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A nonintrusive temperature measuring system for estimating deep body temperature in bed*

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Abstract— **Deep body temperature is an important indicator that reflects human being's overall physiological states. Existing deep body temperature monitoring systems are too invasive to apply to awake patients for a long time. Therefore, we proposed a nonintrusive deep body temperature measuring system. To estimate deep body temperature nonintrusively, a dual-heat-flux probe and double-sensor probes were embedded in a neck pillow. When a patient uses the neck pillow to rest, the deep body temperature can be assessed using one of the thermometer probes embedded in the neck pillow. We could estimate deep body temperature in 3 different sleep positions. Also, to reduce the initial response time of dual-heat-flux thermometer which measures body temperature in supine position, we employed the curve-fitting method to one subject. And thereby, we could obtain the deep body temperature in a minute. This result shows the possibility that the system can be used as practical temperature monitoring system with appropriate curve-fitting model. In the next study, we would try to establish a general fitting model that can be applied to all of the subjects. In addition, we are planning to extract meaningful health information such as sleep structure analysis from deep body temperature data which are acquired from this system.**

I. INTRODUCTION

Body temperature is one of the vital signs that are the indicators of human being's overall physiological states. We can screen for fever or obtain information on viral infections by monitoring body temperature[1]. In hospitals, nurses manually measure each patient's body temperature every 4 hours with digital thermometers or infrared thermometers. In the case of febrile patients, body temperature is more frequently measured, not only imposing heavy workload on nurses but also disturbing patients[2, 3]. Moreover, both thermometers are influenced by operator technique and patient dependent factors[4, 5]. Even though nasopharynx temperature, esophagus temperature, bladder temperature and pulmonary artery temperature can be continuously measured[6], these methods are so invasive that the patients would feel uncomfortable, which means that the existing systems are not suitable for long-term temperature monitoring in awake patients. Therefore, noninvasive temperature monitoring system which can estimate deep body temperature is needed.

Deep body thermometer, the novel kind of device which can estimate deep body temperature from the skin originated from the research of Fox R.J. and Solman A.J. in 1971[7, 8]. Their work is based on Zero-heat-flow method that if the heat flow across the skin is zero, skin temperature would be equivalent to deep tissue temperature. Recently developed noninvasive techniques – Double-sensor thermometer (Drägerwerk AG, 2006) and Dual-heat-flux thermometer (KI. Kitamura, 2010) – use heat flow for the estimation of deep body temperature. Double-sensor thermometer showed high accuracy to be regarded an alternative to distal oesophageal core temperature measurement[9]. Dual-heat-flux thermometer exhibited high correlation with Zero-heat-flow thermometer and good traceability for the rapid temperature change (0.2˚C / min) [10]. However, these noninvasive thermometers need long initial response time because the deep body temperature can be derived after thermal equilibrium is reached. Also, most of the studies on noninvasive thermometers were restricted to measure deep body temperature on forehead by binding probes with elastic headband or tapes [9-12].

In this study, we embedded two kinds of noninvasive thermometers in a neck pillow to measure deep body temperature in bed nonintrusively. This system is expected to reduce heavy nursing workload by automatically monitoring deep body temperature of patients in hospital beds or nursing home. And with stored temperature data, we can provide useful health information such as sleep structure analysis, fever detection, and so on. In addition, it would be the first study to estimate deep body temperature under neck using noninvasive thermometers.

II. MATERIALS AND METHODS

A. *Principle of measurements*

Because all blood vessels that deliver blood to the brain pass through the slender neck, the amount of blood per unit volume is large in neck. And esophagus which offers the gold standard of core body temperature is a part of the neck. The insulated skin temperature over the jungular vein in the neck had strong correlation with oesophageal temperature in cool exposure[13]. We thus decided to measure deep body temperature under neck.

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To measure deep body temperature in bed nonintrusively, we embedded three temperature probes in a neck pillow. Two double-sensor thermometers were embedded in both sides of the pillow and one dual-heat-flux thermometer was inserted in the center of the pillow (Fig. 1). Therefore, dual-heat-flux thermometer was used to assess deep body temperature in supine position and double-sensor thermometer was used in lateral recumbent position.

The deep body temperature can be obtained by the following equations illustrated in Fig. 2, where T_{1-4} are the measured temperatures at each point and T_c means the deep body temperature. R_{1-2} are the thermal resistances of each insulator and R_{tissue} is the thermal resistance of the skin and subcutaneous tissue [9, 10]. To calculate the deep body temperature, the ratio of the thermal resistance (*K-value)* should be obtained in advance through simulation work.

In previous studies, the probe was covered with additional thermal insulator such as urethane sponge to prevent the environmental effect such as air flow and room temperature. The thick layer of cotton in the neck pillow functioned as a thermal insulator in the present study.

B. Simulation experiments

To calculate the K-value in equation of dual-heat-flux thermometer, we used the ratio of insulator thickness because the thermal resistance is proportional to the length of material. The thickness of each insulator in dual-heat-flux thermometer was 5mm, 2mm. Therefore, we substituted the K-value with a value of 2.5 to estimate deep body temperature. For the K-value in double-sensor thermometer, we had to calculate the ratio of the thermal resistance of the tissue and the insulator using the method of Nemoto and Togawa[14]. While maintaining the water temperature at 37˚C and room temperature at 25˚C, we spread the rubber sheet on the copper plate floating on water to simulate the subcutaneous tissue layer of the neck. The thermal conductivity coefficient of rubber sheet is similar to that of skin and the subcutaneous tissue(0.17 W/m·°C). The thickness of rubber sheet was various from 3mm to 18mm to assess the tissue temperature at different tissue depth.

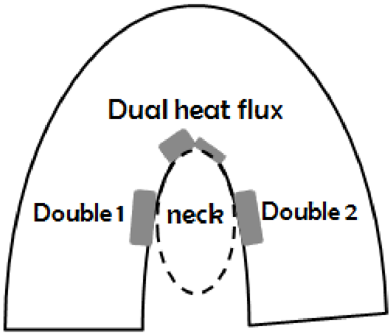
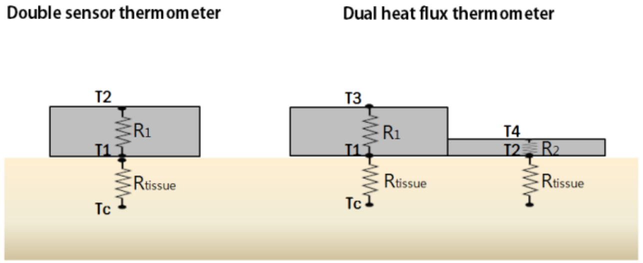


Figure 1. The structure of a neck pillow for measuring deep body temperature.



$$T_C = T_1 + K(T_1 - T_2), K = \frac{R_t}{R_1}$$

$$T_C = T_1 + \frac{(T_1 - T_2)(T_1 - T_3)}{K(T_2 - T_4) - (T_1 - T_3)}, K = \frac{R_1}{R_2}$$

Figure 2. Deep body temperature estimation equations of double-sensor thermometer and dual-heat-flux thermoemter.

C. Deep body temperature measurement in healthy subjects

Seven young, healthy subjects (26.5±2.3 years old) participated in the experiments. To measure deep body temperature at different sleep positions, 3 subjects were required to sleep in the supine position or Fowler's position and other 4 subjects were asked to sleep on their left or right lateral side for an hour while resting head on the neck pillow. The infrared thermometer (ThermoScan IRT 4520, Braun, Germany) was used to measure tympanic membrane temperature every 5 minutes. To obtain an accurate tympanic membrane temperature, we eliminated the earwax with cotton bud and straightened the ear canal by pulling the ear up and back. The room temperature was maintained at 25˚C during experiments.

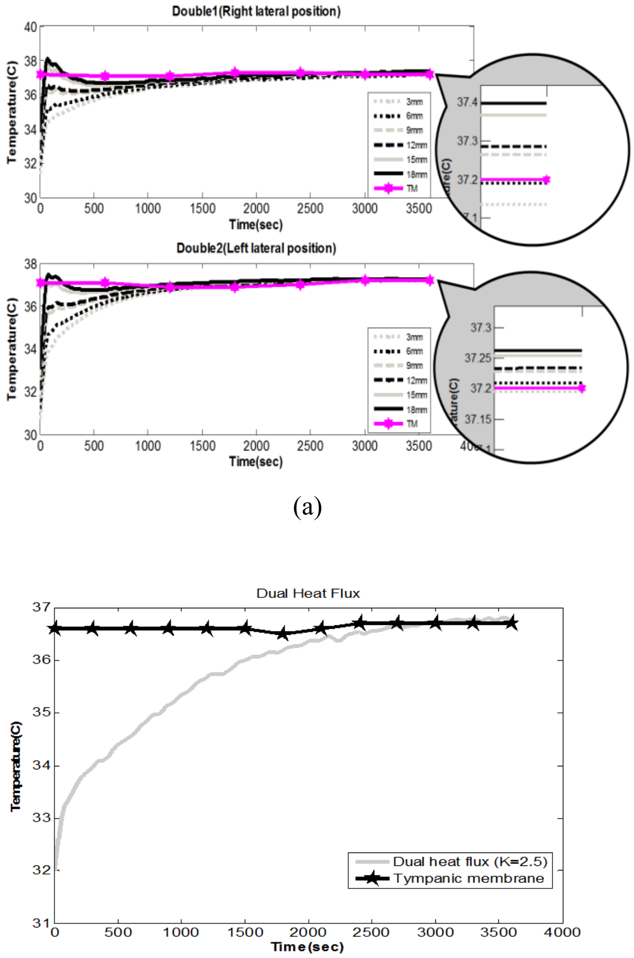
III. RESULTS

We calculated the deep body temperature of the neck using K-value which was obtained through the simulation study and then compared the estimation result with tympanic membrane temperature. And we applied curve-fitting method to reduce the initial response time. Through this trial, this nonintrusive temperature measuring system can be considered as an alternative of existing thermometers which give results in a few minutes.

A. Simulation experiments

Six kinds of rubber sheets (3, 6, 9, 12, 15, 18mm) were used to get K-value at different depth. And we found out that the K-value was increased as the rubber sheet got thicker. After obtaining the K-value at each depth, we drew the temperature curve using K-values and data measured under neck (Fig.3(a)). As a result, K-value at 6mm depth offered the most similar result with the tympanic membrane temperature in each subject. In a case of dual-heat-flux thermometer, K-value, 2.5, which was derived from the ratio of insulator thickness also gave a consistent estimation value with the tympanic temperature. Therefore, we used a value of 2.5 for dual-heat-flux probe, 1.5939 for double-sensor 1 probe, and

1.3050 for double-sensor 2 probe as the K-value to assess deep body temperature.



(a)

(b)

Figure 3. Deep body temperature estimation using various K-values which were acquired in simulation study.

B. *Deep body temperature estimation in different sleep positions*

We measured deep body temperature in 3 sleep positions to verify whether the intrusive temperature measuring system in this study can estimate deep body temperature under various situations. The estimated deep body temperature gave close results to tympanic membrane temperature in each position. And the set of temperature curves in each position were clearly distinguished (Fig.4). In supine position, the gradual temperature curves from more than two probes were observed. This is because the neck covers not only dual-heat-flux probe but also the side-embedded double-sensor probe in supine position. However, in lateral position, we could recognize the rapidly increasing and pointed temperature curve from double-sensor thermometer. For these reasons, the sleep position can be speculated with the set of temperature curves.

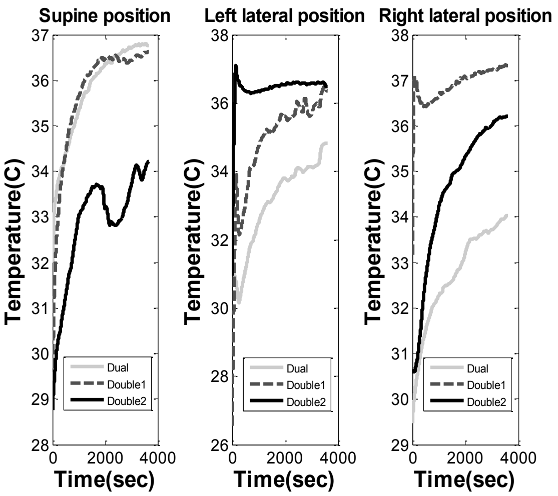


Figure 4. Deep body temperature curves obtained from neck pillow in different sleep positions.

C. *Curve-fitting method*

The initial response time in dual-heat-flux thermometer was much longer than double-sensor thermometer. This means that we have to wait more than 30 min to estimate deep body temperature in supine position. To increase the practicality of this system by reducing the initial wasting time, we tried to apply curve-fitting method to one subject. The fitting model was as follows based on least square method:

$$\text{Estimated deep body temperautre} = 4.8 \times \sqrt{1-\left(\frac{\text{time}-\text{A}}{\text{A}}\right)^2} + \text{Temperautre}_{(\text{time}=0)} \quad (1)$$

As the body temperature doesn't change frequently, the deep body temperature was estimated every 1 min using curve-fitting model. The value 'A' in equation (1) was automatically adjusted every minute with stored temperature data using least square method. After calculating 'A' value, we could acquire the whole temperature estimation curve at each minute. Then, we obtained the deep body temperature by substituting 3600 sec to time because our purpose was to predict the deep body temperature under thermal equilibrium. In Fig.5, the estimated deep body temperature at the first minute gave the similar temperature with the deep body temperature which was measured after an hour.

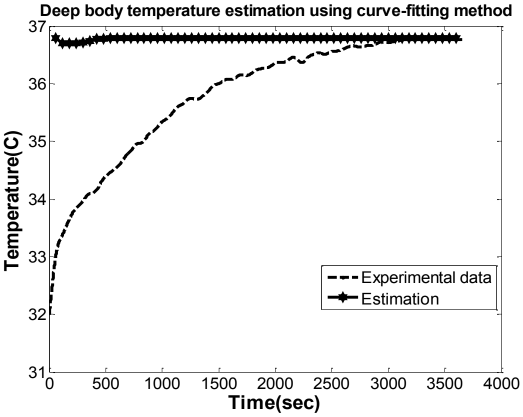


Figure 5. Deep body temperature estimation in each minute using curve-fitting method.

IV. DISCUSSION

Body temperature is a basic and vital signal when monitoring health abnormality. To develop the noninvasive, nonintrusive deep body temperature measuring system, we embedded double-sensor probes and a dual-heat-flux probe in a neck pillow. The deep body temperature estimated under neck was similar with tympanic membrane temperature measured with infrared thermometer. By automatically monitoring the deep body temperature nonintrusively, the patients would be able to rest comfortably on the bed. Also, the nurses can lighten their heavy workload.

The sets of the temperature curves from three probes were obviously distinguished in different sleep position. Therefore, we can provide the sleep related information such as sleep position, the occurrence of body movement, and total sleep time using this system.

Finally, we tried to reduce the initial waiting time of dual-heat-flux thermometer to a short time. And by applying the curve-fitting method, we realized that the appropriate curve-fitting model would shorten the initial waiting time. Even though the curves from different subjects were inconsistent, the curves basically followed the logarithmic change. Therefore, we would devote all efforts to find the general curve fitting model in the future study. Then, this noninvasive, nonintrusive temperature monitoring system would be practical. In addition, we would apply this system for patient temperature monitoring to verify if it gives similar results with gold standards like rectal or oesophageal temperature.

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