Individual Variability in the Peripheral and Core Interthreshold Zones

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Abstract The purpose of the study was to investigate the degree of subject variability in the peripheral and core temperature thresholds of the onset of shivering and sweating. Nine healthy young male subjects participated in three trials. In the first two trials, wearing only shorts, they were exposed to air temperatures of 5°C and 40°C until the onset of shivering and sweating, respectively. In the second experiment, subjects wore a water perfused suit that was perfused with 25°C water at a rate of 600 cc/min. They exercised on an ergometer at 50% of their maximum work rate for 10–15 min. At the onset of sweating, the exercise was terminated, and they remained seated until the onset of shivering, as reflected in oxygen uptake. In the first two trials, rectal temperature (Tre) was stable, despite displacements in skin temperature (Tsk), whereas in the third trial, Tsk (measured at four sites) was almost constant (30–32°C), and the thermoregulatory responses were initiated due to changes in Tre alone. The results of the first two trials established the peripheral interthreshold zone, whereas the results of the third trial established the core interthreshold zone. The results demonstrated individual variability in the peripheral and core interthreshold zones, a proportional correlation between both zones ($r=0.87$), and a relatively higher contribution of adiposity in both zones as compared with those of other non-thermal factors such as height, weight, body surface area, surface area-to mass ratio, and the maximum work load. *J Physiol Anthropol* 26(3): 403–408, 2007 <http://www.jstage.jst.go.jp/browse/jpa2>
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1. Introduction

Regulation of internal body temperature in humans is characterized by heat loss and heat production responses. Common to these responses is the fact that they are each initiated at specific combinations of core and skin temperature,

and they each have a specific responsiveness. That is, the magnitude of the response is determined by the change in core and/or skin temperature.

Thermoregulatory studies normally assess the autonomic responses of sweating, shivering, and vasomotor tone in this manner. Whereas the manner in which thermoafferent signals from the core and periphery are integrated centrally to establish normothermia has been the main focus of most studies in the past, the focus is now shifting towards a better understanding of how non-thermal factors influence temperature regulation. Some non-thermal factors, such as aging for example, have been shown to affect all thermoregulatory responses, whereas others only affect individual autonomic responses (Mekjavic and Eiken, 2006).

Common to all studies investigating the effect of non-thermal factors is that they use homogeneous subject populations. Despite the homogeneity, there remains a substantial degree of individual variability in both the characteristics of the responses and the manner in which non-thermal factors affect the individual responses. Since the focus of many current studies is the elucidation of the influence of non-thermal factors on temperature regulation, the analyses of the results usually incorporate a comparison of averaged responses for conditions in which a given non-thermal response is maintained at different levels. The statistical analyses usually neglect the individual variability in the observed responses.

The present study investigated the degree of individual variability in the autonomic thermoregulatory responses; specifically, it examined the variability in the thresholds of the sweating and shivering responses.

2. Methods

2.1 Subjects

Nine Japanese healthy male subjects participated in the study. They all gave their informed consent to participate in the study, being fully aware that they could withdraw from the study without prejudice at any time. The protocol of the study was approved by the institutional ethics review process.

According to the comprehensive procedure outlined by Drinkwater (1980), anthropometric measurements of skinfold thickness at multiple sites, girth, length and bone breadth of the specific body compartments were made on each subject. The values were then used to estimate regional weights of skin, adipose tissue, skeletal muscle, bone, and residual tissues. The mass percentages of the skin and adipose tissues were combined to obtain a value of adiposity. In order to estimate the subjects' maximum work capacity during an incremental load exercise on a cycle ergometer, subjects were required to pedal at a rate of 60 rpm, and the work rate was incremented by 10 W/min thereafter until exhaustion or until they could not no longer maintain the required cadence.

Their physical characteristics such as age, height, weight, body surface area, surface area-to mass ratio, adiposity, and the maximum work load, together with their answers for susceptibility to heat and cold, are presented in Table 1.

2.2 Experimental protocol

Subjects participated in three trials on separate occasions. In the first two trials, subjects were exposed to ambient temperatures of 5°C and 40°C. In the 5°C trial, the exposure

was terminated at the onset of shivering, as reflected in oxygen uptake. In the 40°C trial, the exposure was terminated at the onset of sweating, measured with a ventilated capsule on the forehead.

In the third trial, we modified the protocol of Mekjavic et al. (1996). As described in Fig. 1, subjects donned a water perfused suit, comprised of three segments: trousers, shirt and hood. By perfusing the segments in parallel with water maintained at 25°C at a rate of 600 cc/min, mean skin temperature was maintained at 28°C. Following the recording of baseline values, subjects commenced exercising at 50% of their maximum work rate on a cycle ergometer. The exercise was terminated once the onset of sweating was observed, which occurred after 10 to 15 min of the exercise. Thereafter, subjects remained seated on the cycle ergometer for an additional 100 min. During this latter phase of the trial, the extraction of heat by the water perfusing the suit initiated cooling of the core region. As a result of the core cooling, sweating abated, and eventually the shivering response was triggered.

Table 1 Subjects' physical characteristics and susceptibility to heat and cold

Subjects	Age (yr)	Height (cm)	Weight (kg)	AD (m ²)	AD/Weight (m ² /kg×10 ²)	Adiposity (N.D.)	Maximum work load (W)	Susceptible to heat	Susceptible to cold
A	21	180.0	58.5	1.74	2.97	0.29	294	○	×
B	21	172.4	60.3	1.71	2.84	0.26	260	○	○
C	21	170.0	57.0	1.66	2.91	0.27	250	○	×
D	21	162.4	47.0	1.49	3.17	0.23	218	×	○
E	19	160.5	55.8	1.58	2.83	0.26	204	○	○
F	21	174.4	82.5	1.94	2.35	0.32	300	○	×
G	21	179.5	62.2	1.78	2.86	0.32	276	×	○
H	21	172.0	60.0	1.71	2.85	0.23	282	○	×
I	20	174.5	70.0	1.83	2.61	0.24	296	○	×
mean±SD	20.7±0.7	171.7±6.7	61.5±9.9	1.7±0.13	2.82±0.23	0.3±0.03	264.4±34.7		

AD: body surface area (m²), ○: susceptible to heat or cold, ×: not susceptible to heat or cold

Fig. 1 Diagram for the cooling system.

A chiller cooled water in the bath and a pump supplied cool water into the vinyl tubes incorporated in the suit. After water perfused through the tubes, it was returned to the water bath and cooled again.

2.3 Measurements

In all trials, rectal (Tre) and skin (Tsk: arm, chest, thigh and calf) temperatures were monitored with thermistors and the values stored every ten seconds with a data logger system (Cadac2 model 9200A, Tokyo, Japan). Sweating rate was measured at the forehead with a sweat rate monitor (model SKD-4000, Skinco Co.). Oxygen uptake was monitored with a gas analyzer (Respirometer RM-300i, Minato Med. Science, Co.).

In the third trial, maintenance of a normal skin temperature while simultaneously extracting 120 W/m² of heat was achieved by having subjects wear a Cool Tubesuit™ (Med-Eng Systems Inc., Ottawa, Ontario, Canada) water perfused suit. Water perfusing the suit was pumped at a rate of 600 cc/min (Water Pump Model Super Tepcon, Terada, CITY, Japan) from a bath, in which the temperature of the water was maintained at 25°C by a Cool Mate Model TE-105M heat exchanger (Toyo Seisakusho Co., CITY, Japan).

2.4 Analysis

The onset of shivering in the 5°C trial, and of sweating in the 40°C trial occurred as a consequence of the change in mean skin temperature (MST; calculated according to the suggestion of Ramanathan, 1976) since Tre remained unchanged. Thus, the combined results of the two trials established the peripheral interthreshold zone for each subject. The boundaries of this zone were the skin temperatures coinciding with the onset of shivering and sweating. Whereas the onset of sweating is quite distinct, the Tsk threshold for shivering was taken as the Tsk which coincided with a significant elevation in the oxygen above resting values. In a similar manner, the boundaries of the core interthreshold zone were determined for each subject in trial 3. In contrast to the 5°C and 40°C trials, the third trial determined the Tre at which sweating abated. Thus, the core interthreshold boundaries are the Tre for cessation of sweating and onset of shivering.

As mentioned earlier, although the primary purpose of the present study is to establish a protocol with which to quantify the individual variability in the core and peripheral interthreshold zones, the data of the present study were also part of a pilot study to examine whether non-thermal factors affect the interthreshold zones. For this purpose, the relationship between the magnitudes of the interthreshold zone and non-thermal factors was examined using the simple correlation analysis. Statistical significance was set at $p < 0.05$.

3. Results and Discussion

Although numerous studies, for example, studies by Stolwijk and Hardy (1966), Nadel et al. (1971) and Kruk et al. (1991), have demonstrated the contribution of mean skin temperature and exercise to the thresholds for sweating and shivering, not many have focused on the peripheral interthreshold zone per se, despite studies by Benzinger (1967). The present study has demonstrated individual

Fig. 2 An example of changes in rectal and mean skin temperatures and oxygen uptake during cold air exposure.

Tre did not change until shivering was observed whereas MST decreased promptly. Shivering was observed at 15 to 25 min from the beginning of exposure.

Fig. 3 An example of changes in rectal temperature, mean skin temperature and sweating rate during hot air exposure.

During heat exposure, Tre did not change for the first part of exposure. However, it started to increase 15 to 20 min from the beginning of exposure. MST increased promptly and then sweating was observed before Tre increased.

variability of both the peripheral and core interthreshold zones and the relation between both zones.

3.1 Peripheral interthreshold zone

Typical responses of MST and Tre are shown in Fig. 2 and Fig. 3. Onset of shivering normally occurred within 20 to 30 min. from the beginning of cold air exposure, and the onset of sweating within 10 to 15 min. from the beginning of hot air exposure. The responses of sweating and shivering coincided with changes in skin temperature only, as there was no displacement of Tre during this time.

As shown in Table 2, MST at the onset of sweating and MST at the onset of shivering varied from 35.0 to 37.0°C and 26.0 to 27.2°C, respectively. Temperature differences between the initial MST and the threshold MST, i.e., $\Delta\text{MST-sw}$ and $\Delta\text{MST-shivering}$, were then calculated to estimate the peripheral interthreshold range. It was found that the peripheral range varied from 9.4°C to 11.9°C. Thus, individual variability in the

Table 2 Peripheral sweating and shivering interthresholds

Subjects	A	B	C	D	E	F	G	H	I	Mean $\pm$ SD
MST-sw	36.2	36.6	35.5	35.2	35.0	35.6	37.0	36.5	36.0	36.0 $\pm$ 0.7
Δ MST-sw	2.2	3.2	1.9	2.2	2.5	3.5	2.7	2.6	1.9	2.5 $\pm$ 0.6
MST-shivering	26.3	26.4	26.5	26.7	26.8	26.7	26.0	27.2	26.1	26.5 $\pm$ 0.4
Δ MST-shivering	-7.2	-8.3	8.5	-8.3	-7.3	-7.1	-9.2	-7.0	-8.1	-7.9 $\pm$ 0.8
Peripheral interthreshold range	9.4	11.5	10.4	10.5	9.8	10.7	11.9	9.6	10.0	10.4 $\pm$ 0.8

MST-sw: peripheral sweating threshold, Δ MST-sw: temperature difference between MST and the initial MST, MST-shivering: peripheral shivering threshold, Δ MST-shivering: temperature difference between MST-shivering and the initial MST

Table 3 Core sweating and shivering interthresholds

Subjects	A	B	C	D	E	F	G	H	I	Mean $\pm$ SD
Tre-sw	37.4	37.6	37.2	37.4	37.2	37.5	37.7	37.4	37.7	37.5 $\pm$ 0.18
Tre-shivering	36.5	36.4	36.3	36.4	36.4	36.5	36.5	36.7	36.9	36.5 $\pm$ 0.17
Δ Tre-sw	0.69	0.03	0.11	0.25	0.03	0.05	0.06	0.15	0.00	0.15 $\pm$ 0.20
Δ Tre-shivering	-0.25	-1.15	-0.77	-0.80	-0.73	-0.96	-1.14	-0.55	-0.78	-0.79 $\pm$ 0.27
Core interthreshold range	0.94	1.18	0.88	1.05	0.76	1.01	1.20	0.70	0.78	0.94 $\pm$ 0.17

Tre-sw: core sweating threshold, Δ Tre-sw: temperature difference between Tre-sw and the initial Tre, Tre-shivering: core shivering threshold, Δ Tre-shivering: temperature difference between Tre-shivering and the initial Tre

thermoregulatory responses by peripheral thermoregulatory drive can be observed.

Benzinger (1967) reviewed sweating and shivering thresholds under various combinations of MST and core temperature (T_{core}), and demonstrated that the peripheral shivering threshold decreases 0.6°C per 0.1°C increase in T_{core} in the range of 36.3°C to 36.7°C. When core temperature was above 36.8°C, MST at the onset of shivering decreases 0.5°C per 0.1°C increase in T_{core} . Therefore, in order to compare individual differences in the peripheral shivering threshold, regardless of central thermoregulatory drive, Tre must be maintained within 0.1°C.

In the present study, mean initial rectal temperatures were 37.1 $\pm$ 0.12°C and 37.1 $\pm$ 0.25°C before hot and cold air exposure, respectively, so there was little difference in mean initial rectal temperature between the two trials. However, individual differences were more than 0.1°C in each trial. Such differences were expected no matter how carefully controlled the experimental protocol. Since all the subjects felt thermally comfortable before exposure, we thought that these individual differences did not contribute to the central thermoregulatory responses.

Individual variability in the thermoregulatory responses by peripheral thermoregulatory drive may be due partly to the effect of body size. In the study by Brück et al. (1971), the peripheral shivering thresholds of infants were compared with those of adults. When ambient temperature decreased from 32°C to 28°C, infants initiated shivering at a higher mean skin temperature than adults to maintain body temperature consistently because of higher sensitivity of the peripheral thermoreceptor. Therefore, the peripheral shivering threshold

may be dependent upon body size, a non-thermal factor.

The relationship between the peripheral interthreshold range and subjects' physical characteristics such as age, height, weight, body surface area, surface area-to mass ratio, and adiposity were then examined using the simple correlation analysis. The results indicated that no physical characteristics representing body size were significantly correlated with the range. However, adiposity showed a relatively higher correlation ($r=0.41$) than those of other non-thermal factors.

3.2 Core interthreshold zone

Following the cessation of exercise, Tre decreased at a rate of 0.5°C per hour, which was about half of that observed during immersion in water at 28°C (Mekjavic et al., 1996). Unfortunately, MST could not be controlled consistently at 28°C due to indirect cooling with the water perfused suit. It varied from 32°C during exercise to 30°C at the end of the 100 min recovery period. Typical responses of Tsk and Tre are shown in Fig. 4.

Benzinger (1967) reported that the core sweating threshold was independent of MST in the range of 33°C to 38°C and MST must be maintained within 0.2°C when individual differences in core sweating thresholds were compared. The results from the present study showed that MST at the onset of sweating varied from 30.7°C to 32.6°C. Therefore, it was possible that MST differences contributed to individual differences in the core sweating threshold. However, since MST changed in the same manner for all subjects, we thought that this did not contribute to the observed individual differences in the thermoregulatory responses.

For some subjects, the onset of shivering could not be

Fig. 4 An example of changes in rectal temperature and mean skin temperature throughout the experiment.

During exercise, the onset of sweating could be observed. Following exercise, subjects were resting until shivering was observed. It took 70 to 90 min from the termination of exercise.

identified clearly, since marked elevations of oxygen uptake were not observed. However, in such subjects, we could visually identify increased muscle tension, concomitant with occasional elevations in oxygen uptake. As shown in Table 3, we were able to demonstrate individual variability in the cessation of sweating and onset of shivering, as well as that in the core interthreshold range that varied from 0.7°C to 1.2°C. Thus, individual variability in the thermoregulatory responses by central thermoregulatory drive can also be observed.

As demonstrated by Kruk et al. (1991), it is known that the core sweating threshold changes with intensity of exercise and ambient temperature. During higher exercise intensities, sweating occurred at similar Tre but at lower MST. The relationship between the core interthreshold range and subjects' physical characteristics such as age, height, weight, body surface area, surface area-to mass ratio and adiposity, and the maximum work load were then examined using the simple correlation analysis. The results revealed that no physical characteristics, including maximum work load, were significantly correlated with the ranges. In the present study, subjects underwent exercise at their 50% maximum work load, so that a relative intensity of exercise was controlled at a given level. From this reason, the contribution of exercise to the ranges is thought to be consistent.

It is interesting to note that, same as the peripheral interthreshold range, adiposity showed a relatively higher correlation ($r=0.43$) than those of other non-thermal factors. Kakitsuba et al. (2005) reported the effects of non-thermal factors on the core interthreshold zone by showing the results that fat-rich subjects initiated shivering at 0.3°C lower Tre than lean subjects. This observation agreed with the implication that adiposity may contribute to the core interthreshold zone.

3.3 Relation of the peripheral and core interthreshold zones

As shown in Fig. 5, the core interthreshold ranges were plotted against the peripheral interthreshold ranges. According to a least-squares linear regression analysis, it was found that

Fig. 5 Relationship between core and peripheral interthreshold ranges.

The core interthreshold range was proportionally correlated with the peripheral interthreshold range. This relation implies that a person who has a narrow peripheral interthreshold range may have a narrow core interthreshold range.

the core interthreshold ranges were proportionally correlated with the peripheral interthreshold ranges. This relation implies that a person who has a narrow peripheral interthreshold range may have a narrow core interthreshold range. This finding may be supported by Boulant (1981), who stated that the preoptic thermosensitive neurons controlled thermoregulatory responses because both respond similarly to changes in preoptic temperature and skin temperature.

In the present study, healthy young Japanese male subjects participated as a specific group in order to clarify the effect of non-thermal factors on individual variability in the peripheral and core interthresholds. The results demonstrated individual variability in the peripheral and core interthreshold zones, a proportional correlation between both zones ($r=0.87$), and a relatively higher contribution of adiposity on both zones as compared with those of other non-thermal factors such as height, weight, body surface area, surface area-to mass ratio, and the maximum work load.

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