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Use of finite element analysis to optimize probe design for double sensor method-based thermometer

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ABSTRACT

Body temperature is an essential vital sign for assessing physiological functions. The double sensor method-based thermometer is a promising technology that may be applicable to body temperature monitoring in daily life. It continuously estimates deep tissue temperature from the intact skin surface. Despite its considerable potential for monitoring body temperature, its key design features have not been investigated. In this study, we considered four design factors: the cover material, insulator material, insulator radius, and insulator height. We also evaluated their effects on the performance of the double sensor thermometer in terms of accuracy, initial waiting time, and the ability to track changes in body temperature. The probe material and size influenced the accuracy and initial waiting time. Finite element analysis revealed that four thermometers of different sizes composed of an aluminum cover and foam insulator provided high accuracy (< 0.1 °C) under various ambient temperatures and blood perfusion rates: R=20 mm, H=5 mm; R=15 mm, H=10 mm; R=20 mm, H=10 mm; and R=15 mm, H=15 mm. The initial waiting time was approximately 10 min with almost the same traceability of temperature change. Our findings may provide thermometer manufacturers with new insights into probe design and help them fabricate thermometers optimized for specific applications.

1. Introduction

Body temperature is one of the most important factors in metabolic processes such as cell division and enzyme reactions (Davidovits, 2012). An abnormal body temperature range implies that these essential processes are not proceeding properly. Therefore, body temperature measurement is a routine procedure in health examinations. Body temperature can also be intentionally adjusted to suppress injury progression or damage cancer cells. Hypothermia therapy reduces the body temperature by approximately 33 °C and is a widely accepted procedure when clinicians operate on patients suffering from traumatic brain injuries or cardiac arrest (Nikolov and Anthony, 2003; H. Alex et al., 2012). In hyperthermia therapy for cancer treatment, the deep tissue layer is heated up to 42–45 °C (Mitobe and Noboru, 2011).

Ever since Hippocrates diagnosed fever using the warmth of his hand in the 5th century, various kinds of thermometers have been developed (Togawa, 1985). In the operating room or intensive care unit of a hospital, body temperature is monitored by inserting a temperature sensor into a body cavity (e.g., rectum, esophagus) or a blood vessel (e.g., pulmonary artery) (Lefrant et al., 2003). Although these methods are expected to be accurate because the sensor directly measures the temperature of deep tissue, they are too invasive and intrusive to be applied to conscious individuals. Infrared ear thermometers and axillary thermometers are commonly used in everyday life and medical care settings because they are easy to use. However, the readings of infrared ear thermometers are influenced by the technique of the operator (Terndrup and Rajk, 1992). Furthermore, axillary thermometers require people to hold an arm down tightly at their side while measuring armpit temperature. Therefore, the application of these thermometers to continuous body temperature monitoring in daily life is restricted.

Many researchers have sought to develop noninvasive body temperature monitoring devices that use the zero heat flow method (ZHFM), double sensor method (DSM), and dual heat flux method (DHFM) (Fox and Solman, 1971; Gunga et al., 2012; Kitamura et al., 2010) (Fig. 1). The ZHFM-based thermometer (Fig. 1a) (Fox and Solman, 1971) uses a servo-controlled heater to reduce the heat flow crossing the tissue to zero and estimates the deep tissue temperature from the skin surface (Fox and Solman, 1971; Fox et al., 1973). It yields temperature measurements similar to those directly measured in the rectum of stable infants in incubators, in muscle (*vastus lateralis*), and in the esophagus of

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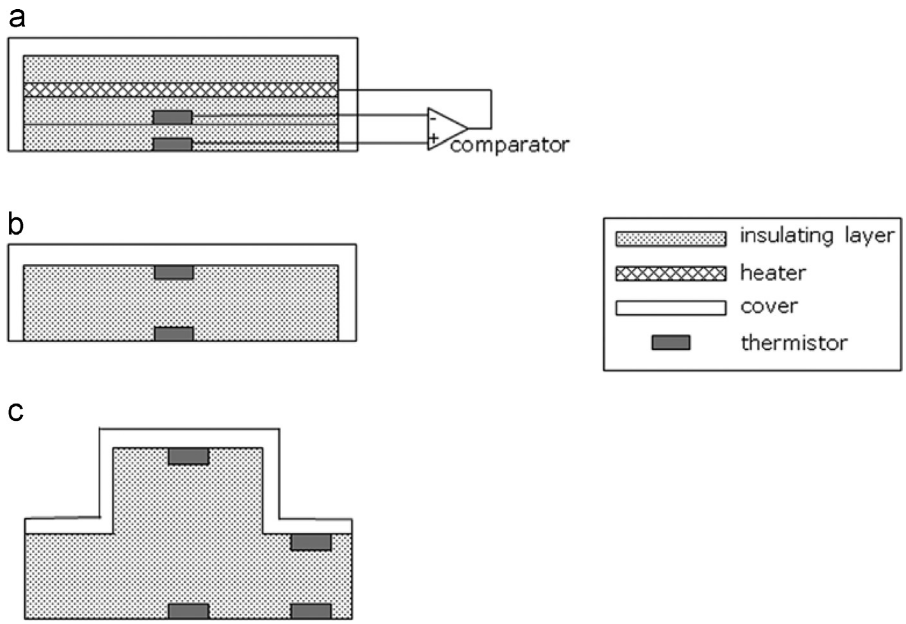

Fig. 1. Structures of noninvasive deep body thermometers: (a) ZHFM-based thermometer, (b) DSM-based thermometer, and (c) DHFM-based thermometer.

healthy subjects in hot and stable ambient conditions (Dollberg et al., 2000; Brajkovic and Ducharme, 2005; Teunissen et al., 2011). The applicability of thermometers using the DSM (Fig. 1b) has been verified under diverse environments (Gunga et al., 2012). They provided similar results to that of rectal thermometers during intensive work under various ambient temperatures (mean ± 2 S.D.: −0.16 ± 0.90 °C at 10 °C, −0.08 ± 0.70 °C at 25 °C, −0.11 ± 0.68 °C at 40 °C) (Gunga et al., 2008). DSM-based thermometers have also exhibited the potential to monitor circadian body temperature rhythms or abnormal body temperatures during cardiac surgery (Gunga et al., 2009; Kimberger et al., 2009). DSM-based or DHFM-based thermometers are suitable for unconstrained body temperature monitoring because they do not require an AC power supply for heating.

Although the usefulness of various types of deep body thermometers was verified, measurement errors still exist. A portion of the error is inherent because deep body thermometers assume that heat flows only in the longitudinal direction and do not take the transverse heat flow into account. Therefore, some studies have investigated the design of thermometers that create measurement conditions that accord closely with the assumption, thereby improving the accuracy. Togawa et al. modified the conventional ZHFM-based thermometer to improve its performance (Kobayashi et al., 1975; Togawa et al., 1976). Steck et al. (2011) carried out numerical simulations to discover the best performing sensor design for a ZHFM-based thermometer. Huang et al. (2014) recently evaluated the structural and thermophysical effects on the accuracy of the DHFM-based thermometer. However, the design of the DSM-based thermometer has not been considered. Therefore, we studied the influence of probe design factors (size and material) on the accuracy, initial waiting time, and traceability of temperature changes. We expect that this study will help researchers obtain insights into the DSM-based thermometer design and fabricate thermometers optimized for specific applications.

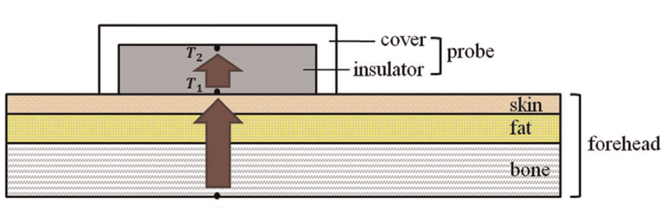

Fig. 2. Schematic diagram of the double sensor method. Heat flows vertically from deep tissue to the cover. T_d is the deep tissue temperature. T_1 and T_2 are the measured temperatures at each point. T_d is estimated from T_1 and T_2 and the ratio of thermal conduction coefficient of the insulator to that of human tissue ($K = K_{insul}/K_{tis}$) using $T_d = T_1 + K \times (T_1 - T_2)$.

2. Materials and methods

We implemented finite element simulations to evaluate the effects of probe size (radius and height) and material (insulator and cover) on the performance of the DSM-based thermometer.

2.1. Principle of the double sensor method

The DSM-based thermometer is comprised of two thermistors, an insulator, and a cover (Fig. 2). The vertical heat flow from deep tissue to the probe cover is used to estimate deep body temperature. Approximately 10 min after attaching the probe to the skin, the thermal conditions around the measurement area reach equilibrium (Kimberger et al., 2009). At thermal equilibrium, the heat flow from the core towards the skin layer and the heat flow across the sensor are balanced. Each heat flow can be expressed as:

$$\begin{cases} H = K_{tis} \times (T_d - T_1) \\ H = K_{insul} \times (T_1 - T_2) \end{cases} \tag{1}$$

where H, T_d, T_1, and T_2 denote the heat flow, deep tissue temperature, skin temperature under the insulator, and the temperature above the insulator, respectively. K_{tis} and K_{insul} are the heat conduction coefficient of the human tissue and insulator, respectively.

Solving the simultaneous equation in Eq. (1), the deep tissue temperature can be estimated using the temperatures measured from two thermistors:

$$T_d = T_1 + K \times (T_1 - T_2) \text{ where } K = \frac{K_{insul}}{K_{tis}} \tag{2}$$