Continuous measurement of tympanic temperature with a new infrared method using an optical fiber

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1Laboratory for Applied Human Physiology, Faculty of Human Development, Kobe University, Kobe 657-8501; 2Production Engineering Laboratory, Shimadzu Company, Atsugi 243-0213; and 3Faculty of Engineering, Kobe University, Kobe 657-8501, Japan

Shibasaki, Manabu, Narihiko Kondo, Hirotaka Tominaga, Ken Aoki, Eiichi Hasegawa, Yoshiyuki Idota, and Toshimichi Moriwaki. Continuous measurement of tympanic temperature with a new infrared method using an optical fiber. J. Appl. Physiol. 85(3): 921–926, 1998.—The purpose of this study was to investigate the utility of an infrared tympanic thermometry by using an optical fiber for measuring tympanic temperature (T_{ty}). In the head cooling and facial fanning tests during normothermia, right T_{ty} measured by this method (infrared-T_{ty}) and esophageal temperature (T_{es}) were not affected by decreased temple and forehead skin temperatures, suggesting that the infrared sensor in this system measured the infrared radiation from the tympanic membrane selectively. Eight male subjects took part in passive-heat-stress and progressive-exercise tests. No significant differences among infrared-T_{ty}, the left T_{ty} measured by thermistor (contact-T_{ty}), and T_{es} were observed at rest or at the end of each experiment, and there was no significant difference in the increase in these core temperatures from rest to the end. Furthermore, there were no significant differences in the core temperature threshold at the onset of sweating and slope (the relationship of sweating rate vs. infrared-T_{ty}, and vs. contact-T_{ty}). These results suggest that this method makes it possible to measure T_{ty} accurately, continuously, and more safely.

infrared sensor; device; core temperature; thermoregulation; humans

CORE TEMPERATURE is one of the most important indexes for clinical practice and thermoregulatory research in humans. It is necessary that the gold standard for measuring core temperature responds to rapid changes in the core temperature. Esophageal (T_{es}) and tympanic (T_{ty}) temperatures have been used to estimate core temperature in clinical practice and thermoregulatory research. Benzinger (1, 2) proposed that T_{ty} reflected the core temperature because of the proximity of the tympanic membrane to the carotid artery, where it flows into the hypothalamus. Although some researchers agree with his opinion (6, 7, 18, 24), others do not accept that T_{ty} is a true measurement of core temperature because T_{ty} is affected by a decrease in skin temperature resulting from facial cooling or fanning (5, 14, 15, 20). In a study directly measuring brain temperature, Shirakai et al. (21) indicated that T_{ty} did not reflect the brain temperature during hyperthermia. On the other hand, Mariak et al. (12) suggested that the changes in brain temperature were better approximated by T_{ty} than by T_{es}. This discrepancy may result from the imperfections in the method used for measuring T_{ty}. Brinnel and Cabanac (6) and Sato et al. (18) reported that when a probe was successfully placed on the tympanic membrane, and the external canal was covered with cotton or a thermal insulating material, then T_{ty} was not affected by ambient temperature or by a decrease in skin temperature on the face or head.

Generally, the traditional methods for measuring T_{es} and T_{ty} require that the thermometry keeps in contact with the esophagus or tympanic membrane, respectively. However, these methods have some risks (spread infection, injure the esophagus or tympanic membrane, and cause subjects discomfort or pain). Infrared tympanic thermometry has been developed to solve these problems, as a method of measuring T_{ty} more safely and conveniently (19). Terndrup noted that this method has been mentioned in many publications since the late 1980s (see Ref. 23 for review). However, the accuracy and reliability of existing devices are not high enough to allow their use in clinical medicine and thermoregulatory research (3, 10, 13, 17, 18, 22, 23). The reasons for such inadequate performance in measuring T_{ty} are attributed to the characteristics of the infrared sensor and its size. An infrared sensor measures the average temperature in its “field of vision.” Existing devices may measure the infrared radiation from the auditory canal as well as the tympanic membrane. Furthermore, existing devices are not suitable for continuous monitoring, although continuous information on the core temperature during experiments is valuable. We have developed an infrared tympanic thermometry with an optical fiber (optical fiber thermometry) to detect the limited amount of infrared radiation from the tympanic membrane. A chalcogenide glass fiber was used for the optical fiber, and this made it possible to detect the temperature of the tympanic membrane selectively.

In this study, we investigated whether the optical fiber thermometry accurately registered the temperature of the tympanic membrane during different experimental maneuvers. Head cooling and facial fanning tests were used to determine whether the temperature registered by the optical fiber thermometry was affected by a decrease in skin temperature. The passive-heat-stress and progressive-exercise tests were used to compare T_{ty} measured by the optical fiber thermometry (infrared-T_{ty}), T_{ty} measured with a thermistor (contact-T_{ty}), and T_{es} measured by a thermocouple. We also used the relationship between the rate of sweating and the two core temperatures in these experiments as an additional test of the utility of the optical fiber thermometry.
MATERIALS AND METHODS

Subjects. Three healthy untrained male subjects participated in the head cooling and facial fanning tests, and these three and five other male subjects took part in the passive-heat-stress and progressive-exercise tests. Their mean age, height, weight, and body surface area were 22.8 ± 0.9 (SD) yr, 1.70 ± 0.05 m, 64.5 ± 9.8 kg, and 1.74 ± 0.14 m², respectively. Each subject was informed of the nature of the procedures and the risks associated with the experiments, and each signed an informed consent agreement when he first visited our laboratory.

Procedures. For the first group of tests, each subject sat on a chair in an environmental chamber (SR-3000, Nagano Science, Osaka, Japan) maintained at an ambient temperature of 25°C and 50% relative humidity. After a 5-min baseline period, the subject's temple was cooled by application of an ice pack or his forehead was cooled by air blown from an electric fan. Cooling lasted for 15 min followed by a 10-min recovery period. The two tests were performed on different days.

For the second group of tests, the subjects wore only shorts and entered an environmental chamber maintained under the same conditions. They remained seated for at least 1 h to reach equilibrium, during which time the measuring devices were attached. After baseline values were measured for 3 min, they then performed either the passive-heat-stress test or the progressive-exercise test. The passive-heat-stress test involved immersion of the subjects' lower legs in a hot water bath at 42°C for 60 min. The progressive-exercise test involved pedaling on a cycle ergometer (model M50, Combi) at a frequency set to 60 rpm. The subjects cycled at 50 W for 1 min, and then the exercise intensity was increased by 1 W every 15 s for 30 min, for a total of 31 min. One subject was exhausted 27 min after the start of exercise, so only the first 27 min of data are used for all of the subjects. These two tests were performed in a random order, with at least 2 days between tests.

Measurement of Tty and Tes. In this study, two types of tympanic thermometry were used to measure Tty. The first was an optical fiber thermometry, consisting of an infrared sensor and an optical fiber. The infrared sensor used was a pyroelectric infrared detector (DLATGS, Shimadzu). This infrared sensor can detect infrared energy independent of the wavelength of the radiation emitted by an object (11), but the incident infrared radiation must be interrupted at regular intervals. Therefore, this system is equipped with a mechanical chopper, inserted between the infrared sensor and the optical fiber (Fig. 1), which has two blades that rotate at 120 Hz.

The optical fiber used was the most suitable for detecting human body temperature. The core temperature in humans is normally between 36 and 40°C, and the wavelength of infrared radiation corresponding to these temperatures is ~9.38–9.26 µm. A chalcogenide glass fiber (NTEG, NOG) is the most suitable optical fiber for transmitting infrared radiation at these wavelengths. This fiber has been used in some machines: CO laser, thermal imaging, and so on. This optical fiber transmits the infrared radiation from the tympanic membrane better than do other optical fibers (16). The transmission loss below 1 dB/m for the infrared wave with a wavelength of 9.35 µm is matched to ~37°C. The fiber we used is 0.63 mm in diameter and 500 mm in length. NTEG makes it possible to detect the infrared radiation from the tympanic membrane without the measurement being influenced by the temperature of the surrounding ear canal wall and without contacting the tympanic membrane.

The basic characteristics of the optical fiber thermometry, such as stability (sensor and system drift) and linearity, were investigated by using a blackbody temperature that was controlled by a Peltier element. The optical fiber thermometry was calibrated with the blackbody before each experiment.

To position the optical fiber in the extra-auditory canal, a polyethylene sponge was glued to the fiber. This also insulated the auditory canal from the ambient temperature (Fig. 1). Each subject compressed the polyethylene sponge and carefully inserted the optical fiber into his right ear canal while he listened to the spinning noise of the mechanical chopper that traveled through the fiber and we monitored the temperature. The noise seems louder as the fiber approaches the tympanic membrane, and the temperature of tympanic membrane is maximal in the auditory canal. We used these parameters to determine whether the optical fiber thermometry was properly positioned to accurately measure Tty. The temperature from the infrared sensor was sampled every 5 s and sent to a personal computer (9801T, NEC).

The other method of thermometry was a thermistor sensor (Sensor Technica), which measured the temperature of the contralateral tympanic membrane (contact-Tty). This information was sent to the personal computer (9801NST, NEC) with a data logger (K730, Techno Seven) every 4 s. The thermistor probe was gently inserted into the left ear canal by the test subject while we monitored the temperature. We used the sharp pain felt by the subject and the scratching noise heard before and after each experiment to determine that the sensor was in contact with the tympanic membrane. The auditory canal was then filled with cotton wool and taped to prevent movement of air inside the auditory canal.

Tes was measured by a copper-constantan thermocouple with silicon coating at the tip. The thermocouple was inserted through the nose to a distance equal to one-quarter of each subject's height. The temperature was recorded every second and was stored in the personal computer (9801RA, NEC) with a data logger (HR2300, Yokogawa). Average values for infrared-Tty, contact-Tty, and Tes were calculated for each minute. The control and final temperatures were the average values for the 3-min before the start and at the end of each experiment, respectively. The change in the core temperatures (ΔTcore) was the difference between the control and final values.

Measurement of skin temperatures, sweating rate, and heart rate. During the tests of head cooling and facial fanning, the skin temperature of the forehead and right temple was measured with the copper-constantan thermocouple. These temperatures were sampled every second. During the passive-heat-stress and progressive-exercise tests, the local sweating rate and heart rate were measured. Sweating rate was...
recorded continuously at two sites, the left side of the chest and the forearm, by the ventilated capsule method. Dry nitrogen gas was pumped through the capsules (chest: 8.54 cm², forearm: 5.31 cm²) at a rate of 1.5 l/min. The humidity of the nitrogen gas flowing out of the capsules was measured with a capacitance hygrometer (HMP 133Y, Vaisala, Finland). The skin temperatures and hygrometer output signals were stored in the same system used for measuring Tₑₛ and were calculated every minute. Heart rate was measured by using lead V₅ of an electrocardiogram.

Regression equations between sweating rate and the core temperature were calculated for each subject during each test from the data sampled every minute. Whenever the relationship showed a sigmoidal pattern, the points representing the steepest portion of the curve were fitted by regression analysis to obtain the slope. Infrared-Tₜᵥ, contact-Tₜᵥ, and Tₑₛ thresholds for sweating were the values for each core temperature after which sweating rate increased above its equilibrium value.

Statistical analysis. A one-way analysis of variance was performed to assess the difference between calculated and measured values for the thermal parameters, e.g., the control values, the final values, ΔTₑₛ, and the slope of sweating rate vs. core temperature. Repeated two-way analysis of variance with repeated measures was used to assess the change in thermal parameters with time. Values of infrared-Tₜᵥ, Tₑₛ, and contact-Tₜᵥ sampled every 5 min were used for the statistical analysis. In addition, Sheffé's test was used to test treatment mean values among the parameters when there were significant differences. Statistical significance was set at P < 0.05 for all statistical tests.

RESULTS

The results of the stability and linearity tests of the optical fiber thermometry, carried out with the blackbody, are shown in Fig. 2. The stability tests that used the blackbody calibrated at 37°C were carried out at an ambient temperature of 25°C for 60 min. There is no long-term drift in this system, and the maximum difference between the temperature the optical fiber thermometry measured and the temperature of the blackbody was ±0.2°C (Fig. 2A). The temperature measured by the optical fiber thermometry shows a good linear relationship with that of the blackbody (Fig. 2B).

The head cooling and facial fanning tests were used to investigate whether the optical fiber thermometry accurately measured only the limited amount of infrared radiation from the tympanic membrane. The skin temperatures on the right temple and forehead decreased remarkably when the ice pack was pressed against the right temporal region (Fig. 3A) or the electric fan blew air in the subject's face (Fig. 3B). Infrared-Tₜᵥ and Tₑₛ, however, are not influenced by the decrease in these temperatures. The differences in infrared-Tₜᵥ between the control and final values in the cooling and fanning tests are 0.0026 ± 0.0480 (SD) and 0.0411 ± 0.0731°C, respectively.

No significant differences between infrared-Tₜᵥ, contact-Tₜᵥ, and Tₑₛ are observed for the control and final values and for ΔTₑₛ in the passive-heat-stress and progressive-exercise experiments (Table 1). During both experiments, there are no significant differences in the changes in infrared-Tₜᵥ, contact-Tₜᵥ, and Tₑₛ over time (Fig. 4). In the progressive-exercise experiment, there was a significant delay in the rise in infrared-Tₜᵥ and contact-Tₜᵥ compared with Tₑₛ. There was no significant difference in the onset of the elevation in infrared-Tₜᵥ, contact-Tₜᵥ, and Tₑₛ in the passive-heat-stress experiment (Table 1). The correlation between infrared-Tₜᵥ and contact-Tₜᵥ in both experiments is statistically significant [correlation coefficient: 0.82 ± 0.01 (passive-heat-stress test) and 0.87 ± 0.07 (progressive-exercise test)].

There are highly positive correlations, which range from 0.864 to 0.950, between sweating rate on the chest and forearm and the core temperatures. There are no significant differences in the slopes of sweating rate vs. infrared-Tₜᵥ and sweating rate vs. contact-Tₜᵥ at each site in both experiments. No significant differences in the threshold values of infrared-Tₜᵥ, Contact-Tₜᵥ, and Tₑₛ for sweating were observed for either site.

DISCUSSION

Although many thermometries have been developed and used to measure core temperature, use of these devices involves great risks, technical difficulties, and controversies (4). Recently, a method of infrared tympanic thermometry that did not involve contact with the tympanic membrane was developed to measure Tₜᵥ safely and easily. The accuracy of predecessors has been questioned (3, 10, 13, 17, 22). The insufficient
accuracy is caused by the fact that these devices may measure the temperature of the auditory canal. To prevent this, we used a chalcogenide glass fiber to detect infrared radiation solely from the tympanic membrane (Fig. 1). Because the optical fiber thermometry accurately measured the regulated temperature of a blackbody (Fig. 2), it is believed that the optical fiber thermometry measurements are stable and have a linear response, making the optical fiber suitable for thermometry.

Because the tympanic membrane is near the point where the carotid artery enters the hypothalamus, Tty is believed to reflect the brain and core temperatures.

| Table 1. Thermal parameters at rest and end periods of each test, increase in core temperature from the rest period to the end period, onset time of rising core temperature from the control value, slopes between sweating rate and core temperature, and threshold for onset of sweating during a passive-heat-stress and a progressive-exercise test |
|----------------|----------------|----------------|----------------|----------------|----------------|
|                | Control, °C    | End, °C        | ΔTcore, °C     | Onset of Rising | Slope          | Threshold, °C  |
| 1. Passive heat stress | Infrared-Tty    | 36.69 ± 0.21  | 37.51 ± 0.32  | 0.81 ± 0.31    | 5.4 ± 2.5      | 1.00 ± 0.44    | 0.79 ± 0.23*    | 36.74 ± 0.35  |
|                 | Contact-Tty     | 36.49 ± 0.34  | 37.39 ± 0.39  | 0.91 ± 0.26    | 5.1 ± 2.0      | 0.71 ± 0.24*   | 0.57 ± 0.10*    | 36.58 ± 0.24  |
|                 | Tthese          | 36.62 ± 0.14  | 37.40 ± 0.25  | 0.78 ± 0.19    | 3.0 ± 0.9      | 1.31 ± 0.50    | 1.04 ± 0.26     | 36.84 ± 0.20  |
| 2. Progressive exercise | Infrared-Tty    | 36.91 ± 0.24  | 37.75 ± 0.54  | 0.84 ± 0.41    | 6.9 ± 1.9*     | 1.17 ± 0.60    | 0.69 ± 0.22     | 36.83 ± 0.35  |
|                 | Contact-Tty     | 36.80 ± 0.25  | 37.76 ± 0.46  | 0.96 ± 0.29    | 7.0 ± 1.4*     | 0.90 ± 0.33    | 0.55 ± 0.15     | 36.73 ± 0.26  |
|                 | Tthese          | 36.86 ± 0.19  | 37.86 ± 0.49  | 1.00 ± 0.36    | 3.5 ± 1.2      | 1.54 ± 0.78    | 1.08 ± 0.56     | 37.04 ± 0.28  |

Values are means ± SD for 8 men. Control and end values represent average values for 3 min before start and end of each thermal stress, respectively. Tty, tympanic temperature; Tthese, esophageal temperature measured by thermocouple; Tcore, core temperature; infrared-Tty, Tty measured by infrared tympanic thermometry with optical fiber; contact-Tty, Tty measured by thermistor; Control, rest; End, end period of each test; Slope, relationship between sweating rate and Tcore. *Significant difference from Tthese, P < 0.05.
Thermoregulatory sweating responses are generally assessed by two parameters, the core temperature threshold for the onset of sweating and the slope of the relationship between core temperature and the rate of sweating (i.e., sensitivity). We used these two parameters to investigate whether infrared-T<sub>ty</sub> could be used to evaluate the thermoregulatory sweating responses as well as contact-T<sub>ty</sub> and T<sub>es</sub>. In this study, there was a remarkable positive relationship between the core temperatures measured by the three methods and sweating rate on the chest and forearm. In both experiments, there were no significant differences in the sensitivity of measurement determined by sweating rate vs. infrared-T<sub>ty</sub> and sweating rate vs. contact-T<sub>ty</sub> at each site. Furthermore, there were no significant differences in infrared-T<sub>ty</sub>, contact-T<sub>ty</sub>, and T<sub>es</sub> thresholds for sweating in both experiments (Table 1), although the increase in infrared-T<sub>ty</sub> and contact-T<sub>ty</sub> lagged behind the rise in T<sub>es</sub> during exercise (Fig. 4). Consequently, these results also suggest that infrared-T<sub>ty</sub> accurately reflects the temperature that determines the thermoregulatory sweating response and can be used in thermoregulatory research and clinical medicine.

In conclusion, the optical fiber thermometry performs extremely well, and it accurately measures the T<sub>ty</sub>. Head cooling and facial fanning tests proved that the optical fiber thermometry accurately measured only the limited amount of infrared radiation from the tympanic membrane. The changes in infrared-T<sub>ty</sub> during the passive-heat-stress and progressive-exercise experiments were the same as those in contact-T<sub>ty</sub>. Furthermore, the changes in infrared-T<sub>ty</sub> and contact-T<sub>ty</sub> were similar to those in T<sub>es</sub> during both experiments. There were also no significant differences between infrared-T<sub>ty</sub> and contact-T<sub>ty</sub> and the changes in the two parameters for monitoring sweating responses (threshold temperature and sensitivity). Therefore, we can recommend the optical fiber thermometry as a device for continuously measuring T<sub>ty</sub>.

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