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Validity of Infrared Tympanic Temperature for the Evaluation of Heat Strain While Wearing Impermeable Protective Clothing in Hot Environments

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Abstract: The purpose of this study was to investigate the validity of infrared tympanic temperature (IR T_{ty}) as a thermal index to evaluate the heat strain of workers in hot environments, in comparison with rectal temperatures at various depths ($T_{re\text{-}4,\ \text{-}8,\ \text{and}\ \text{-}16}$ for 4, 8 and 16 cm from the anal sphincter). Eight males underwent twelve experimental conditions: two activities (rest and exercise) × three clothing levels [Control, HDPE (high-density polyethylene coverall) and PVC (polyvinyl chloride coverall) condition] × two air temperatures (25 and 32°C with 50%RH). The results showed that 1) in the conditions with most heat strain (HDPE or PVC condition at 32°C), IR T_{ty} was equal to or even higher than T_{re}; 2) during exercise, physiological strain index (PSI) using IR T_{ty} did not underestimate PSI-values using $T_{re\text{-}16}$, and overestimated those PSI-values from $T_{re\text{-}16}$ in HDPE and PVC conditions at 32°C; 3) during exercise, the relationships between IR T_{ty} and heart and total sweat rate were stronger than those between $T_{re\text{-}16}$ and heart and total sweat rate. These results indicated that IR T_{ty} is valid as a thermal index to evaluate the heat strain of workers wearing impermeable protective coveralls in hot environments. However, the application of IR T_{ty} is limited only for strenuous works wearing encapsulated personal protective clothing with a hood in heat.

Key words: Infrared tympanic temperature, Rectal temperature, Heat strain, Protective clothing, Exercise

Introduction

The combination of protective clothing, environmental heat, and high metabolic rate increases the likelihood of heat-related injuries. Full-encapsulating protective clothing can raise the micro-climate inside the suit a further 10°C WBGT above ambient temperature[1)]. In particular, vapor impermeable protective clothing hinders evaporative heat loss from the body. Since workers wearing impermeable protective clothing in hot environments are exposed to the common risk of heat-related illness, the monitoring of physiological and subjective changes of workers has been suggested for preventing heat-related injuries. Self-monitoring based on subjective judgment typically relies on the recognition of the onset of symptoms of heat-related disorders. However excessive physiological strain often precedes such overt symptoms[2)]. The monitoring of heart rate is quick, easy to use and non-invasive, but heart rate alone is an inadequate variable for the incidence of exhaustion during uncompensated heat stress[3)] or prolonged moderate

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work in hot environments. Multiple monitoring of heat strain through core body temperature and heart rate as well as subjective evaluation is required to adequately stop work before heat stroke occurs.

Rectal temperature has been positioned as a reasonable and acceptable index of the internal body temperature for clinical and experimental settings because rectal temperature is higher in temperature readings, more reliable, more stable and less erroneous to detect internal body heat than other deep body temperatures[4–8], but there is still considerable controversy as to the best anatomical site for core temperature[9]. Furthermore, rectal temperature is relatively invasive and often requires privacy for a real-time monitoring in industrial fields. The thermal inertia in the rectum would behave as a critical drawback in work areas requiring rapid monitoring of workers in hot environments. It is known that rectal temperature has a considerable time lag compared to other core temperatures because of its thermal inertia[10–13], which is related to the vascular insulation in the pelvis[6, 14]. In addition, it is reported that rectal temperature often changes in an opposite direction from esophageal temperature during quick transition from exercise to rest and back to exercise because rectal temperature has a relatively longer time lag and weaker initial drop at the beginning of exercise, when compared to esophageal temperature. Moreover, its suitability for thermal monitoring is further called into question with the consideration that rectal temperature is greatly affected by the physical activity of legs when compared to the comparable levels of arm work[15].

In this regard, infrared tympanic thermometry can be a substitute for internal body temperature in industrial settings because of its non-invasiveness, quick response to change, and ease of use in outside operations. Because of its anatomical proximity to the hypothalamus, it is reported that tympanic temperature follows brain temperature more closely than rectal temperature or esophageal temperature[16, 17]. Even though some have doubted that tympanic thermometry is sufficiently accurate to measure core temperature[18], there are also many reports that tympanic temperature is a good index of core temperature when measured accurately[19–21]. However, most research on tympanic temperature reported intermittent recordings, not continuous monitoring, particularly with unclothed or lightly clad subjects. A considerable portion of the tympanic thermometry was obtained from infrared tympanic thermometer that devised for anecdotal home use, not for continuous recording through a telemetry system. There currently remains little information on the comparison of continuous monitoring of infrared tympanic temperature based on a telemetry system with rectal temperatures to evaluate the heat strain of individuals. In particular, the validity of infrared tympanic temperature as a thermal index to evaluate the heat strain of workers wearing impermeable protective clothing has not been established. The lack of available standards for infrared tympanic temperature of workers wearing impermeable protective clothing has limited the use of tympanic temperature as a valid thermal index to evaluate heat strain.

Furthermore, it should be noted that rectal temperature varies depending on how deep the thermometer is inserted into the rectum[22]. The change in an opposite direction between rectal and esophageal temperature as reported in Kolka and colleagues[12] was also found within rectal temperatures at the various depths of a rectum during transition from exercise to rest and back to exercise[22]. Even though it is currently recommended that the rectal probe must be inserted to a depth of at least 10 cm[3] or at least 8 cm[10, 14, 23] to obtain a true rectal temperature, some authors reported rectal measurements at depths shallower than 8 cm[5, 24–26]. In this regard, it is required that the evaluation on the validity of tympanic temperature in comparison with rectal temperature should be coincided with the examination of rectal measurements at various depths.

We hypothesized that infrared tympanic temperature would not differ from rectal temperature and show significant relationships with other physiological parameters, while wearing encapsulated protective clothing in hot environments. We examined the thermal dynamics of infrared tympanic temperature in comparison with rectal temperature at various depths, under the various environmental combinations of activities, clothing, and air temperature.

Methods

Subjects

Eight healthy male volunteers [Mean (SD): Age 24.1 (2.8) yr, height 173.0 (3.9) cm, body mass 66.3 (9.7) kg, body surface area 1.82 (0.13) m^2, total body fat: %BF 17.3 (4.7)%, peak oxygen uptake ($\dot{V}O_{2peak}$) 48.0 (16.7) ml kg^{-1} min^{-1}, maximum heart rate (HR_{max}) 193 (8) bpm] participated in this study. For determination of VO_{2peak}, participants performed a graded exercise test using a treadmill in a climatic chamber at an air temperature (T_a) of 25°C with 50% relative humidity (RH). Each participant was required to start to walk at 2.74 km·h^{-1} at a slope of 10%, and then the speed and the slope of the treadmill were gradually increased according to the Bruce protocol every three minutes until volitional exhaustion. Their expired gas was continuously measured by an automatic respiromonitor (AE-300S, Minato Medical Science, Japan). VO_{2peak}

was calculated by averaging data for 30 s before the subject was exhausted. During the VO_{2peak} test, heart rate was simultaneously monitored every second (RS400, Polar Electro Oy, Finland). Body surface area was estimated according to Lee and colleagues[27]. Total body fat (%BF) was estimated using a bioelectrical impedance method (Karada Scan HBF-354, OMRON Co. Ltd, Japan). None of the participants were professional athletes. All tests were performed in the middle of summer (July to Sep 2009). Before participation, subjects completed a health status questionnaire and signed a written informed consent form. The experimental protocol was approved by the Institutional Review Board of the Kyushu University.

Experimental conditions: climate, clothing and activity

Experimental conditions consisted of a total of 12 conditions: two activities × three clothing levels × two air temperatures (T_a of 25°C and 32°C with 50%RH in still air; WBGT 19.4°C and 25.4°C for 25°C and 32°C, respectively). Three types of experimental ensembles were employed: Control (Total clothing weight of 590 g except running shoes), HDPE condition (Tyvek® made of high-density polyethylene fibers by DuPont; 787 g), and PVC condition (Transparent plastic polyvinyl chloride (PVC); 1,245 g). For Control, subjects wore a round neck T-shirt with short sleeves (130 g), under shorts (84 g), shorts (117 g), a mesh vest (205 g), socks (54 g) and running shoes (678 g). For the HDPE condition, subjects added the following items to the Control: HDPE coverall (140 g), cotton gloves (25 g) and HDPE shoe-covers (32 g). For the PVC condition, PVC coverall (278 g), rubber gloves (60 g), PVC shoes covers (26 g), and PVC boots covers (126 g) were added to the HDPE condition, removing the HDPE shoe covers. Both HDPE and PVC coveralls had hoods and elastic cuffs around the wrists and ankles attached. Total thermal insulation (I_T) and evaporative heat resistance were directly determined using a sweating thermal manikin with 17 body segments (JUN, KEM, Japan; BSA 1.658 m^2). The I_T for Control, HDPE, and PVC conditions were 1.05, 1.39 and 1.46 clo, respectively. Total evaporative heat resistances were 0.016 and 0.035 $m^2 \cdot kPa \cdot W^{-1}$ for Control and HDPE conditions, respectively. For PVC condition, the measurement of evaporative heat resistance was discarded due to the limitation of the calculation, and the evaporative heat resistance of PVC condition was assumed as an infinite resistance. The details regarding methodological procedures and calculations using the Manikin "JUN" were described in Tamura[28]. Two levels of metabolic activities were assigned at (1) rest on a chair (60 min per trial) and (2) exercise on the treadmill (80 min per trial). Subjects underwent both rest and exercise conditions on different days. For the exercise protocol, subjects performed two bouts of exercise on the treadmill at a speed of 6–8 $km \cdot h^{-1}$ and the measured metabolic rate had a mean of 318 (SD 48) $W \cdot m^{-2}$ for the Control condition at 25°C. The exercise protocol consisted of 10 min stabilization on a chair, 20 min exercise on a treadmill, 10 min rest on the chair, 20 min exercise on the treadmill, and 20 min recovery on the chair. Only for the PVC condition at 32°C, the test protocol was shortened to 10 min stabilization, 20 min exercise and 10 min rest (40 min per trial). For the exercise sessions, participants completed the sessions, with at least two days rest between each session. The trial order was counterbalanced across participants.

Measurements and calculations

Rectal temperature (T_{re}) and infrared tympanic temperature (IR T_{ty})

T_{re} was measured by a multi-thermistor probe every two seconds. The multi-probe consisted of three thermistor sensors (LT-ST08-00, Gram Corporation, Japan; resolution of 0.01°C, accuracy of ± 0.1°C) located at 4, 8, and 16 cm beyond the anal sphincter. The rectal temperatures at three depths were defined as T_{re-4}, T_{re-8} and T_{re-16} in this study. In the present study, the T_{re-4} was not considered as a deep body temperature. However, the reason for the measurement of the T_{re-4} was to compare with the dynamics of the IR T_{ty}, because the 4 cm-depth in the rectum has a similar distance as the that of the tympanic membrane from the outer ear (approximately 35 mm long). As such, the measurement of T_{re-4} has a significant meaning in the present research. First, the rectal sensors' heads were arranged at each position, and then the lines of the sensors were bound with adhesive tape. The whole set of multi-sensor probe (a bundle of three lines) were covered with a specially designed cover. A tangible point was marked using surgical tape on the cover (at 0 cm) and the subjects were instructed to insert the whole set of sensors to the marked point. Then we fixed the set of the lines on the upper buttock skin using surgical tape. When the set of sensors slipped out from the rectum during exercise, we had repeated the experiment on the other day (There were a total of ~3 incidents). More details on the methodology were introduced in Lee and colleague[22].

A telemetry system to measure infrared tympanic temperature (IR T_{ty}) was employed (CE Thermo, Nipro Corporation, JAPAN; resolution of 0.01°C, accuracy of ± 0.1°C). The infrared tympanic membrane sensor was designed to primarily detect the infrared radiation emanating from tympanic membrane, but it was assumed that the sensor actually detected most infrared radiation from the auditory canal and the tympanic membrane because the auditory canal is a slightly curved tube about 35 mm long in an adult. Because the ear probe was disposable with a limited use of 24 h per probe, we exchanged each probe with a new one before expiry. The infrared probe was equipped with a silicon mould to fit into the ear, which lessens erroneous values due to an inadequate seal. The probe was gently introduced into the ear canal, so that the probe correctly positioned towards the tympanic membrane. Then the outer ear was tightly sealed using surgical tape. The ear probe was mounted in the ear canal throughout the whole exposure. For all subjects, the ear canals were clean with no visible hair and cerumen before measurements were taken. All measurements were done in the left ear. The telemetry system consists of the ear probe with the infrared sensor, a transmitter and a wireless data receiver. Infrared temperature information was transmitted to the wireless data receiver outside of the body every two seconds.

Heart rate (HR) and total sweat rate (TSR)

Heart rate (HR) was measured every second throughout the experiment using HR monitor (RS400, Polar Electro, Finland). Heart rate capacity (HRC) is defined as the range of heart rates that a person can achieve to support work, expressed as the difference between HR_{max} and HR_{rest}. Percentage of heart rate capacity (%HRC) was calculated as follows: %HRC = $[(HR-HR_{rest}) / (HR_{max}-HR_{rest})]100$. Total sweat rate (TSR) was determined by weighing nude subjects before and after the heat exposure using a calibrated scale (ID2, Mettler-Toledo, Germany; resolution of 1 gram). Using the core temperatures and heart rate, physiological strain index (PSI)[29] was calculated. PSIs based on infrared tympanic temperature and rectal temperatures measured at 4, 8 and 16 cm depths were compared.

Physiological Strain Index (PSI) =

$$\frac{5(T_{re\,t} - T_{co\,0})}{(39.5 - T_{co\,0})} + \frac{5(HR_t - HR_0)}{(180 - HR_0)}$$

$T_{co\,t}$ and HR_t are simultaneous measurements taken at any time during the exposure and T_{co0} and HR_0 are the initial measurements. T_{co} was estimated using tympanic temperature (T_{ty}) and rectal temperature ($T_{re\text{-}16}$) each.

Procedures

Subjects rested around 60 min in a preparation room that maintained a T_a of 22–24°C during instrumentation. Subjects were allowed to drink freely before the commencement of testing to achieve euhydrated state. Then they wore only shorts and were weighed on a body scale. Every single garment was weighed in a dry state before being donned by the subjects. After weighing, the instrumentation of temperature sensors and the HR monitor on the subjects was completed and subjects donned the experimental clothing in the pre-room. After confirming rectal temperature ($T_{re\text{-}16}$) within normal ranges (37.0 ± 0.4°C), subjects entered the experimental chamber that was maintained at the target environmental condition of the session. During the test, subjects were prohibited to drink. After completing each trial, subjects were weighed again with and without clothing on the same scale. The experimental garments were also weighed again after completing the experimental session. The tests were terminated if rectal temperature ($T_{re\text{-}16}$) reached 39.2°C or 95% of maximal heart rate, or if any subject felt unable to continue.

Statistics

Results were expressed as mean and standard deviation [SD]. To examine the degree of agreement between readings using different methods, the limit of agreement (LOA) between infrared tympanic and rectal temperature readings was investigated by Bland-Altman plotting the individual differences between readings against their means[30]. One-way ANOVA was carried out to test the differences among infrared tympanic and rectal temperatures at three depths. Two-way ANOVA was used to identify any differences among core temperatures using three types of clothing ensembles and two levels of climates. Tukey's Post hoc test was conducted for the items showing significant differences by ANOVA. Pearson's correlation coefficients were calculated to assess the strength of association among physiological variables. Significance was set at $p<0.05$.

Results

Infrared tympanic and rectal temperatures

At rest at 25°C, infrared tympanic temperature (IR T_{ty}) was lower than rectal temperature measured at the depth of 16 cm ($T_{re\text{-}16}$) and higher than T_{re} at the depth of 4 cm ($T_{re\text{-}4}$), but the differences for the last 10 min were not significantly different (Fig. 1, Table 1). The influence of T_a was significant in all core temperatures (Table 1). At rest, the changes in T_{ty} (ΔT_{ty}) were significantly greater than $\Delta T_{re\text{-}16}$ for all conditions ($p<0.05$, Fig. 2). In particular, the difference between ΔT_{ty} and $\Delta T_{re\text{-}16}$ was the most remarkable for PVC condition at 32°C (0.77 [0.25] in T_{ty} vs. 0.15 [0.18]°C in $T_{re\text{-}16}$, $p<0.001$). The directions of changes were not consistent between ΔT_{ty} and $\Delta T_{re\text{-}16}$, and even among ΔT_{re} at three depths (Fig. 2).

During exercise, T_{ty} was lower than $T_{re\text{-}16}$ for Control and HDPE conditions, but finally reached to/exceeded

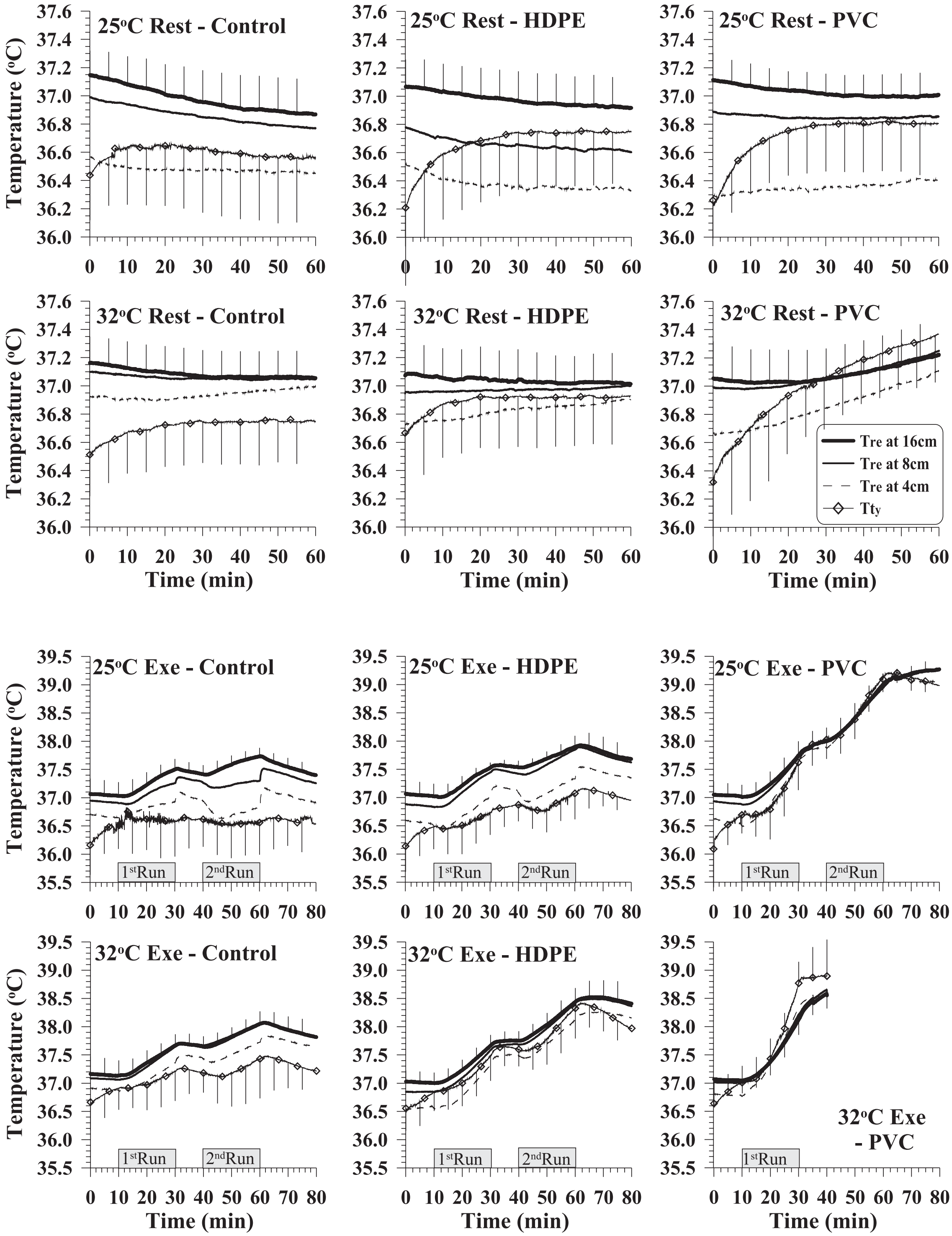

Fig. 1. Time courses of infrared tympanic and rectal temperatures at rest and during exercise in the air temperatures of 25 and 32°C (All temperatures were recorded every 2 s. Values were expressed as mean and SD. SD was expressed every 5 min).

Table 1. Summary of infrared tympanic and rectal temperatures at rest and during exercise

		25°C-Rest			32°C-Rest				*p* values[b)]	
		Control	HDPE	PVC	Control	HDPE	PVC	T_a	Clothing	T_a × Clothing[c)]
T_{ty}	M[a)]	36.6	36.7	36.8	36.8	36.9	37.3	0.009	0.013	N.S
	SD	0.5	0.4	0.4	0.3	0.3	0.3			
$T_{re\text{-}16cm}$	M	36.9	36.9	37.0	37.1	37.1	37.2	0.009	N.S	N.S
	SD	0.2	0.2	0.2	0.2	0.2	0.3			
$T_{re\text{-}8cm}$	M	36.8	36.6	36.9	37.0	37.0	37.2	0.003	N.S	N.S
	SD	0.4	0.5	0.3	0.2	0.3	0.3			
$T_{re\text{-}4cm}$	M	36.5	36.3	36.4	37.0	36.7	37.1	0.018	N.S	N.S
	SD	0.8	0.7	0.8	0.4	0.6	0.5			
p values[d)]		N.S.	N.S.	N.S.	N.S.	N.S.	N.S.			
		25°C-Exe			32°C-Exe				*p* values[b)]	
		Control	HDPE	PVC	Control	HDPE	PVC	T_a	Clothing	T_a × Clothing[c)]
T_{ty}	M[e)]	36.6	37.1	39.0	37.4	38.2	38.3	0.008	<0.001	N.S
	SD	0.6	0.4	0.2	0.7	0.5	0.3			
$T_{re\text{-}16cm}$	M	37.7	37.8**	38.8	38.0*	37.8	37.9*	0.001	<0.001	0.021
	SD	0.2	0.2	0.3	0.2	0.2	0.3			
$T_{re\text{-}8cm}$	M	37.3	37.8**	38.9	38.0*	37.7	38.0	0.063	<0.001	0.023
	SD	0.8	0.2	0.3	0.3	0.4	0.2			
$T_{re\text{-}4cm}$	M	36.8	37.3	38.9	37.7	37.4*	38.1	N.S	<0.001	N.S
	SD	1.6	0.6	0.4	0.3	0.7	0.4			
p values[d)]		N.S.	0.001	N.S.	0.018	0.032	0.046			

[a)]Average for the last 10 min; [b)]Two-way ANOVA; [c)]Interaction effect; [d)]One-way ANOVA among tympanic and rectal temperatures; [e)]Average for the last 5 min of last exercise; * $p<0.05$, ** $p<0.01$, *** $p<0.001$, significant difference when compared to tympanic temperature by Tukey post-hoc test.

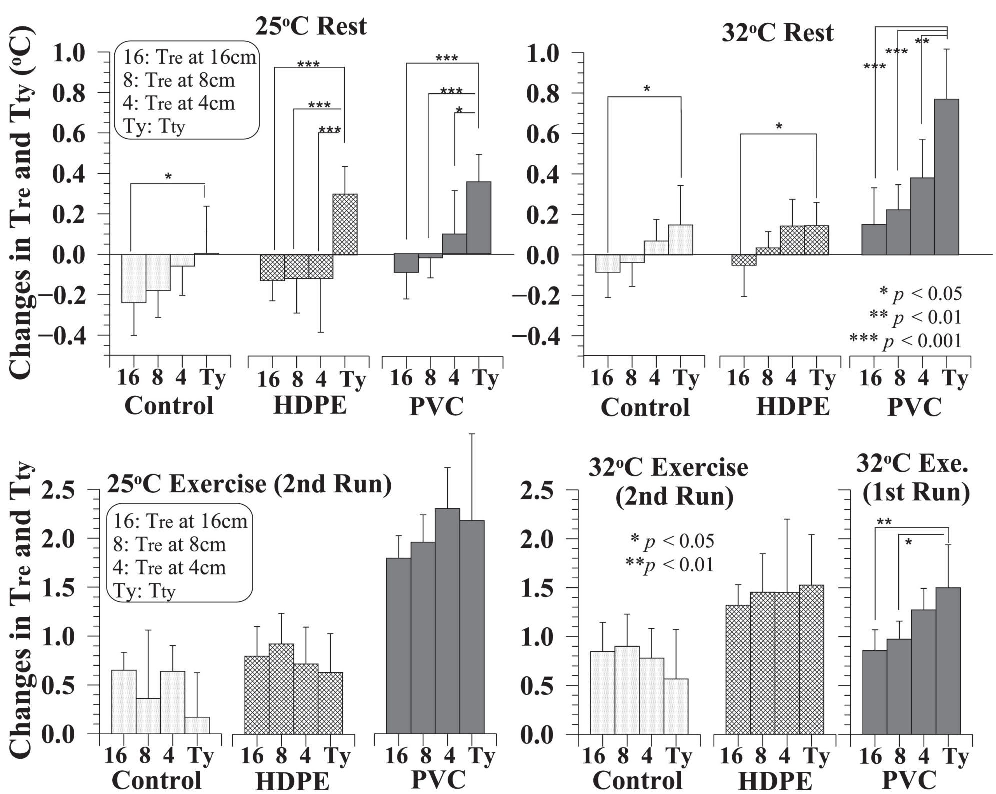

Fig. 2. The changes of rectal and infrared tympanic temperatures during resting and exercise in the air temperatures of 25 and 32°C. Values are expressed as mean (SD).

(Changes are rises from the average of the first 10 min to the average of the last 10 min for rest conditions [the last 5 min of the last running for exercise conditions]).

T_{re-16} for PVC conditions at both 25 and 32°C (Fig. 1). The last values during exercise in PVC condition at 32°C had a mean of 38.3 [SD 0.3] and 37.9 [SD 0.3]°C for T_{ty} and T_{re-16}, respectively (p<0.05, Table 1). During exercise at 32°C, the differences between T_{ty} and T_{re} were significant for all clothing conditions (p<0.05), but the differences were dependent on the depths of rectal measurements (Table 1). For PVC condition, T_{re} at various depths tended to be converged from one another as exercise went on (Fig. 1). During exercise, the directions of ΔT_{ty} and ΔT_{re-16} were consistent for all conditions (Fig. 2). There were no significant differences between ΔT_{ty} and ΔT_{re-16} during exercise, except PVC condition at 32°C (1.50 [SD 0.44] for ΔT_{ty} and 0.86 [SD 0.21]°C for ΔT_{re-16}, p<0.01).

Physiological strain index (PSI)

The PSI-values with T_{ty} and T_{re} did not show any significant difference during exercise at 25°C, while PSI-value using T_{ty} during exercise at 32°C was significantly greater than that using T_{re-16} for both HDPE and PVC conditions (p<0.05; PSI 7.0 [SD 1.1] based on T_{ty} and PSI 5.9 [SD 0.7] based on T_{re-16} for HDPE condition; 7.7 [SD 0.9] T_{ty} and 6.6 [SD 0.7] T_{re-16} for PVC condition; Fig. 3). For all conditions, PSIs using T_{ty} did not underestimate PSIs using T_{re}.

Limits of agreement between IR T_{ty} and T_{re}

The limits of agreement (LOA) between T_{ty} and T_{re-16} were examined using the Bland-Altman plots according to clothing levels (Fig. 4). The mean differences were –0.58 [SD 0.54]°C for Control, –0.15 [SD 0.51]°C for HDPE condition and 0.14 [SD 0.33]°C for PVC condition. The limit of agreement was the smallest for PVC condition (LOA of –0.53 to 0.81°C). There was no obvious consistency in the relation between the difference and the mean for PVC condition.

Relationships between IR T_{ty} and T_{re}

The relationship between T_{ty} and T_{re} were significantly strong for all rectal readings at three depths (r=0.753, 0.814, and 0.809 for T_{re-16}, T_{re-8}, and T_{re-4}; p<0.01). In particular, the correlation coefficient between T_{ty} and T_{re-16} was the greatest for PVC condition (r=0.929,

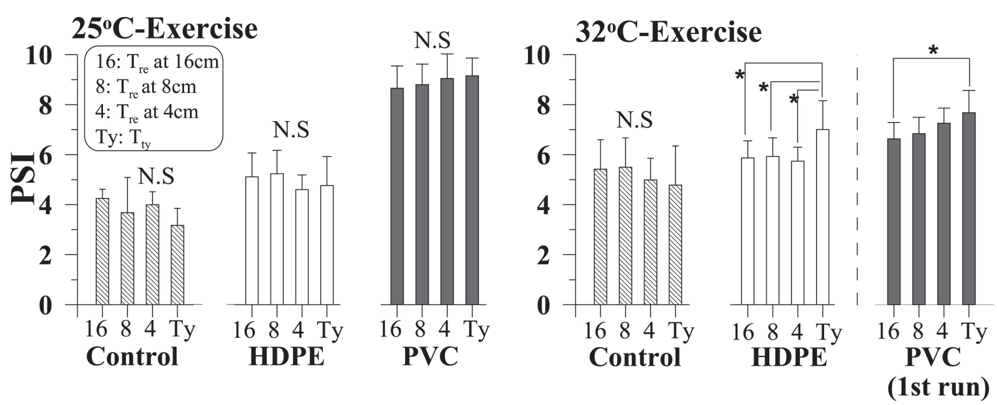

Fig. 3. Comparisons of physiological strain index (PSI) values which employed from various core temperature readings for exercise conditions at 25 and 32°C.

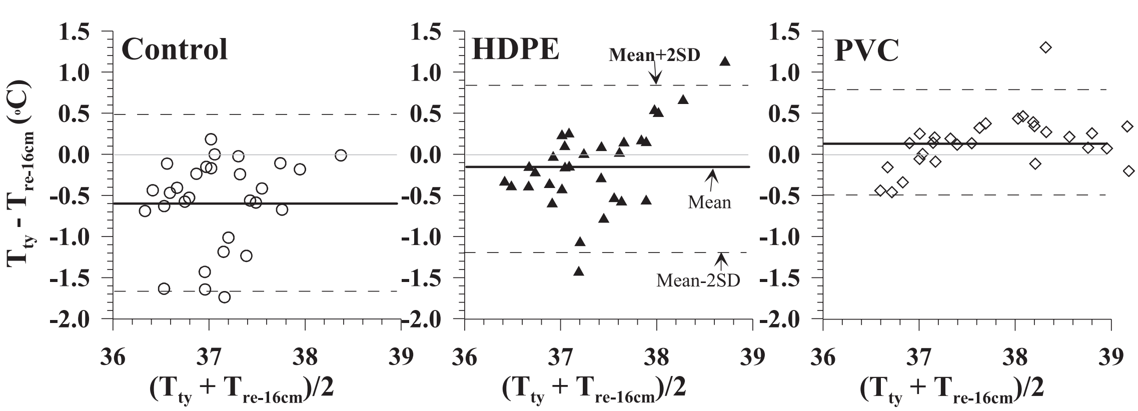

Fig. 4. Bland-Altman plots between infrared tympanic temperature (IR T_{ty}) and rectal measurement at 16 cm in depth ($T_{re-16cm}$).

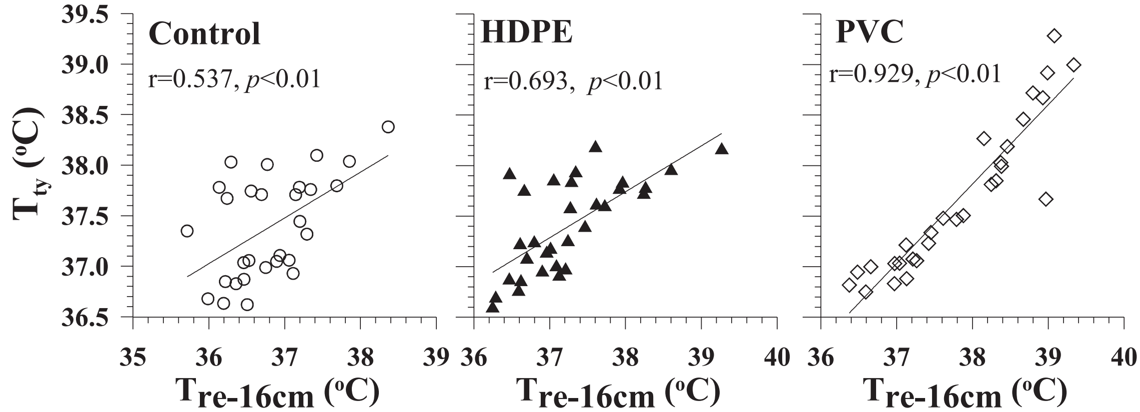

Fig. 5. Relationships between infrared tympanic temperature (IR T_{ty}) and rectal temperature at 16 cm in depth ($T_{re\text{-}16cm}$).

Table 2. Pearson's correlation coefficients between core temperatures and other physiological variables

	Total (n=96)	Activity		Clothing conditions		
		Rest (n=48)	Exercise (n=48)	Control (n=32)	HDPE (n=32)	PVC (n=32)
HR_{last} vs. $T_{re\text{-}16cm\ last\ mean}$	0.883**	0.585**	0.555**	0.931***	0.905**	0.864**
HR_{last} vs. $T_{ty\ last\ mean}$	0.743**	0.656**	0.834**	0.442*	0.740**	0.925**
TSR vs. $\Delta T_{re\text{-}16cm}$	0.815**	0.342*	0.529**	0.715**	0.910**	0.764**
TSR vs. ΔT_{ty}	0.745**	0.364*	0.684**	0.412*	0.852**	0.831**

HR_{last}, $T_{re\text{-}16cm\ last\ mean}$, and $T_{ty\ last\ mean}$ (The average of the last 10 min for rest conditions; the last 5 min of the last running for exercise sessions), TSR (Total sweat rate), $\Delta T_{re\text{-}16cm}$ and ΔT_{ty} (Changes from the average of the last 10 min [the last 5 min for exercise sessions] to that of the first 10 min);
*$p<0.05$, **$p<0.01$, *** $p<0.001$.

$p<0.01$) and the smallest for Control (r=0.537, $p<0.01$; Fig. 5).

Relationships between core temperatures and other physiological variables (Table 2)

Relationships with heart rate during the 2nd exercise (HR_{last}) were strong for both T_{ty} and $T_{re\text{-}16}$ (r=0.883 with T_{ty} and r=0.743 with $T_{re\text{-}16}$; Table 2). During exercise, the correlation coefficient with %HRC was greater in T_{ty} than $T_{re\text{-}16}$ (r=0.827 with T_{ty} and r=0.603 with $T_{re\text{-}16}$; $p<0.01$). In particular, the coefficients between HR_{last} and T_{ty} showed greater values as the increase of the thermal insulation of clothing (Control < HDPE < PVC), while HR and T_{re} showed high correlation coefficients irrespective of the clothing condition (Table 2). For the relationship with total sweat rate (TSR), similar results as those with HR were observed (Table 2).

Discussion

First of all, it is true that most studies have reported lower values in IR T_{ty} than in T_{re}. Infrared tympanic temperature (aural or ear canal temperature) is lower than T_{re} at rest[14, 26, 31, 32], or when exercising in heat[33, 34]. However, an important finding from the present study is that IR T_{ty} was not lower than T_{re} in strenuous conditions among the 12 conditions. The exceptional cases appeared when wearing the PVC coverall in the rest condition at 32°C, wearing the HDPE coverall in the exercise condition at 25°C, and wearing the PVC coverall in exercise conditions at 25 and 32°C. For those four conditions, IR T_{ty} was higher than $T_{re\text{-}16}$ or similar to $T_{re\text{-}16}$ (Fig. 1). Furthermore, the Bland-Altman plot in the present study shows greater agreement between IR T_{ty} and $T_{re\text{-}16}$ for the PVC condition than other clothing conditions (Fig. 3). Reports on the higher or similar T_{ty} than other core temperatures are rare but were found in several previous studies. Muir and colleagues[35] observed that ear canal temperature finally increased to higher values than T_{re} during exercise wearing impermeable coverall at 30°C. Nadel and Horvath[36] reported that tympanic temperature was higher than T_{re} at T_a of 34, 39 and 40°C, while tympanic temperature was not higher at T_a of 10, 16, 22 and 28°C. Infrared tympanic and rectal temperatures were not different for febrile patients (38.9 and 38.8°C)[37] and for the presence of fever in children[38]. These findings indicate that tympanic (or ear canal) temperature would not be lower than T_{re} for the hyperthermic states that is caused by impermeable protective clothing, heavy exercise, severe heat and/or fever.

What factors in hyperthermic situations are attributed to higher or similar IR T_{ty} than T_{re}? The tympanic membrane temperature is influenced by the skin temperature of the head[39)], and the brain is metabolically one of the most active organs in the body accounting for 20% of the resting total body oxygen consumption[39)]. In the present study, the PVC and HDPE coveralls have an attached PVC and HDPE hoods, respectively, which inhibits convective and evaporative heat loss from the head. For these cases, it is assumed that the temperature of the surrounding ear canal wall reaches values similar to that of the tympanic membrane. In particular, it could be highlighted that IR T_{ty} rose up higher than T_{re} in PVC conditions, even though participants were at rest in T_a of 32°C (Fig. 1). According to Brinnel and Cabanac[19)], it is generally admitted that the temperature of a given site within the body depends on: (a) local metabolism, (b) the temperature of the arterial blood supplying the site; (c) heat flow through the site from or to the nearby structures. They discussed that regional heat flow is probably the most powerful factor influencing tympanic temperature because the local metabolism of the tympanic membrane should have only a very small influence on tympanic temperature; the vascularization of tympanic membrane is not homogeneous; and the blood supply is poorest in its deepest region. Since the human brain is known to produce 20 times more heat than other tissues at rest, excluding kidney, heart, and liver[19)], the excessive heat from the head needs to be removed and dissipated to avoid any excessive increase in brain temperature[17)]. Herein, it is reasonable to assume that the temperature of the surrounding ear canal wall reaches values similar to that of the tympanic membrane when the subject's head is encapsulated by the vapor impermeable PVC hood. It seems that the higher IR T_{ty} than T_{re} in the present study was attributed to the protective hood over the head that inhibited heat loss from the human head at T_a of 32°C or during exercise. Despite long arguments on the validity of T_{ty} as a thermal index, there are reports that T_{ty} followed brain temperature more closely than the rectal temperature[17)], and T_{ty} was consistent to the patterns of the brain temperature but T_{re} was abandoned as unpredictable in their relation to temperature in the cranium temperature[9)]. Given findings from present and previous studies, the following conclusion could be drawn: IR T_{ty} is a valid index to reflect the thermal burden of workers wearing impermeable protective clothing with a hood in heat. However, the limited application of IR T_{ty} should be carefully considered.

Secondly, the change in core temperatures as well as the absolute value has been considered as an index to evaluate heat strain. In the present study, the change in IR T_{ty} at rest was significantly greater than that in T_{re}, while the rise in IR T_{ty} during exercise did not differ from that in T_{re} except the PVC condition at 32°C (Fig. 2). These results somewhat concur with previous reports. Infrared tympanic temperature was elevated after heat exposures (max 0.8°C) and tended to decrease briefly after cold exposure (max 0.7°C), but T_{re} remained stable during the exposures[40)]. While it is the case that without knowing what a gold standard is among various deep body temperatures, any conclusion about whether overestimation or underestimation of true core temperature would remain speculative, it looks clear that T_{re} is more stable than IR T_{ty} at rest. Further, during uncompensated heat stress (exercising in the PVC condition at 32°C), the maximum rise in core temperature was found in IR T_{ty} not in T_{re}. The use of IR T_{ty} can lead to more conservative criteria to evaluate the heat strain of workers wearing impermeable protective clothing in hot environments. Thus, the monitoring IR T_{ty} might be a more precautionary and conservative measure than the monitoring of T_{re} for workers wearing impermeable protective clothing in heat. The PSI also supports the above idea as shown in Fig. 3.

Thirdly, the examinations of relationships with other physiological variables will give us insights into what is a valid heat strain index. Brinnel and Cabanac[19)] reviewed that T_{ty} has been found to be a better indicator of heart rate, sweating and vasomotor response than T_{re}. The present study found strong relationships of IR T_{ty} with heart rate and sweat rate during exercise, which validates IR T_{ty} to evaluate a heat strain index. Another important point in the present study is that the strength of relationships between IR T_{ty} and physiological variables (e.g., HR and TSR) is affected by clothing conditions. The correlation coefficients between IR T_{ty} and the physiological variables were the greatest for the PVC condition and the lowest for the Control (Table 2). These findings remind that IR T_{ty} could not be justified as a thermal index to evaluate heat strain while wearing vapor permeable light clothing.

Fourthly, the significance of the depth in the rectum when compared to IR T_{ty} needs to be carefully discussed. As described in the introduction, numerous studies compared T_{ty} to T_{re}, but some clinical studies reported T_{re} that was measured at the shallow depths of 2.5 to 5 cm for adults[24–26)]. Rectal temperature indeed varies depending on how deeply the thermometer is inserted into the rectum[21)]. The differences in measuring depths may make differences in (a) the magnitude of rise, (b) a time lag response, and (c) the direction of the change in T_{re} during exercise. With regard to the magnitude of rise in T_{re}, Lee and colleagues[22] simultaneously measured T_{re} at depth of 4, 6, 8, 10, 13, 16, and 19 cm during bicycling exercise. They found small but statistical differences by depth in the magnitude of rise in T_{re}. The present results are somewhat in agreement with Lee and colleagues[22] for PVC conditions. In particular, for treadmill exercising in PVC conditions, the rise in T_{re} was greater as the depth in the rectum became shallower (Fig. 2). These results indicate that there is a likelihood that different conclusions may be drawn when compared to IR T_{ty} according to the depths that measuring rectal temperatures.

For the lag response during exercise, it is known that T_{re} responds slowly to the rapidly changing environments when compared to other deep body temperatures[5, 7, 13]. Lee and colleagues[22] reported that the latent period of T_{re} during exercise was significantly longer at 13, 16, and 19 cm in depth than at 4 and 6 cm in depth. In the present study, Fig. 1 demonstrates that T_{re} at 8 and 16 cm in depth responded more slowly at the commencement of exercise when compared to T_{re} at 4 cm in depth. On the contrary, IR T_{ty} responded quickly as soon as exercise began for PVC conditions (Fig. 1). It has been reported that tympanic membrane temperature responded much more rapidly to transient thermal situation than did the temperature of the rectum[14, 36]. The present result is in agreement with the previous reports.

The opposite direction of changes between rectal and esophageal temperatures during transitions from exercise to rest as observed in Kolka and colleagues[12], was also found within rectal temperatures themselves, according to the depths measured[22]. For some resting conditions, a rise was found in T_{re} at 4 cm in depth while a drop was found in T_{re} at 16 cm in depth, simultaneously, which suggests there was dynamic heat exchanges among the core, shell body and the environment even in stabilization (Fig. 2). During recovery after exercise, the directions of changes between IR T_{ty} and T_{re} are distinct from each other. For recoveries in the HDPE condition at 32°C, PVC conditions at 25°C and 32°C, changes in IR T_{ty} shows distinguished slopes from those in T_{re} (Fig. 1). That is, the present study indicates that IR T_{ty} did not track well T_{re} during recovery after exercise, as reported in Hower and Blehm[40].

Lastly, it is noteworthy that the diameter of the tympanic probe tip, the technique of measurement (aim and pressure), and the individual characteristics of the ear canal (curvature, diameter, length, cerumen, and tympanic inflammation) could significantly affect the infrared tympanic temperature[10, 32]. Some discrepancies in previous research may result from imperfections in the method used for measuring IR T_{ty}[21]. It needs to note again that the infrared tympanic thermometer used in the present study was the specially designed instrument for the continuous monitoring of industrial workers, not for the one-shot measurement for a daily use. Those factors may have something to do with a considerable individual variation in IR T_{ty} reported in Doyle and colleagues[41]. However, for the present study, standard deviations in IR T_{ty} in PVC conditions did not show big differences when compared to standard deviations in $T_{re\text{-}16}$ (Table 1). This result justifies the reliability of IR T_{ty} as a suitable index to evaluate heat strain of workers wearing vapor impermeable protective clothing with a hood in which the heat exchange between the head and the environment is limited.

Conclusions

We examined the validity of infrared tympanic temperature (IR T_{ty}) as a thermal index to evaluate the heat strain of workers wearing vapor impermeable protective clothing in hot environments, in comparison with rectal temperatures (T_{re}) that measured at 4, 8 and 16 cm in depth from the anal sphincter. The validity and suitability of IR T_{ty} were justified by the following five findings: (1) IR T_{ty} was lower than T_{re} in most cases, but was not lower than T_{re} during exercise wearing PVC coveralls, which suggests that IR T_{ty} is not lower than T_{re} in hyperthermic states. (2) The rise in IR T_{ty} was greater than that in T_{re} during exercise wearing PVC coveralls at 32°C, which suggests that IR T_{ty} would yield more conservative and precautionary criteria than T_{re} in the hyperthermic states. (3) IR T_{ty} had strong relationships with both heart rate and sweat rate during exercise. The strength of the relationships was the greatest for PVC conditions. (4) The correlation coefficient between IR T_{ty} and $T_{re\text{-}16}$ was the greatest for PVC condition. (5) Individual variations in IR T_{ty} for PVC conditions did not show big differences when compared to those in T_{re}. Apart from these findings, it needs to be noted that T_{re} was more stable than IR T_{ty} at rest, and IR T_{ty} did not track T_{re} well during recovery after exercise because of the thermal inertia in T_{re}. Furthermore, it should be emphasized that the validity of IR T_{ty} is supported in hyperthermic states in which the heat transfer between the head and the environment is limited.

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