Technique for Continuously Monitoring Core Body Temperatures to Prevent Heat Stress Disorders in Workers Engaged in Physical Labor

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Abstract: Technique for Continuously Monitoring Core Body Temperatures to Prevent Heat Stress Disorders in Workers Engaged in Physical Labor: Chikage NAGANO, et al. Department of Health Policy and Management, Institute of Industrial Ecological Sciences, University of Occupational and Environmental Health, Japan—Objectives: Measuring core body temperature is crucial for preventing heat stress disorders in workers. We developed a method for measuring auditory canal temperatures based on a thermocouple inserted into a sponge-type earplug. We verified that the tip of this thermocouple is positioned safely, allowing the wearer to engage in normal physical tasks; this position averaged 6.6 mm from the tympanic membrane. Methods: To assess this technique, we had six healthy male students repeat three cycles of exercise and rest (20 min of exercise and 15 min of rest) in a temperature-controlled chamber with temperatures set at 25, 30, or 35°C, while monitoring the auditory canal, esophageal, rectal, and skin temperatures. Results: We observed differences of a mere 0.30–0.45°C between rectal temperatures and auditory canal temperatures measured with the thermocouple, the smallest such difference reported to date in studies involving auditory canal temperature measurement. Conclusions: We conclude that monitoring temperatures based on a technique involving an auditory canal plug can be used to estimate rectal temperatures accurately, and thereby to avoid conditions leading to heat stress disorders.

Key words: Auditory canal, Body temperature, Heat stress disorders, Occupational health, Skin temperature

Although controlling ambient temperatures is the ideal approach to eliminating heat stress disorders, this is often not possible. This makes it especially important to optimize work schedules by reducing hours worked, providing workers with frequent breaks, or having workers work in alternating shifts. Ideal work schedules should be based on evaluations of physiological response, including perspiration rates and heat balance, as defined in the ISO7933 Predicted Heat Strain model. In practice, however, measuring the parameters required for this model poses major difficulties. The indices available for workplace evaluations include various proxies for core temperature (tₐ) measurements, including measurements of skin temperature (tₛ), heart rate (HR), and body weight. Monitoring tₐ in vivo is essential to preventing heat disorders.

According to ISO 9886, the term “core” refers to all tissue located at depths sufficient to remain unaffected by the temperature gradient existing on surface tissue. Esophageal temperature (tₑ), rectal temperature (tᵣ), intra-abdominal temperature (tᵢₐ), oral temperature (tₒ), tympanic temperature (tₜ), auditory canal temperature (tₐ) and urine temperature (tᵤ) have been proposed as core temperature indices. The transducer of tₑ is placed in the lower part of the oesophagus, which is in contact over a length of 50 to 70 mm with the front of the left auricle and with the rear surface of the descending aorta. Consequently, tₑ reflects the temperature of the arterial blood with a very short reaction time. tₑ is independent of ambient conditions because the rectum is surrounded...
by a large mass of abdominal tissues with low thermal conductivity. A transducer is inserted in the rectum to measure $t_{re}$. Measurements of $t_{an}$ and $t_{ac}$ are generally too invasive for workplace implementation. A transducer is swallowed to measure $t_{ac}$. The record of $t_{ac}$ will vary according to whether it is located in an area close to large arterial vessels or to organs with high local metabolism or near the abdominal wall. While $t_{ac}$ can be measured using CorTemp\textsuperscript{TM} 2000 (a core temperature telemetry monitoring system in the form of an ingestible thermistor capsule), such devices also tend to be in constant motion within the digestive tract, and the results sometimes require expert interpretation. The transducer of $t_{ac}$ is positioned as close as possible to the tympanic membrane whose vascularisation is provided in part by the internal carotid artery which also irrigates the hypothalamus. However, as the tympanic membrane is also vascularised by the external carotid artery, $t_{ac}$ is influenced by local thermal exchanges existing in the area vascularised by this artery. Measurements of $t_{ac}$ with contact type sensors are associated with risk of injury to the eardrum; measurements with non-contact types may measure temperatures only in the external auditory canal, $t_{ac}$ varies in tandem with $t_{ac}$, except the time constant is somewhat greater and its actual value is systematically lower than $t_{ac}$ by 0.2 to 0.5°C. Measurements of $t_{ac}$ are possible only during urination and are dependent on the quantity of urine available in the bladder. This leaves oral temperature $t_{or}$ and auditory canal temperature $t_{ac}$ as the only feasible indices of core temperature under real workplace conditions.

Various studies have been performed to elucidate the characteristics of $t_{ac}$ and $t_{an}$ and to determine the superior index of core temperature, with comparisons generally involving a rectal temperature reference. Cooper\textsuperscript{19} et al. have concluded that $t_{ac}$ more closely tracks changes in the carotid artery than $t_{or}$ and that $t_{ac}$ is unaffected by changes in ambient temperatures, unlike $t_{or}$. The transducer of $t_{ac}$ is placed underneath the tongue and is therefore in close contact with deep arterial branches of the lingual artery. $t_{ac}$ is affected by external conditions, being dependent on whether the mouth is open or not. After measuring $t_{ac}$ by various methods, IH Muir et al. reported that a method involving a thermistor covered with ordinary ear plugs was most suitable ($t_{ac}$ being equal to $t_{ac} + 0.6°C$ when measured by the method\textsuperscript{41}). Darowski et al. measured $t_{ac}$ 1–2 mm from the tympanic membrane in external auditory canals closed with cotton balls, assuming negligible temperature gradients inside the external auditory canal\textsuperscript{15}. Comparing measurements of $t_{ac}$ at various distances from the tympanic membrane, JE Greenleaf et al. found that $t_{ac}$ at 10 mm is least affected by ambient temperature and most closely matches $t_{ac}$. On this basis, they proposed the following equation to calculate rectal temperatures at ambient temperatures between 5–35°C\textsuperscript{46}:

$$t_{ac} = 0.8t_{re} + 0.2t_{ac}$$

(only between ambient temperatures of 5–35°C)

Measuring $t_{an}$ and $t_{ac}$ as subjects exercised in hot and cold environments, Morgans et al. report that $t_{ac}$ is 0.5–0.9°C lower than $t_{re}$. These studies suggest $t_{ac}$ can be estimated from $t_{re}$. However, Edwards et al. report that $t_{ac}$ measured at a point 10 mm from the tympanic membrane when the external auditory meatus is sealed with a cotton ball cannot be used to predict $t_{re}$ due to the effects of changes in temperature on the head skin surface\textsuperscript{49}. Hansen\textsuperscript{50} et al. report that $t_{ac}$ measured with a contactless infrared sensor does not adequately reflect $t_{re}$, due to the effects of perspiration and changes in ambient temperature on the surface of the surrounding skin. Fuller et al. report that $t_{ac}$ does not adequately reflect $t_{re}$ when measured during athletic exertion\textsuperscript{10}. In short, many studies support the validity of $t_{ac}$ as a proxy for $t_{re}$, while some studies identify limitations, especially when temperatures differ between $t_{ac}$ at the head and $t_{re}$.

As noted in ISO 9886, the external auditory canal is vascularised by the external carotid artery, and cutaneous blood flows around the ear and in adjacent areas of the head affect ear canal temperatures. Cooper\textsuperscript{19} et al. report gradually widening differences between $t_{ac}$ and $t_{re}$ as the point of measurement moved farther from the tympanic membrane (e.g., 0.5°C at 2 mm and 0.83°C at 17 mm). Noting this temperature gradient, ISO 9886 emphasizes the importance of adequately insulating the ear and placing the transducer less than 10 mm from the tympanic membrane. ISO 9886 also states that $t_{ac}$ can be interpreted to reflect $t_{re}$ only when $t_{re}$ is measured within environments that differ in air temperature by less than 10°C.

In light of these preceding studies, we developed a new method for measuring $t_{ac}$ that involves the secure insertion of a temperature sensor through a sponge-type earplug that seals the external auditory canal. We expected this method would be easy to use and would not cause undue discomfort, since the sensor is buried in the earplug and secured in place, even when actual work tasks are performed. Applying this method, we measured $t_{ac}$ continuously and compared our measurements with $t_{ac}$ as our subjects performed various physical tasks in various warm environments, seeking to determine if changes in $t_{ac}$ can be used to track changes $t_{re}$.

**Methods**

**Subjects**

The subjects were six healthy male volunteers, all Japanese, aged 20.5 ± 1.8 yr (mean ± SD) and measuring 171.8 ± 6.4 cm in height, 60.5 ± 4.4 kg in weight, with BMI values in the range of 20.5 ± 1.3 kg/m\(^2\). The subjects reported no history of heat stroke in responses to a questionnaire. All experiments were performed during autumn to spring when the subjects were not acclimatized...
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to hot environments. All subjects signed a written consent form. The study was reviewed and approved by the ethics committee of the University of Occupational and Environmental Health, Japan.

Procedures
The subjects were asked to strip to the waist and to wear only underwear and short pants. They were barred from eating within 4 h prior to the experiments, but were permitted to drink water during this time.

The experiments were performed in a climatic chamber (Model TBL-15FW5CPX, Tabai Espec) installed at the Bio-information Research Center at the University of Occupational and Environmental Health, Japan, in November 2003 and March 2004. The relative humidity in this chamber was kept at 60%. The experiments were repeated at three different dry-bulb temperature ($t_a$) settings: 25, 30, and 35°C.

The subjects were asked to remain at rest in the room for at least 30 min before the experiments began to allow $t_{ac}$, $t_{re}$, and HR to stabilize. We assumed an actual work-rest cycle occurring in a warm environment and asked the subjects to sit still for 10 min, then to pedal a bicycle ergometer (Corival 400, LODE) at a pace sufficient to generate 75 W continuously for 20 min, then to rest in the saddle for 15 min. This 20 min exercise session was repeated twice with intervening 15 min rest periods, followed by a 20 min rest period after the last exercise session.

Measurements
We configured thermal sensors to measure $t_{ac}$ as follows: First, we formed a small canal in an ear plug (3M 1110, 3M Health Care) along the long axis; then we inserted a copper-constantan thermocouple probe into this canal, and stuck out the thermocouple tip within 1 mm from the inner side of the ear plug. The probe tip was covered with a cotton ball measuring about 2 mm in diameter (Fig. 1). After gaining adequate experience with inserting these ear plugs, we placed this probe in the external auditory canals of our subjects and set it at the deepest location. We verified the actual locations of the tip of the probe through CT scans of the sphenoid bone area in three subjects.

Following zero adjustments and calibration, we used an analog digital converter (Remote Scanner DE1200, NEC) to convert voltage fluctuations from the thermocouple to digital signals and saved this data on a personal computer (Mate NX, NEC) at 5-sec intervals. We also measured and monitored $t_{ac}$, $t_{re}$, and $t_{sk}$; and temperatures at the right frontal plane of the forehead ($t_{forehead}$), right chest ($t_{chest}$), right forearm ($t_{forearm}$), the dorsal surface of the right hand ($t_{hand}$), right thigh ($t_{thigh}$), right calf ($t_{calf}$), and the dorsal surface of the right foot ($t_{foot}$) using copper-constantan thermocouple probes. We measured $t_{re}$ with a polyethylene-sealed thermocouple probe measuring 4 mm in diameter and covered with a YSI thermocouple probe cover (Nikkiso YSI) made of latex rubber, which was inserted 12–15 cm beyond the anal sphincter. We asked the subjects to swallow a polyethylene-sealed $t_{re}$ probe measuring 2 mm in diameter for positioning at the heart level and monitored maximum values for $t_{re}$. The mean skin temperature ($t_{sk-mean}$) was calculated from skin temperatures measured at seven different points using the weighting factors described by Hardy & Dubois et al. An electrocardiogram with a telemetric system (Bioview1000, NEC) was used to measure heart rate (HR).

Statistical analysis
One-factor ANOVA was used for the evaluation of the effect and a stepwise regression model was performed to estimate $t_{re}$ from $t_{ac}$ or $t_{re}$. All the statistical tests were carried out with Stat view 5.0 for Windows (SAS Institute Inc.).

Results
Location of $t_{ac}$ probe
The distance between the tympanum and the
Fig. 2. Trends in $t_{\text{f}}$ and $t_{\text{sk-mean}}$ at various $t_a$ (N=6). $t_{\text{f}}$=temperature of forehead; $t_{\text{che}}$=temperature of chest; $t_{\text{fore}}$=temperature of forearm; $t_{\text{hand}}$=temperature of hand; $t_{\text{thigh}}$=temperature of thigh; $t_{\text{calf}}$=temperature of calf; $t_{\text{foot}}$=temperature of foot; $t_{\text{sk-mean}}$=mean skin temperature calculated from the 7 skin temperatures using the weighting factors proposed by Hardy and Dubois$^{11}$; $t_a$=ambient temperature (△: 25°C, ▲: 30°C, and ●: 35°C).
thermocouple of the $t_s$ probe, as detected by CT, was 3.0, 10.0, and 6.8 mm, and its average was 6.6 ± 3.5 mm (average ± SD).

**Skin temperature $t_s$**

Figure 2 shows the trends for seven different $t_s$ and $t_{sk-mean}$ when the ambient $t_a$ was 25, 30, or 35°C. The figure was plotted by drawing straight lines between the mean values of $t_s$ and $t_{sk-mean}$ measured at 5-minute intervals. Among all $t_s$, $t_{head}$ demonstrated the smallest range of temperature distributions throughout the experiment. In contrast, average $t_{chest}$ tended to decrease as the exercise was repeated. This trend became more pronounced when $t_a$ was elevated. The effects of exercise were more evident in $t_s$ of the lower regions of the body $t_{hand}$, $t_{forearm}$, $t_{thigh}$, $t_{calf}$, and $t_{foot}$. Higher $t_a$ values were associated with higher values for these parameters. Calculating overall mean ± SD values for $t_{sk-mean}$ during the experiment, we obtained 32.9 ± 0.14, 33.9 ± 0.16, and 36.0 ± 0.19°C, respectively, at $t_a$ of 25, 30, and 35°C.

**Heart rate**

Figure 3 shows the trends in mean HR at 5-minute intervals. HR rose and decreased rapidly following the start and completion of exercise. The overall HR mean ± SD values calculated during the experiment were 93.9 ± 19.4, 98.8 ± 18.2, and 109.0 ± 18.6 beats/min, respectively, at $t_s$ of 25, 30, and 35°C. The mean ± SD values clearly rose as $t_s$ increased from 30 to 35°C.

**Core temperature $t_c$**

The overall mean ± SD values of $t_c$ throughout the experiment were calculated to be 36.9 ± 0.12, 37.1 ± 0.15, and 37.4 ± 0.15°C, respectively, at $t_c$ of 25, 30, and 35°C. Elevation of mean $t_c$ in accordance with $t_a$ was pronounced, with a steeper gradient between 30°C and 35°C. The overall mean ± SD values for $t_{es}$ were 37.4 ± 0.20, 37.4 ± 0.21 and 37.6 ± 0.20°C; the corresponding values for $t_{re}$ were 37.4 ± 0.15, 37.5 ± 0.21 and 37.7 ± 0.23°C, respectively, at $t_a$ of 25, 30, and 35°C. The increase in mean $t_{es}$ and $t_{re}$ following the increase in $t_a$ was less remarkable than with $t_c$. Figure 4 illustrates the trends in mean ± SD values for $t_{sk}$, $t_{sk-mean}$, $t_{head}$, $t_{forehead}$, $t_{shoulder}$, and $t_{shoulder}$ at 5-minute intervals during the experiment.

Table 1 provides a tabular summary of the mean ± SD values and minimum–maximum values for $t_{sk-mean}$, $t_{es}$, $t_{re}$, and $t_{re}-t_{sk}$ during each period of rest and exercise at various values of $t_a$.

Multivariate analysis shows that the average of $t_{sk}$, $t_{es}$, and $t_{re}$ tended to rise over time and with repeated exercise. In contrast, mean $t_{sk}$ over the same timeframe tended to decline. Mean $t_{re}-t_{sk}$ grew larger over time and with repeated exercise. As $t_a$ rose from 25 to 30°C and from 30 to 35°C, the differences between the two measures narrowed.

Fig. 3. HR trends at various $t_a$ (N=6). HR=heart rate (beats/min); $t_a$=ambient temperature (□: 25°C, ▲: 30°C, and ●: 35°C).
Estimating \(t_e\) from \(t_a\) or \(t_c\)

We applied a multiple regression model to estimate \(t_e\) at each \(t_a\) using the two independent variables of time from the initiation of each exercise period (T) and \(t_c\) or \(t_a\) using all data obtained during the three exercise periods. Then, we also calculated an overall equation to estimate \(t_e\) using three independent variables of \(t_a\), T, and \(t_c\) or \(t_a\). Table 2 gives the equations, the values assigned to the various terms, and the squares of the correlation coefficient (\(R^2\)).

Higher \(t_e\) corresponded to decreasing \(R^2\) between \(t_e\) and \(t_a\). However, this tendency was not observed with the \(R^2\) between \(t_e\) and \(t_c\). \(R^2\) between \(t_e\) and \(t_a\) was always higher than \(R^2\) between \(t_e\) and \(t_a\) under all \(t_a\) conditions. We applied a stepwise regression model to estimate \(t_e\) with \(t_a\). Table 2 also provides the equations used to calculate these results and the \(R^2\) values. It shows that the correlation between \(t_e\) and \(t_a\) was higher than that between \(t_e\) and \(t_c\).

Discussion

Simply measuring ambient temperatures is a relatively ineffective safeguard against heat stress disorders. Individual factors such as underlying health, lifestyle, and genetic background can also affect the occurrence of heat stress disorders. A more reliable method for monitoring core body temperatures in the workplace would allow detection of individuals at risk before the symptoms of heat stress disorder actually became visible.

All previously reported methods for measuring auditory canal temperatures various limitations with respect to actual implementation in workplace settings. Greenleaf et al. concluded that the distance of the thermocouple from the tympanic membrane should be no more than 10 mm to ensure accurate estimates of core temperatures\(^6\). The only article evaluating the use of auditory canal temperatures in actual workplace settings concludes that the method was a poor index of core temperature; however, that report failed to report the precise positioning of the thermocouple\(^10\). Muir et al. used infrared sensors to measure auditory canal temperatures and observed differences from rectal temperatures exceeding 0.6°C, but failed to verify the location of the sensor\(^4\). Some studies have placed the thermocouple within a few millimeters of the tympanic membrane. Despite this proximity, with the ear canal closed with cotton wool, Edwards concluded

**Fig. 4.** Changes over time in mean ± SD values of \(t_e\), \(t_a\), \(t_c\), and \(\Delta t_e = t_e - t_c\) at various \(t_a\) (N=6). \(t_e\)=rectal temperature (■); \(t_a\)=esophageal temperature (○); \(t_c\)=auditory canal temperature (■); \(\Delta t_e\)=differences between \(t_e\) and \(t_c\); \(t_a\)=ambient temperature (■: 25°C, ▲: 30°C, and ●: 35°C); SD=standard deviation.
<table>
<thead>
<tr>
<th>Body temperature (°C)</th>
<th>25°C</th>
<th>30°C</th>
<th>35°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>t&lt;sub&gt;re&lt;/sub&gt; (mean ± SD)</td>
<td>(37.0 ± 0.0)</td>
<td>(37.1 ± 0.0)</td>
<td>(37.1 ± 0.0)</td>
</tr>
<tr>
<td>t&lt;sub&gt;ac&lt;/sub&gt; (mean ± SD)</td>
<td>(37.1 ± 0.0)</td>
<td>(37.2 ± 0.0)</td>
<td>(37.3 ± 0.0)</td>
</tr>
<tr>
<td>t&lt;sub&gt;es&lt;/sub&gt; (mean ± SD)</td>
<td>(37.0 ± 0.0)</td>
<td>(37.1 ± 0.0)</td>
<td>(37.2 ± 0.0)</td>
</tr>
<tr>
<td>Mean t&lt;sub&gt;ac&lt;/sub&gt;, t&lt;sub&gt;es&lt;/sub&gt;, and ∆t&lt;sub&gt;ac&lt;/sub&gt; for periods of rest and exercise at various values of t&lt;sub&gt;t&lt;/sub&gt; (N=6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0°C</td>
<td>1°C</td>
<td>2°C</td>
</tr>
<tr>
<td>t&lt;sub&gt;sk-mean&lt;/sub&gt; (N=6)</td>
<td>32.6 ± 0.0</td>
<td>33.1 ± 0.0</td>
<td>33.0 ± 0.0</td>
</tr>
<tr>
<td>(minimum–maximum)</td>
<td>(32.4–33.0)</td>
<td>(33.1–33.0)</td>
<td>(33.0–32.9)</td>
</tr>
<tr>
<td>t&lt;sub&gt;re&lt;/sub&gt; (mean ± SD)</td>
<td>(37.0 ± 0.0)</td>
<td>(37.1 ± 0.0)</td>
<td>(37.1 ± 0.0)</td>
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<tr>
<td>t&lt;sub&gt;ac&lt;/sub&gt; (mean ± SD)</td>
<td>(37.1 ± 0.0)</td>
<td>(37.2 ± 0.0)</td>
<td>(37.3 ± 0.0)</td>
</tr>
<tr>
<td>t&lt;sub&gt;es&lt;/sub&gt; (mean ± SD)</td>
<td>(37.0 ± 0.0)</td>
<td>(37.1 ± 0.0)</td>
<td>(37.2 ± 0.0)</td>
</tr>
<tr>
<td>Mean t&lt;sub&gt;ac&lt;/sub&gt;, t&lt;sub&gt;es&lt;/sub&gt;, and ∆t&lt;sub&gt;ac&lt;/sub&gt; for periods of rest and exercise at various values of t&lt;sub&gt;t&lt;/sub&gt; (N=6)</td>
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that temperatures did not accurately track rectal temperatures\(^8\). Morgan observed differences from rectal temperatures exceeding 0.5°C\(^7\). Hansen also observed differences exceeding 1.0°C even when using molded medical-use earplugs\(^9\). We hypothesize that these temperature discrepancies are due to a narrow open space around the thermocouple inserted alongside the earplug, which we eliminated by inserting the thermocouple into a sponge-type earplug. To avoid injury, the thermocouple cannot be positioned too close to the tympanic membrane. Ideally, according to Greenleaf, measurements of auditory canal temperatures should be performed within 10 mm of the tympanic membrane\(^6\), to minimize divergence from rectal temperatures while ensuring safety in actual workplace settings. Our method for inserting the thermocouple and placing it at the tip of the earplug meets their recommendations and the criteria specified by ISO 9886 for measuring core temperatures via auditory canal temperatures\(^2\). Our present study is the only study featuring verified thermocouple positioning to report differences from rectal temperatures of less than 0.5°C.

The auditory canal temperatures measured in this experiment successfully tracked rectal temperatures, with average differences of 0.30–0.45°C, less than in any other study. This new method minimizes the temperature gradient inside the auditory canal by tightly sealing the canal. We measured auditory canal temperatures for a period of 120 min, longer than any other past study. Idealistically, we should have asked the subjects to continue exercise and follow up the trend of \(t_e\) until their \(t_e\) reached 38.5°C, the maximal allowable limit of trained workers. However, we curtailed the heat exposure at 120 min to avoid excessive health risks to the subject. We encountered no problems or breakdowns in the apparatus or discomfort reported by the subjects. We measured the temperature at 5-sec intervals, the shortest interval reported in the studies cited above, confirming that this method enables monitoring of minimal changes in body temperature as an early sign of heat stress disorder.

When ambient temperatures rose, auditory canal temperatures closely followed rectal temperatures, indicating the method we used is an ideal early detector of heat stress disorders in workers engaged in physical labor in hot environments. We observed narrowing divergence between rectal temperatures and auditory canal temperatures as subjects repeated the exercise sessions, indicating that auditory canal temperatures may accurately track rectal temperatures during physical exertion. In a unique feature of this study, subjects were asked to perform exercises at 15-minute intervals, since time-consuming physical tasks in hot working environments are rare in actual workplace settings (workers in such settings are generally allowed breaks). We observed increasing differences between rectal temperature and auditory canal temperature as the subjects repeated the exercise. However, during the course of the experiment, the effects of exercise and ambient temperatures tended to diminish, enabling consistent estimates of rectal temperature based on temperatures measured with the ear plug sensors. Sufficient repetition of this procedure should result in a value for the difference between the two temperatures that approaches a constant. Such conditions are often encountered in real workplace settings, and auditory canal temperatures represent a promising reliable proxy for measurements of rectal temperature.

Based on the equation developed to estimate rectal temperatures based on auditory canal temperatures and taking ambient temperatures into account, we calculated the permissible maximum working times to avoid core temperatures of 38.5°C, the threshold temperature associated with high risk of heat stress disorder. In this experiment, we also monitored \(t_e\) to evaluate whether it might react as a more sensitive indicator for heat disorder of the subjects. In general, it reflects the temperature of

### Table 2. Estimates of \(t_e\) based on \(t_{es}\) or \(t_{ae}\) (N=6)

<table>
<thead>
<tr>
<th>(t_a)</th>
<th>Calculations</th>
<th>(p) value</th>
<th>(R^2)</th>
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<tbody>
<tr>
<td>25°C</td>
<td>(t_e=1.096t_{ac}–3.108)</td>
<td>&lt;0.0001***</td>
<td>0.811</td>
</tr>
<tr>
<td></td>
<td>(t_e=0.52t_{ac}+17.906)</td>
<td>&lt;0.0001***</td>
<td>0.488</td>
</tr>
<tr>
<td>30°C</td>
<td>(t_e=1.089t_{ac}–2.968)</td>
<td>&lt;0.0001***</td>
<td>0.746</td>
</tr>
<tr>
<td></td>
<td>(t_e=0.768t_{ac}+8.677)</td>
<td>&lt;0.0001***</td>
<td>0.720</td>
</tr>
<tr>
<td>35°C</td>
<td>(t_e=1.227t_{ac}–8.221)</td>
<td>&lt;0.0001***</td>
<td>0.684</td>
</tr>
<tr>
<td></td>
<td>(t_e=0.798t_{ac}+7.640)</td>
<td>&lt;0.0001***</td>
<td>0.517</td>
</tr>
<tr>
<td>(t_a)</td>
<td>(t_e=4.984+0.879t_{ac}+0.003T–0.011t_{es})</td>
<td>&lt;0.0001***</td>
<td>0.967</td>
</tr>
<tr>
<td></td>
<td>(t_e=24.212+0.33t_{ac}+0.022T–0.0007169t_{es})</td>
<td>&lt;0.0001***</td>
<td>0.890</td>
</tr>
</tbody>
</table>

\(t_e=\)rectal temperature; \(t_{ac}=\)auditory canal temperature; \(t_{es}=\)esophageal temperature (25, 30, and 35°C); \(T=\)time length after the initiation of exercise (min); \(p\) value=calculated by a stepwise regression model, \(R^2=\)squares of the correlation coefficient of these equations.
the arterial blood with a very short reaction time; however, it is easily affected by salivary temperature from swallowing, especially at lower $T_a$ and, moreover, it fluctuates based on the rapid change of $T_e$, especially after the exposure to $T_a$ lower than 24°C. Therefore, we decided to use $T_e$ rather than $T_a$ as an index of core body temperature of the subjects in this experiment.

Despite the limited number of subjects in this experiment, the relationship among the three core temperatures during exercise in three different environments was similar for all the individuals. We believe measurements of auditory canal temperatures would also prove valid for the general population. Although we did not evaluate the effects of movement of the upper limbs on auditory canal temperatures, work described in a previous report indicates such movements would actually reduce discrepancies between auditory canal and rectal temperatures.

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