37.37±0.05 | 37.47±0.03 | 37.52±0.07 |
| Estimated $T_{\text{core}}$ [°C] | 37.34±0.07 | 37.49±0.05 | 37.58±0.13 |
| $\Delta T_{\text{core}}$ [°C] | 0.03 | -0.02 | -0.06 |

**Table 2.** Comparison of measured and estimated core temperature after setting temperature change of water bath.

| Thermal insulation | 6 mm/12 mm | 5 mm/10 mm | 5 mm/9 mm |
|--------------------|------------|------------|-----------|
| Response time [min] | 20.8 | 24.8 | 19.2 |
| Measured $T_{\text{core}}$ [°C] | 37.77±0.02 | 37.77±0.02 | 37.81±0.04 |
| Estimated $T_{\text{core}}$ [°C] | 38.03±0.04 | 37.84±0.03 | 37.78±0.04 |
| $\Delta T_{\text{core}}$ [°C] | -0.26±0.03 | -0.08±0.03 | 0.03±0.06 |

### 4. Conclusion

1. There was a difference in core temperatures depending on the measured body part, the rectum being the highest, followed by the sublingual, and the tympanic.
2. It was confirmed that the increase in core temperature with running motion was the largest in the tympanic with the best response by the sublingual.
3. A non-invasive measurement of core temperature based on the dual-heat-flux method was examined by heat transfer experiments, and sufficient temperature accuracy was guaranteed.

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