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Development of a new method for the noninvasive measurement of deep body temperature without a heater

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ABSTRACT

The conventional zero-heat-flow thermometer, which measures the deep body temperature from the skin surface, is widely used at present. However, this thermometer requires considerable electricity to power the electric heater that compensates for heat loss from the probe; thus, AC power is indispensable for its use. Therefore, this conventional thermometer is inconvenient for unconstrained monitoring. We have developed a new dual-heat-flux method that can measure the deep body temperature from the skin surface without a heater. Our method is convenient for unconstrained and long-term measurement because the instrument is driven by a battery and its design promotes energy conservation. Its probe consists of dual-heat-flow channels with different thermal resistances, and each heat-flow-channel has a pair of IC sensors attached on its top and bottom. The average deep body temperature measurements taken using both the dual-heat-flux and then the zero-heat-flow thermometers from the foreheads of 17 healthy subjects were 37.08 °C and 37.02 °C, respectively. In addition, the correlation coefficient between the values obtained by the 2 methods was 0.970 ($p < 0.001$). These results show that our method can be used for monitoring the deep body temperature as accurately as the conventional method, and it overcomes the disadvantage of the necessity of AC power supply.

1. Introduction

Core body temperature is the deep body temperature of the internal organs in the abdominal, thoracic, and cranial cavities. Core body temperature shows individual physiological states that contribute to its variability, including the metabolic rate (the rate at which the body consumes energy while at that point), physical conditions such as menstruation, and the ingestion of various medications. Therefore, the measurement of core body temperature has been thought to assume greater significance in the care of seriously ill patients who cannot comment about their own physical conditions. This is particularly the case in the management of hypothermia, in paediatrics, and in anaesthesia [1–5].

The method generally used for the measurement of human core body temperature involves the direct insertion of a sensor into a natural body cavity such as the rectum. However, the human body does not have such suitable cavities in which the thermal sensor can be inserted to measure the core temperature satisfactorily over a long time period, especially in subjects that are awake. Furthermore, these measurements in a body cavity can cause complications such as tympanic membrane perforation during general anaesthesia [6,7]. Another example of the complications that can arise while measuring the core body temperature is the risk of perforation of the rectum by the probe, especially in children [8]. In order to avoid these problems related to temperature measurement, the indirect measurement of the deep body temperature from the skin surface has been considered desirable. However, the measurement of the thermal resistance values of the skin and the subcutaneous tissue is difficult. Moreover, the thermal resistance value differs according to the part of the body, even in the same subject, and is strongly influenced by the blood flow at a particular time point [9].

In 1971, Fox and Solman [10,11] introduced a novel noninvasive technique for the measurement of the deep body temperature using the zero-heat-flow method. Their method provides an isothermal zone by using an electronic servocontrolled heater to prevent the heat loss by outflow. Although this technique is now widely used for monitoring the deep body temperature in cardiac surgery and intensive care units [12,13], this heating method requires a considerable amount of electric power. Therefore, the AC power supply is indispensable for this method of thermometry, which makes this method inconvenient for unconstrained monitoring. We have

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developed a new dual-heat-flux method using simplified heat flow simultaneous equations in thermal insulators with two different thermal resistance values. A new method described herein, allows for the indirect measurement of deep body temperature from the skin surface without the need for a heater to compensate for heat loss; we evaluated the measurement performance of this method by comparing the results with the conventional zero-heat-flow method.

2. Materials and methods

2.1. Principle of measurement

As shown in Fig. 1(a), when the body surface is covered with a thermal insulator and the temperature reaches equilibrium, the 2 heat flows—1 flow from the deep body tissue to the body surface beneath the thermal insulator and the other flow through the thermal insulator—are balanced. We assumed that there is a constant and vertical heat flow from the deep body to the surface of the thermal insulator. Therefore, when the thermal equilibrium is attained in the thermal insulator and the subcutaneous tissue, the heat flow can be calculated using the thermal resistance value of the thermal insulator and the temperatures at the 2 ends of the thermal insulator. The heat flow I is obtained by the following equation in the equivalent circuit illustrated in Fig. 1(b):

$$I = \frac{T_S - T_U}{R_I} \tag{1}$$

where T_S and T_U are temperatures at the skin beneath the insulator and at the top surface of the insulator, respectively, and R_I is the thermal resistance of the thermal insulator. Similarly, the heat flow I can also be determined from the deep body temperature beneath the insulator, the skin temperature, and the thermal resistance of the skin and hypodermic tissue. Then, the heat flow I can also be obtained by the following equation:

$$I = \frac{T_B - T_S}{R_S} \tag{2}$$

where T_B is the deep body temperature and R_S is the thermal resistance of the skin and subcutaneous tissue. Then, we can combine Eqs. (1) and (2) as follows:

$$I = \frac{T_S - T_U}{R_I} = \frac{T_B - T_S}{R_S} \tag{3}$$

Therefore, the deep body temperature can be obtained by modifying Eq. (3):

$$T_B = T_S + \frac{(T_S - T_U)R_S}{R_I} \tag{4}$$

However, the thermal resistance value R_S of the tissue beneath the insulator cannot be measured and is strongly influenced by the hypodermic blood flow at a particular time point.

When the body surface is covered with 2 closely placed thermal insulators with different thermal resistance values R_1 and R_2, as shown in Fig. 1(c), the deep temperature of each heat insulator can be obtained as follows:

$$\left.\begin{aligned} T_B &= T_1 + \frac{(T_1 - T_3)R_S}{R_1} \\ T_B &= T_2 + \frac{(T_2 - T_4)R_S}{R_2} \end{aligned}\right\} \tag{5}$$

where T_1 and T_2 are the skin temperatures beneath the 2 insulators, and T_3 and T_4 are the temperatures at the upper surface of the 2 insulators. Since the 2 insulators are placed close to each other, the thermal resistance R_S of the skin and subcutaneous tissue are nearly the same and can be eliminated from (5). We define the thermal resistance ratio R_1/R_2 as K; then, Eq. (5) can be rearranged as follows:

$$T_B = T_1 + \frac{(T_1 - T_2)(T_1 - T_3)}{K(T_2 - T_4) - (T_1 - T_2)} \tag{6}$$

When the ratio of the thermal resistance K is obtained, we can get the deep body temperature using Eq. (6).

As for the determination of K, we can modify Eq. (6) as follows:

$$K = \frac{(T_B - T_2)(T_1 - T_3)}{(T_B - T_1)(T_2 - T_4)} \tag{7}$$

In order to obtain the value of K, we conducted a simulation experiment in which we placed the probe containing the 2 insulators on a rubber sheet that was placed over the inner bottom of a copper vat floating in a water bath, and we then measured T_1, T_2, T_3, and T_4. Since the water temperature (T_B) in the simulation experiment was known, we could calculate the thermal resistance ratio K of the probe by using Eq. (7). Finally, the deep body temperature T_B can be calculated by the estimated K value using Eq. (6).

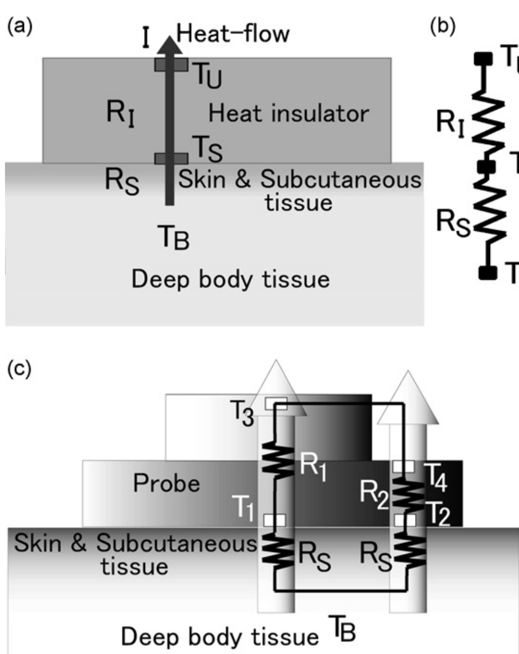

Fig. 1. Schematic diagrams of the heat flow and its equivalent circuits. (a) A schematic diagram of the heat flow when a part of the body surface is covered with the heat insulator. (b) A diagram of the equivalent circuit of (a), where the temperature, heat flow, and heat resistance correspond to the voltage, current, and resistance, respectively. (c) A schematic diagram of 2 channels of heat flow and its equivalent circuit, which is formed when the body surface is covered with 2 kinds of heat insulators with different thermal resistances R_1 and R_2. T_U, the temperature at the upper surface of the insulator; T_S, the temperature at the skin surface beneath the insulator; T_B, the deep body temperature; R_I, the thermal resistance of the insulator; R_S, the thermal resistance of the skin and subcutaneous fat; I, the heat current. T_1 and T_2 are the skin temperatures beneath the insulator, and T_3 and T_4 are the temperatures at the upper surface of the insulator.

2.2. Thermometer probe

Fig. 2(a)–(c) shows the thermometer probe, which is constructed using 4 integrated circuit (IC) temperature transducers (AD590, Analog Devices, Norwood, USA), a heat insulator, a copper disc, a copper ring, and a copper cap. The bottom of this probe contains the copper disc and the copper ring with good thermal conductivity, and they are directly placed on the body surface. Two ICs are placed at the bottom of the copper disc and the copper ring to monitor the skin temperatures T_1 and T_2. In addition, there are 2 ICs to monitor the temperatures T_3 and T_4 on the upper surface