2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Core body temperature estimation by eyeglass-type device: thermal analysis of radiation heat measured from caruncle

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***Abstract*—This paper describes a method for estimating core body temperature from radiation heat of the caruncle and an eyeglass-type device for measuring the temperature of the caruncle to prescreen for infectious diseases such as COVID-19. As a precise prescreening method, monitoring a person's continuous core body temperature is desired. By monitoring the continuous core body temperature, including circadian rhythm, in our daily life, infections can potentially be discovered when body temperature is higher than normal. Although monitoring the core body temperature is effective, continuous and precise monitoring requires the use of an invasive instrument. To overcome this, we (1) design an eyeglass-type device for measuring the caruncle temperature and (2) model the correlation between the caruncle temperature and the core body temperature. Experimental results revealed that hypothalamic temperature could be estimated within ± 0.3 °C between 20 and 30 °C by using the eyeglass-type device.**

I. Introduction

Since the outbreak of the COVID-19 pandemic, more than 100 million cases have so far been reported worldwide [1][2]. To counter the spread of COVID-19, a standard response has been to detect and isolate infected people at an early stage.

The most widely used means of detecting the presence of COVID-19 is polymerase chain reaction (PCR) testing [3]. However, determining the results of a PCR test takes two to three days, and people are required to expend time and effort to visit a dedicated testing location. In addition, infected people often test negative even after symptom onset [4]. Therefore, medical personnel may want to carry out periodic PCR tests on people who may be infected. However, periodical tests can be difficult to conduct due to government policy or limited medical resources. Therefore, in some countries, only those who meet certain diagnostic criteria are tested [5]. The most commonly used diagnostic criterion is body temperature, but there is a concern that the differences in body temperature between East Asians and Westerners can make it difficult to judge whether someone's body temperature is normal or high [6].

Unlike other infectious diseases such as influenza, COVID-19 is said to rarely cause high temperatures over 38 °C. Therefore, COVID-19 is often diagnosed in hospitals on the basis of temperatures of 37.3 °C [7]. On the other hand, general commercial facilities use a standard of 37.5 °C for screening [8]. At this time, the temperature accuracy should preferably be ± 0.3 °C or less [9].

However, body temperature varies between individuals and times of the day. The body temperature of elderly people is said to be about 0.5 °C lower than that of young people [10]. For example, if the basal body temperature is less than 36.5 °C, an increase of 1 °C from normal does not meet the diagnostic criteria of 37.5 °C. There is also a 24-hour cycle of fluctuations in body temperature called circadian rhythms [11]. This can lead to a difference of more than 1 °C between the maximum and minimum measurements. Therefore, one suggested diagnostic criterion is an average body temperature that is 0.5 °C higher than that of an average person for 3 days [12]. However, it is impractical to monitor a person's average body temperature for 3 days in a testing facility. In short, instantaneous body temperature measurements are ambiguous and insufficient to use as references, and continuous body temperature measurements are desirable but impractical.

For simple screening, general commercial facilities use a noncontact thermometer or thermographic camera to measure the temperature of the forehead surface. However, temperature is difficult to measure accurately and continuously with a noncontact thermometer because the measured value fluctuates depending on the distance to the measured part, the air temperature, and the environment [13]. Also, since the thermographic camera has a fixed installation position, it cannot continuously measure a moving individual. In addition, the 37.5 °C body temperature used as a criterion for infection is based on temperatures close to the core of the body, such as the temperature of the rectum and ear canal. Therefore, the temperature of the forehead surface, which is the body surface temperature, is not appropriate to consider as an infection criterion [14]. Consequently, because it is impractical to continuously measure people's core body temperatures by inserting thermometers into their rectums or ear canals, a noninvasive method is needed to continuously measure people's core body temperatures in medical facilities and perform simple screening in commercial facilities.

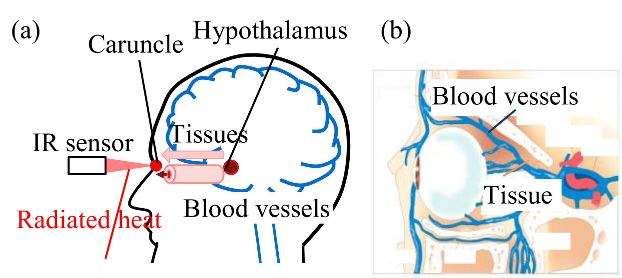

Fig. 1 shows our conceptual diagram of core body temperature estimation from the caruncle in the human head: (a) overview and (b) details.

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In this paper, we propose an eyeglass-type device as a simple screening system that incorporates a method for estimating people's core body temperatures continuously from their caruncle temperatures. Fig. 1 shows the conceptual diagram of estimating the core body temperature from the caruncle in the human head. The heat at the caruncle propagated from the hypothalamus through the human core is measured by the infrared (IR) temperature sensor [Fig. 1(a)]. As for the temperature of the caruncle, we assume two types of heat propagations: (1) the heat conduction in tissue between the caruncle and the hypothalamus, and (2) the heat transport by the blood flow in the blood vessels [Fig. 1(b)]. The caruncle, which we focus on, has parallel arteries and veins, so the heat for the blood flow in the blood vessels is easily transmitted to the body surface. The caruncle temperature is the body surface temperature that best reflects the core body temperature. Thus, we think that core body temperature, i.e., hypothalamic temperature, can be calculated by heat transfer between tissue and by blood vessels from the hypothalamus to the lacrimal colliculus.

To assess the feasibility of our proposal, we did the following. First, to measure the radiated heat at the caruncle, we prototyped an eyeglass-type device. Second, to estimate the core body temperature, we constructed models of the heat propagation in the human head and simulated them. Third, to verify the accuracy of our device, we carried out experiments for thermometry. Finally, we compared the measured temperature with estimated temperature and analyzed the results.

The experimental procedures involving human subjects described in this paper were approved by the Institutional Review Board.

II. METHOD

We explain the concept of this wearable device. To continuously monitor heat generation, an eyeglass-type device was created that senses body temperature using an infrared temperature sensor. However, as described above, the value measured by the infrared temperature sensor is the body surface temperature, so a temperature lower than the core body temperature is measured. Therefore, we measure the temperature of the caruncle, which is close to the core body temperature, because it is not covered by skin, and the angular artery and vein run in parallel. The body temperature is measured from an infrared temperature sensor by estimating the core body temperature from the caruncle temperature [15].

A. Device

Fig. 2 shows our proposed eyeglass-type device. The infrared temperature sensor was placed on the spectacle bridge. It was designed so that the temperature of the lacrimal caruncle can always be observed and acquired from the same position by fixing the distance between the caruncle and the sensor so that it does not change. Only a simplified eyeglass frame is used for the eyeglass-type device in the prototype experimental system, making it possible to directly measure the caruncle temperature with an infrared temperature sensor.

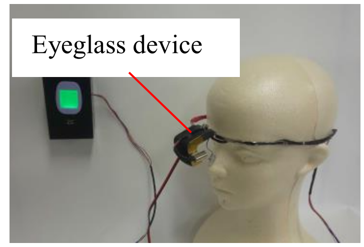

Fig. 2 Eyeglass-type device appearance

B. Model

The thermal model is shown in Fig. 3. The 65-Node Thermoregulation-Model was developed to estimate core body temperatures [16]. We developed a simplified head model on the basis of the Two-Node Model to estimate core body temperatures from caruncle temperatures. The calculation cost can be reduced by making only the head model. In creating the model, the temperature in the hypothalamus, which controls body temperature, was set as the core body temperature. Heat transfer from the lacrimal caruncle to the hypothalamus was considered to be heat transfer between tissues and heat transfer by blood vessels. To obtain the core body temperature, the following bio-heat equation was used [17].

$$k\frac{\partial^2 T}{\partial x^2} = \rho_t c_t \left(\frac{\partial T}{\partial t}\right) + W_b c_b (T - T_a) \qquad (1)$$

T [°C] is the temperature, t [s] is the time, x [m] is the location ρ_t [kg/m^3] is the density, c_t [J/(kg.)] is the specific heat, k [W/(m. °C)] is the thermal conductivity, subscript a is the artery, and subscript b is the blood. ω_b [m^3/(Sm^3)] is a physical property called the blood perfusion rate, which represents the flow rate of blood flowing into a unit volume of biological tissue. The second term on the right represents heat generation and endotherm due to blood flow, assuming that blood entering the tissue flows out in an equilibrium with the tissue. Therefore, this is a linear heat-generation term with respect to the temperature of the tissue. Microscopic elements such as the geometrical state of the vascular network are not considered.

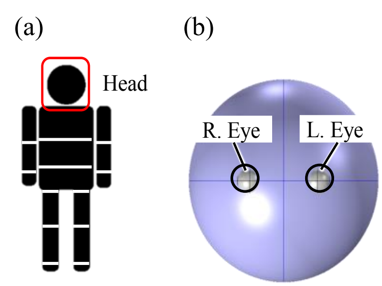

Fig. 3 Thermal Model: (a) 65-Node Thermoregulation-Model, and (b) Our proposal head model

Our simplified head model divides the head into seven nodes: the hypothalamus, brain, cerebrospinal fluid, skull, skin, blood vessels, and eye. Six nodes (the hypothalamus, brain, cerebrospinal fluid, skull, skin, and eye) were modeled as virtual spheres. The vascular nodes reproduced the vasculature leading to the internal carotid artery, ophthalmic artery, supraorbital artery, and angular artery. The present estimation aims to determine the body core body temperature at rest from the temperature of the lacrimal caruncle and does not take into account heat production by the muscles or heat transfer from the trunk during movement or exercise.

Using this model, we derived a relational equation between the temperature of the lacrimal caruncle and that of the hypothalamus in COMSOL®. As a result, the relationship shown in Fig. 4 was derived.

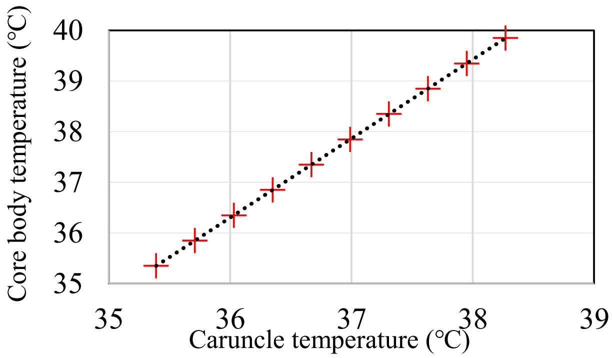

Fig. 4 Relationship between the caruncle temperature and hypothalamic temperature

C. Evaluation of measurement accuracy of the caruncle temperature

Table 1 shows the verification results of the fabricated eyeglass-type device. We measured the caruncle temperature using the LT-2 skin temperature sensor (Temperature accuracy ± 0.02 °C) as a reference temperature. We compared the results with those measured simultaneously by the eyeglass-type device. We measured the temperature of the lacrimal colliculus with each device once every minute for 10 minutes to compare. Since the LT-2 skin temperature sensor and the infrared temperature sensor cannot be measured at the same point, we measured the right caruncle with the eyeglass-type device and the left caruncle with the LT-2 skin temperature sensor. The difference between the right and left sides of the caruncle temperature was verified experimentally and found to be 0.02 °C, which is over one order of magnitude smaller than the goal accuracy of ± 0.3 °C [8]. As shown in Table 1, when the measured values of LT-2 were compared with the measured values of the eyeglass-type device, the temperature difference was 0.080 °C. We conducted two one-sided tests to compare values of the prototype eyeglass-type device and the LT-2 skin temperature sensor. The difference in the mean was within the confidence interval of ± 0.3 as shown in Fig. 5. Therefore, the lacrimal caruncle temperature was measured by the LT-2 skin temperature sensor. The caruncle temperature measured by our proposed device can be said to be equivalent to the caruncle temperature measured by the LT-2 skin temperature sensor.

TABLE 1 Verification of eyeglass-type device

	Our proposal device	**LT-2**
Cumulus temperature	36.22	36.14
Standard deviation	0.080	0.121

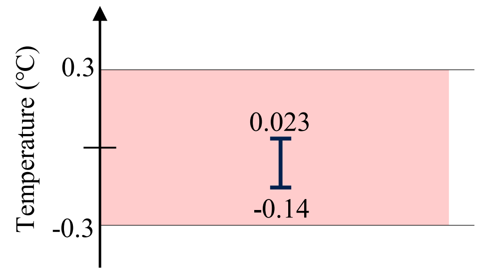

Fig. 5 Two one-sided tests of measured temperature on LT-2 and measured temperature on eyeglass-type device

D. Core body temperature estimation verification of experimental system

The experimental setup is shown in Fig. 6. In this experiment, the ambient temperature was controlled in an environment control room, and the core body temperature and the caruncle temperature were measured simultaneously. We experimented in the environment control room of TABAI ESPEC TBL-9W4YPX ((W) 5000 * (H) 2250 * (D) 4000 (mm)) [18]. The set temperature of the environment control room was varied from 5 to 35 °C in 5 °C increments. However, there was a difference between the set temperature and the temperature around the subject due to the difference in the measurement location. Therefore, we placed a wet-bulb global temperature (WBGT) meter around the subject, and plotted its temperature assuming the ambient temperature. The humidity setting was fixed at 30% relative humidity (RH). We used the ear canal temperature of the left ear measured using an ear thermometer (Nipro CE Thermo) as the core body temperature, and the tear duct temperature of the outer side of the right eye was measured by using the eyeglass-type device.

In general, the core body temperature often indicates the rectal temperature. However, the rectal temperature has been found to have a time lag for changes in hypothalamic temperature. Therefore, in this experiment, the external ear canal temperature was measured as the core body temperature, not the rectal temperature.

The measurement procedure for each temperature plot was as follows. After the temperature in the chamber reached the set temperature, the subject entered the chamber. The measurement started 10 minutes later to allow the subject to acclimatize to the room temperature. Core and cumulus temperatures were measured simultaneously and repeatedly 10 times per plot. Since the difference between the set temperature of the environment control room and the ambient temperature when it reached 35.0 °C at high temperature was 3 °C or lower, the measurement was carried out again after 10 minutes.

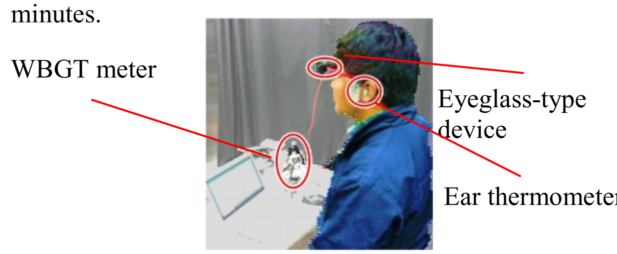

Fig. 6 Experiment for thermometry with our proposed device in an environment control room

III. RESULTS

This experiment was conducted on a single male in his 20s.We tested the eyeglass-type device and verified the ambient temperature dependence of the core body temperature estimated from the caruncle temperature.

Experimental results

Fig. 7 shows the relationship between the core body temperature measured in the ear canal and the core body temperature estimated from the caruncle temperature measured with the eyeglass-type device when the ambient temperature was changed. The WBGT temperature meter was measured in 8 plots at 5.7, 11.4, 15.1, 21.0, 23.1, 27.3, 30.8, and 32.1 °C. For each plot, the average, maximum, and minimum values of 10 measurements are shown. The measured and estimated core body temperatures have slopes of 0.015 and 0.076 with respect to ambient temperature variation, respectively. This indicates that the temperature of the caruncle has a slope of 0.043 with respect to the variation of the ambient temperature, and the estimated core body temperature affected this variation. The confidence interval of the difference in the mean was within ± 0.3 when the ambient temperature was 21.0, 23.1, and 27.3 °C as shown in Fig. 8. At 5.7, 11.4, and 15.1 °C, the estimated core body temperature was calculated to be 0.3 °C or more lower than the core body temperature measured in the ear canal, and at 30.8 and 32.1 °C, it was calculated to be 0.3 °C or more higher. Therefore, the core body temperature estimated from the core body temperature measured in the external auditory canal and the caruncle temperature were equivalent when the ambient temperature was 21.0, 23.1, and 27.3 °C but different when the ambient temperature was above or below those temperatures.

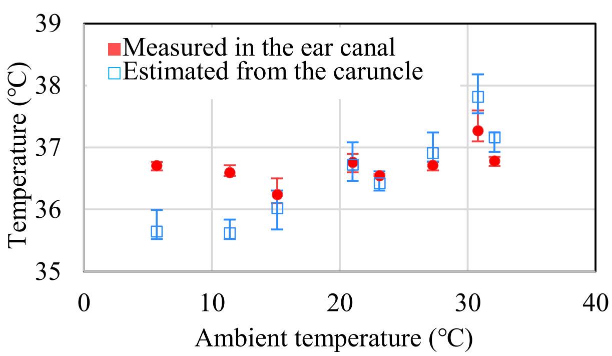

Fig. 7 Relationship between ambient temperature and body temperature

IV. DISCUSSION

One reason that the core body temperature could not be estimated from the caruncle temperature when the ambient temperature was above or below 21.0 ~ 27.3 °C is that the temperature of the caruncle was affected by the environment. The effects of wind and humidity are also considered in addition to the ambient temperature. The skin temperature is affected by the ambient temperature. Depending on the measurement place, when the temperature changes by 20 °C, the skin temperature changes by 10 °C or more. Since the fluctuation of the skin temperature is smaller than the fluctuation of the ambient temperature, the difference from the measured value is 0.3 °C. In this experiment, the temperature was changed to 35.5 ~ 37.0 °C, though the fluctuation due to the ambient temperature was not as large as described above, since the angular artery and vein flow cross in the vicinity in the caruncle. On the other hand, the core body temperature fluctuates by only 36.6 ~ 37.2 °C, indicating that the core body temperature fluctuates less than the caruncle temperature. Therefore, it is possible that the core body temperature value cannot be estimated from the caruncle temperature as the difference between the caruncle temperature and the ambient temperature is large. Thus, the environment in the vicinity of the lacrimal hill must be measured and substituted into a relational expression corresponding to the environment or to derive a relational expression including an environmental parameter.

In this experiment, we prototyped the eyeglass-type device consisting of only the frame to measure the caruncle temperature. However, the effect of the environment may change depending on the actual design. If a lens is attached to the spectacle frame, the lens may conceivably reduce the effect of environmental change from the face front.

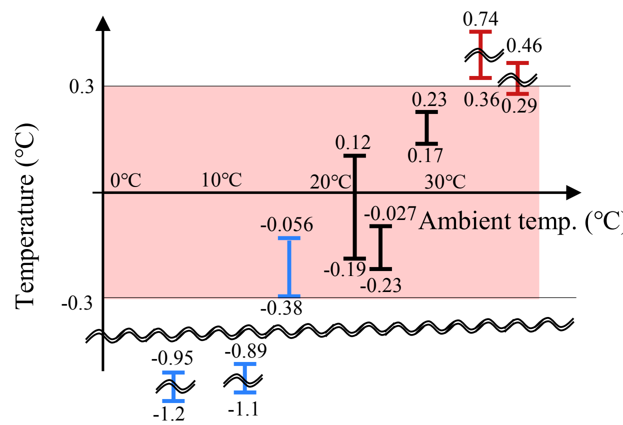

Fig. 8 Two one-sided test of measured temperature in the ear canal and estimated temperature from the caruncle

V.CONCLUSION

In this paper, an eyeglass-type device that measures the caruncle temperature was proposed as a convenient daily screening system for infectious diseases such as COVID-19. In the ambient temperature range from 21 to 27.5 °C, the difference between the core body temperature measured in the ear canal and the core body temperature estimated from the caruncle temperature was within ± 0.3 °C. Therefore, the core body temperature value may be able to be estimated by measuring the caruncle temperature. However, since the ambient temperature and wind cause the caruncle temperature colliculus to fluctuate more than the core body temperature, the eyeglass-type device needs to be evaluated in experimental conditions that more closely reflect the real world. Since body temperature also varies depending on individual differences, a relational expression corresponding to individual differences also needs to be derived.

ACKNOWLEDGMENTS

The authors thank Mr. Sudo of Exact Works Inc., Mr. So and Mr. Hasegawa of NTT Advanced Technology Corporation, and Mr. Higuchi of NTT TechnoCross Corporation.

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