Optimization of a Wearable Device for Core Body Temperature Monitoring Based on the Dual-Heat-Flux Model

Jiayueyuan Fang\textsuperscript{1,*}, Congcong Zhou\textsuperscript{1,b} and Xuesong Ye\textsuperscript{1,2,*}

\textsuperscript{1}Biosensor National Special Laboratory, College of Biomedical Engineering and Instrument Science, Zhejiang University
\textsuperscript{2}State Key Laboratory of CAD & CG, Zhejiang University, Hangzhou 310027, PR China

*Corresponding author e-mail: yxesong@zju.edu.cn, fangjiayueyuan@zju.edu.cn, zjdxzcc@zju.edu.cn

Abstract. This paper presents an improved structure of core body temperature (CBT) probe based on the dual-heat-flux (DHF) principle. A new frustum-shaped architecture of sensor, instead of traditionally cylinder-shaped, is presented to decrease the transverse heat flow which is the major obstacle to fit the DHF theory. Besides, finite element simulation is conducted to compare the heat concentration in those two structures and reveal the relationship between the measuring accuracy and the thermal conductivity of the shell. Nylon Glass Fiber Mixture (NGFC) is introduced to improve the performance of probes based on the above simulation. Finally, to verify the effectiveness of the models simulated accordingly, wearable probes based on CBT monitoring system is presented and hot-plate (produced by Thermo Scientific) experiments are carried out. The new probe shows an error, i.e. 0.09±0.05°C, at different CBTs, which promises higher stability within acceptable error in congeneric researches.

1. Introduction

The core body temperature (CBT) is considered as a barometer of human health. CBT usually keeps steady at the range of 36.5-37.5°C under normal metabolism, whereas skin temperature is susceptible to the fluctuation of external environment \cite{1}, sweat evaporation and clothes, etc. Furthermore, in sick states such as fever and chills, the change trend of body surface temperature may even be opposite to the core temperature. In addition, CBT can provide an accurate prediagnosis of heat stroke, heat exhaustion and other conditions caused by heat waves or long-time intense outdoors physical activity. Therefore, monitoring long-term core temperature is more valuable and significant.

However, it can only be exactly measured by invasive methods such as the intubation in rectal, pulmonary or bladder in order to obtain a strictly numerical value. The abovementioned invasive methods require professional medical personnel to operate, while causing physiological discomfort to patients. There are also some indirect, non-invasive methods such as infrared tympanic thermometer, microwave radiation thermometer, ultrasonic thermometer, and magnetic resonance thermometer. Among them, infrared tympanic thermometer lacks accuracy due to blood circulation near the tympanic membrane, while others are at the cost of high price, low resolution, or demand of...
cumbersome equipment [2]. Therefore, they are not suitable to be a smart device for long-term CBT monitoring.

Wearable devices are becoming more and more popular. Currently, probes that continuously monitor core temperature are mainly based on heat flow method. The continuous core temperature monitoring method that can be applied in surgery is zero-heat-flow method [3-5]. Although this method has achieved high measurement accuracy, it is difficult to become the mainstream of wearable devices due to the need for alternating current power supply, which restricts the users' free movement. Single-heat-flow method [6, 7] consumes lower power, but its measurement model needs to get the resistance of the skin and subcutaneous tissue layer, which differs with individuals. The double-heat-flow method makes up the defect of individual difference, and predecessors have drawn a systematic conclusion on the structure and size of the measurement probe through computer simulation [8-10], hot-plate experiment, water bath and even human body experiment [1]. Nevertheless, the method still has some defects which restrict continuous monitoring, such as long response time, unstable prediction and easy to be affected by environment temperature. The biggest difference between the actual prediction model and the theoretical model is the transverse heat flow, which introduces the systematic error [8, 11].

As is suggested in [8], previous literature usually use modified formula to compensate for horizontal heat. In this paper, on the basis of [1], the prediction performance is further improved by optimizing the probe structure and material to make the probe more consistent with the theoretical model. To reach this target, 3-D models are built based on the finite element method (FEM) and study the impact of 1) different structures, 2) thermal conductivity of the shell material. The mock-up experiment is applied afterward to validate the performance of the new structure. A reformative probe composed of Nylon Glass Fiber Mixture (NGFC) shell and frustum-shaped PDMS filler can shorten response time to 20 minutes and reduce the error to less than 0.1°C in a large number of repeated experiments. In addition, the influence of external temperature field on prediction performance is studied.

2. Materials and methods

2.1. The principle of DHF model

In general, as long as there is a temperature difference, there will be heat transfer. Fourier’s law of heat conduction (1) is a general expression of steady state heat transfer of an object. Among those parameters, the temperature T is a function of three coordinates (x, y and z) of the object and \( \nabla T \) represents the temperature gradient at a point in space. The minus sign in (1) indicates that heat is being transferred in the opposite direction to temperature. The equation (2) is a heat transfer process involving convection, which represents the change in temperature distribution over time and space in a solid heat transfer field, where \( \rho \) is the density (kg/m\(^3\)), \( C_p \) is the specific heat capacity (J/kg∙℃) and \( k \) is the thermal conductivity (W/m∙℃) of the local tissue. The first term is the time inertia term, which represents the temperature change caused by the gradual accumulation of energy inside the solid with time. The second term is the convection term representing the influence of the external field on the solid temperature, where \( \mathbf{u} \) represents the velocity of the fluid (i.e. the air) in the outer field. The third term is the diffusion term and characterizes the conduction of heat inside the solid. The parameter Q represents the energy absorbed by the subject. The thermal radiation is also influenced by the external field, which is defined as a boundary condition by the following (3). The parameters \( \varepsilon, \sigma, \text{Tamb} \) respectively represent surface emissivity, Stefan-Boltzmann constant and ambient temperature. The left side of the equation represents the radiation energy of the external temperature field to the probe.

\[
\mathbf{q} = -k \nabla T \tag{1}
\]

\[
C_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q \tag{2}
\]
The DHF model is a theoretical hypothesis based on (1), which assumes one-direction steady-state heat conduction, no internal heat source and no external field action. As is shown in Figure 1, taking the heat fluxes in two channels into consideration only, the predicted CBT could be finally calculated by (4) where $K$ is defined as the ratio of thermal resistances [1]. Due to the horizontal heat flow, $K$ is acquired by (5) in practical applications, for which preliminary experiments are needs to seek. In this paper, the horizontal heat flow was reduced because of the structural design of frustum shape. As heat travels from the bottom to top, the radius of the heat conductors, i.e. white blocks, decrease while the other blocks increase, which means the heat will be more concentrated in longitudinal channels. The above methods aim to reduce horizontal heat flow.

$$E_b(T) = \varepsilon \sigma (T_{amb}^4 - T^4)$$  \hspace{1cm} (3)

$$T_{\text{Ctest}} = T_{d1} + \frac{(T_{d1} - T_{u2})(T_{d1} - T_{u1})}{K(T_{d2} - T_{u2}) - (T_{d1} - T_{d1})}$$ \hspace{1cm} (4)

$$K = \frac{(T_c - T_{u1})(T_{d1} - T_{u1})}{(T_c - T_{d1})(T_{d2} - T_{u2})}$$ \hspace{1cm} (5)

**Figure 1.** Illustration of DHF model. The heat fluxes $F_1$, $F_2$ from human tissue are through the probe longitudinally and CBT can be calculated by sensors $T_{d1}$, $T_{u1}$, $T_{d2}$, $T_{u2}$. This is a sectional view of the probe.

### 2.2. FEM simulation

The above solid heat transfer model was built, simulated and analysed with LiveLink for MATLAB based on COMSOL Multiphysics 5.4 (COMSOL Inc., Stockholm, Sweden). The finite element method (FEM) uses a mathematical approximation to simulate a real physical system with simple and interactive elements. The effects of blood perfusion and metabolic processes are not considered here. The purpose is twofold: the first is the kind of evenly distributed heat source would alter the actual value of the measurement somewhat but would not invalidate the qualitative relation from the simulation [12] and the second is to better fit and guide the hot-plate experiment. In order to simulate an infinite element domain in a finite volume, the side wall of the skin layer is set as the thermal insulation layer in this model, as well as to ensure the heat in the layer flow vertically upward along the axial direction. In this model, natural convection is simulated by introducing a heat-flux boundary condition while the amount of heat radiation is simulated by changing the emissivity $\varepsilon$ of the surface of the probe. The filling materials of the heat conductor and insulator module are PDMS (Polydimethylsiloxane) and foam respectively. The parameter $C_p$ represents constant pressure heat capacity, $\rho$ represents density and $k$ represents thermal conductivity, which are listed in Table 1.
Table 1. Display the necessary parameters of the required materials in the simulation model.

| Parameter | \( C_p \) [J/kg*K] | \( \rho \) [kg/m^3] | \( K \) [W/(m*K)] |
|-----------|-------------------|-------------------|-------------------|
| PDMS      | 1460              | 970               | 0.16              |
| Foam      | 730               | 2200              | 0.06              |
| Skin      | 3391              | 1109              | 0.37              |

In the simulation phrase, we seek to compare the performance of the cylinder-shaped probes in [1] with that of the frustum-shaped proposed in this paper. Therefore, an experimental group is built as shown in Figure 1 while a control group in Figure 2. The inner part of every model is a thermal conduction module, which is wrapped by an external insulation unit. In addition to the different structure of the thermal conduction module, other parameters such as thermal conductivity of the thermal modules and insulators, the height and radius of the probe, the material, and thickness of the skin layer are all the same. These parameters are listed in Table 2. We intend to map the heat distribution of the two probes during stabilization to visually show whether the heat is concentrated due to structural changes. In addition, the contrast of the heat flux in a given volume will be plotted.

![Figure 2](image.png)

Figure 2. Sectional view of two types of probes. The white area represents the heat conductors while the gray is an insulation unit. The sensors \( T_{d1}, T_{u1}, T_{d2}, T_{u2} \) is used to calculate CBT.

Table 2. Comparison of geometric parameters of the above two structures (unit: mm).

| Parameter | Frustum | Cylinder |
|-----------|---------|----------|
| Radii     | 18      | 18       |
| radii     | 17      | 17       |
| cap       | 5       | 17       |
| height    | 1       | 1        |
| \( H \)   | 11      | 11       |
| \( h \)   | 5       | 5        |

Furthermore, the thermal conductivity \( k \) of foam is changed in the list \([0.001, 0.005, 0.008, 0.01, 0.02, 0.004, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, \text{ and } 0.11] \) W/(m*K) to hunt for a better insulator. In fact, because a solid material with a thermal conductivity lower than 0.029 W/(m*K) is rare, we introduce those conductivities just for the whole picture of the relation between conductivity and accuracy. Subsequently, we set \( k \) as 0.06 W/(m*K) and change the heat emissivity \( \varepsilon \) or whether the natural convection boundary condition is introduced to study the influence of the two on the prediction performance.

In above experiments, the environment temperature is set as 23°C without introducing natural convection and radiation protection layer. The difference is that the bottom boundary of the skin layer is set up as the CBT of 37°C in the first experiment while the second and the third are tested at six CBT gradients (Tc=37-42°C).
2.3. Experiments on hot-plate

2.3.1. Fabrication of Prototypes. Several prototypes are fabricated, which are composed of some probes based on the simulation result and the circuit board, a unit used to transmit the temperature signal collected by the probes to the processor terminal written in C#. The probes mainly consist of a pair of frustum-shaped probes (size: Table 2). The shell is made of Nylon Glass Fiber Mixture (NGFC), filled with PDMS. The sensors used inside the probe are made of negative temperature coefficient thermistor (NTFT, by CANTHERM) with high precision and volume, which is calibrated by FLUKE’s high-precision digital thermometer 1502A. Their average error within the designed working range (21-42°C) was 0.01°C.

2.3.2. Measuring System. The system mainly includes a probe, a temperature sensing unit, a power supply module, a microcontroller processing module, a wireless transmission module, and a host computer display module.

The central circuit board, as shown in Figure 3, collects temperature data every 2 seconds and wirelessly transmits them to the computer via Bluetooth to facilitate the data processing. The board performs analog-to-digital conversion on the 12-bit A/D module of the MCU (MSP430F2617, TI) to obtain a digital signal and then filter them. For wearable portability, the system is powered by a 3.7V battery.

![Figure 3. System Architecture and central circuit board display.](image)

2.3.3. Mock-up experiment. The mock-up experiment is carried out on a hot-plate, while the temperature of its surface is set as CBT. A processed and cured PDMS on the hot-plate plays a skin-like role in this system, which is connected with the probe by medical double-sided tape. Calibrated NTC sensors are placed on the surface of the hot-plate and near the test system to record changes in core temperature and ambient temperature in real time, respectively. Through this phase of the experiment, we hope to explore whether the new structure and shell material would influence the accuracy as analysed by the simulation and figure out the impact of the natural convection on prediction ability by setting a control group covering the cotton on the probe. The experiment is divided into two CBT gradients, 37°C and 38°C, while the ambient temperature varies randomly at 24-28°C. The hot-plate experiment lasts for 70 minutes at each CBT without preheating.

3. Result

3.1. Result of Simulation

3.1.1. Comparison of two structures. The core temperatures of both probes were same while the ambient temperature kept constant, and the heat in the core temperature zone passed through the skin
to form a specific temperature distribution in the probe, as shown in Figure 4. It can be qualitatively demonstrated that the characteristic of the new structure reduces the flux of horizontal heat flow. The higher the temperature is, the heat in the indicated area is more. As for the frustum-shaped probe, the heat is relatively more concentrated in the part close to the central axis while the heat flow distributed on both sides relatively small.

![Figure 4. Comparison of two probe profile temperature (℃).](image)

In order to get a more accurate representation quantitatively, we calculated the energy integral of the z-axis direction of the volume in the red dotted box in Figure 4 (a) and Figure 4 (b) respectively, and the curve of the result changing with time is shown in Figure 5. The heat flux of the two structures decreases gradually with the establishment of heat balance, and finally, the energy tends to level. At the beginning of the process of establishing the heat balance, the heat flux through the central region of the frustum and the cylinder is basically the same. As the thermal equilibrium is gradually established, the energy flowing through the cylindrical structure is significantly less than that flowing through the circular platform in an area of the same size. For each probe, we assume that the energy flowing into the probe from the skin layer is equal so that more energy in the z-axis direction can almost be considered as a corresponding decrease in horizontal heat flow.

![Figure 5. Energy integration under equal volumes of two different structures not effective.](image)

3.1.2. What is a suitable shell? The temperature data in the simulation model were accurate to the fourth decimal place. Figure 6 provides a reference for how to select a suitable thermal conductivity shell material, in which the markers in the curve denotes the estimated error with corresponding conductivity and that the curve goes up and down represents the results with the conductivity from 0.001 to 0.11 W/(m*K). Except for the sharp peak value from 0.03 to 0.05 W/(m*K), the error value corresponding to other thermal conductivity is less than 0.002°C. In accordance with the above the
results, we choose the Nylon Glass Fiber Mixture (0.065-0.08 W/(m*K)) to make the shell in the hot-plate experiment. In short, the picture tells us not only to use the shell but also to add a suitable shell.

![Trend Chart]

**Figure 6.** The trend chart of error changing with thermal conductivity.

### 3.1.3. External field.

The external field mainly refers to the ambient temperature field and its influence is as follows. The horizontal axis and the vertical axis in Figure 7 still represent the core temperature gradient and the prediction error respectively. The three curves in the figure correspond to three different input conditions of the external field. As is shown in the chart, the probe of the control group is without radiation protection layer and don’t introduce convection. The probe which introduces convection on the basis of the control group shows a large error more than 0.2°C at each core temperature, while the probe with the radiation protection layer based on the control group performs much lower than the other two groups, even less than 0.02°C. In practical applications, due to the low emissivity of the metal, a metal layer is usually added on the outer surface of the probe to reduce heat radiation; the outer side of the probe is covered with a material that reduces convection, such as cotton.

![Convection/Radiation Effects]

**Figure 7.** Convection/radiation effects.
3.2. Result of hot-plate Experiment
According to the simulation results, we use the new probes with new materials and structures, whose average error (0.09±0.05℃) after 20 minutes of response time can attain the acceptable margin of error. The surfaces of probes are covered with cotton.

3.2.1. The performance of new Prototype. Figure 8 shows the changing trend of temperature in each channel. At each CBT, the temperature of the four sensors in the probe can reach 95% of the final stable value within 20min after CBT value is basically unchanged. In the first stage (CBT=37℃), the temperature of the sensor is balanced within 40 minutes because it takes 20 minutes for the hot-plate to heat up. The temperature value of the hot plate is changed at the 70th minute of the experiment, and all the four temperature values reached a stable state at the 90th minute of the experiment. As is shown in Figure 9, it is found that the predicted CBT differs little from the actual CBT by comparing the two curves when the probes enter a stable state and follows the actual CBT well.

3.2.2. The impact of natural convection. Compared with the control group covered with the cotton, the probe exposed to the air obtained a larger error and is equally effective against the strong convection near the probe such as direct air blowing from the air conditioner.

![Figure 8. Temperature curves of each sensor of the prototype during the experiment. Tamb represents the ambient temperature while CBT is the actual temperature of the hot-plate surface.](image)

![Figure 9. Demonstration of new prototypes’ prediction.](image)
4. Discussion
As is shown in Table 3, this paper compared the research content with other two similar articles. The cylinder-shaped structure is as described above, whose heat conduction channel is similar to that of the boss-shaped structure. The frustum-shaped structure acquires a better result, i.e. 0.09±0.05°C, whose error is small and stable. The original intention of the frustum-shaped structure is that the radius of its top is smaller than that of the bottom, and the heat uploaded from the skin layer will pass through the heat conduction module as much as possible and the insulator as little as possible based on (6). In all transfer process of nature, the transferred amount is equal to the ratio of forces to resistances. The equation illustrates when the temperature difference ∆ , the driving force of this process, is consistent, the greater the thermal resistance R is, the smaller the heat flux Φ through a plane with the same area will be. Therefore, the heat dissipated horizontally decreases.

\[ \Phi = \frac{\Delta T}{R} \]  

In this paper, Nylon Glass Fiber Mixture (0.065-0.08W/(m*K)) was finally adopted as the shell material to improve the prediction accuracy under the guidance of simulation experiments. The shell with extremely low thermal conductivity was added in order to keep the sides as adiabatic as possible, thereby reducing the horizontal heat flow on the sides. Therefore, as shown in Figure 6, we found that the prediction error is small at the stage where the thermal conductivity is less than 0.03 W/(m*K). However, the thermal conductivity of air is 0.029 W/(m*K) and there are few solid materials in nature that have a lower thermal conductivity. In addition, due to the particularity of the frustum-shaped structure, the relationship between thermal conductivity and prediction error is not linear, which is different from other literature. The guess is that the structure is up and down asymmetrical, so the growth rate of the longitudinal heat flow and the horizontal heat flow are different. When the latter is large, the prediction accuracy is reduced. The influence of the thermal conductivity of the probe’s internal heat conductor on the prediction results was also studied, which was not mentioned because its variation with the range of 0.15 to 0.32 W/(m*K) had little impact.

The dual heat flow model is based on the assumption of the one-dimensional and steady-state heat conduction model. One-dimension means that the temperature of a heat conduction object changes only in one coordinate direction. The condition requires us to reduce the horizontal heat flow as much as possible and concentrate the heat in the longitudinal heat conduction channel. The integral of the energy in the volume of the central region is to describe the concentration of heat in the new structure, which means less horizontal heat flow. In addition, other thermal properties of the material such as C_p and p in Table 1 affect the transient analysis of the model, such as the response time of the probe.

| Literature | [12] | [1] | This paper |
|------------|------|-----|------------|
| Evaluation | 0.17±0.06°C | 0.08±0.20°C | 0.09±0.05°C |
| Structure  | boss  | cylinder | frustum    |
| Shell      | sponge cover | sponge cover | Nylon Glass Fiber Mixture |
| Size       | Radii=55, H=15, h=9 | Radii=19, H=12, h=6 | Radii=18, H=11, h=5 |
| Response time | ~20min | ~23.5min | ~20min |
| Sensor inside probe | LM73 | NTCs | NTCs |

By means of system calibration and linear interpolation, the error of NTCs reached ±0.01°C, which guarantee the high precision measurement of the system. The NTC sensor is smaller and easier to embed inside the probe than some integrated sensor units. The introduction of Bluetooth transmission improves the wearable performance of the probe.

Essentially, the effect of natural convection on the probe is the flow of heat due to the temperature difference between the fluid air and the probe surface. A layer of cotton-like material is added to
prevent this heat exchange. Similarly, it can reduce the heat lost from the inside of the probe in the form of thermal radiation by adding a metal layer to the outer surface because of the low emissivity of the metal material.

5. Conclusion
This paper has provided a detailed description of a new frustum-shaped structure based on the dual-heat-flux model and put forward a scheme with acceptable accuracy and stability: 1) a shell with suitable thermal conductivity; 2) a smaller size; 3) a cotton-like case to prevent natural convection. This design has a level of less than 0.002°C in simulation experiment and less than 0.1°C in the numerous and repeated hot-plate experiments. Besides, the simulation has shown the heat concentration in the longitudinal heat conduction channel.

In addition, there are still some works should be done to improve the performance of the proposed system in future. For instance, although the response time has been reduced to 20min, it is still a far from being used in clinic and daily life.

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