생활과학석사 학위논문

Sweating Distribution and Active Sweat Glands on the Head of Young Males in Dry and Humid Environments

건조한 환경과 습한 환경에서의
젊은 남성의 머리부위 능동한선 및 발한 특성

2017년 8월

서울대학교 대학원
의류학과
정 다 희

Sweating Distribution and Active Sweat Glands on the Head of Young Males in Dry and Humid Environments

지도 교수 이 주 영

이 논문을 생활과학석사학위논문으로 제출함

2017년 6월

서울대학교 대학원

의류학과

정 다 희

정다희의 생활과학석사학위논문을 인준함

2017년 6월

위 원 장 ______________________ **(인)**

부위원장 ______________________ **(인)**

위　　원 ______________________ **(인)**

Abstract

Sweating Distribution and Active Sweat Glands on the Head of Young Males in Dry and Humid Environments

Dahee Jung

Department of Textiles, Merchandising and Fashion Design

College of Human Ecology

Seoul National University

Sweating is one of the mechanisms of thermoregulation for heat dissipation to maintain body temperature. Sweat rate is known to be different according to the region of the human body, with the highest rate on the back and the lowest rate toward the periphery. The head has a greater sweat response than all other body segments except the hands and feet. Many studies have reported forehead sweating as representative of sweating on the head; however, there is a lack of information about regional differences in sweating on intra-segmental hairy sites. The purpose of this study was to investigate the effects of humidity on sweat distribution and active sweat glands on the head during passive heating in a hot-dry environment (32 ℃, 30%RH) and a hot-humid environment (32 ℃, 85%RH). Passive heating was induced by immersing in hot water (42 ℃) for 1 h. Despite differences in humidity, the results showed that there was no significant difference in sweat rates for the head, and the total sweat rate was significantly greater in the dry environment than the humid environment. The local sweat rate was greater in the frontal region than the vertex region of the head. Active sweat glands were counted by the iodine-impregnated paper method, and the number in the humid environment was greater than that in the dry environment. The sweat distribution pattern of the head was different compared with that of the entire body. These findings could be applied to headgear design for reducing the heat stress of the wearer. The thermal comfort of headgears can be improved by adding a vent hole to the front and back of headgears for ventilation, and the top of headgears should be made of breathable material with enhanced durability.

Keyword : Sweat distribution, Active sweat glands, Non-hairy head, Air humidity, Total sweat rate

***Student Number* :** 2015-23101

Contents

List of Tables

List of Figures

List of Equations

List of Abbreviations

ASGs	Active sweat glands
ASGD	Active sweat glands density
HD	Hot and dry condition
HH	Hot and humid condition
HR	Heart rate
LSR	Local sweat rate
SGO	Sweat output pet glands
SS	Sweat sensation
SM	Skin moisture
T_{re}	Rectal temperature
TC	Thermal comfort
TS^1	Thermal sensation
TS^2	Thirsty sensation
T_{sk}	Skin temperature
$\bar{T}_{sk}$	Mean skin temperature
TSR	Total sweat rate

Chapter1. Introduction

For firefighters, industrial field workers, cyclists, and motorcyclists, protective helmets and headgears are mandatory for protection against flames or shocks. Because these protective headgears are worn regardless of the weather or season, it can cause discomfort and heat stress especially in the hot summer season and thus could be a secondary risk factor. One of the reasons why people are reluctant to wear a helmet is that they feel uncomfortable (Li et al. 2008; Patel and Mohan 1993; Skalkidou et al. 1999) when they wear a protective headgear that restricts airflow and sweat evaporation (Liu and Holmer 1995).

In general, sweat glands on the human skin secrete fluids directly to the skin surface, which include the apocrine glands, eccrine sweat glands, and apocrine glands. Among these glands, the eccrine sweat glands are known to be activated by thermal loading, and the total number of sweat glands has been determined to be 2.38 million over the entire skin of the human body (Kuno 1956). The density of sweat glands is the highest on the palm and sole followed by the head, trunk, and extremities (Kuno 1956). Variations in sweating between different regions have been reported to be substantial (Cotter et al. 1955; Hertzman et al. 1952; Patterson et al. 2000; Weiner 1945), and there are several studies with regard to body sweat distribution. According to Havenith et al. (2008), the amount of sweating is the highest on the back and is the lowest toward the periphery. In addition, other researchers have confirmed a variation in sweating according to different parts of the torso (Machado-Moreira et al. 2008a), arms and hands (Smith et al. 2007), and foot (Taylor et al. 2006). Sweat rate could be modified by changes in the active sweat gland density (ASGD) and/or sweat output per gland (SGO). A study has reported that changes in forearm sweat rate depend on both the active sweat glands (ASGs) and SGO, whereas further increases in sweat rate are dependent on increases in the SGO (Kondo et al. 2000). Local SGO corresponds to sweat rate and results in regional differences in sweating throughout the body (Inoue and Shibasaki 1996).

The head is known to play an important role in heat dissipation. In terms of the reduction of heat stress, many studies have regarded sweating on the forehead as representative of sweating on the head. The forehead has a greater sweat response than all other body segments during thermal loading, and it has one of the highest sweat gland densities (Cotter et al. 1995; Hertzman et al. 1952; Szabo 1962). Machado-Moreira et al. (2008b) found that the sweat secretion pattern within the hairline is not uniformly distributed across the surface of the head, with the top of the head having the lowest secretion. Smith and Havenith (2011) reported that the sweat rate of the medial head is approximately 70% of the sweat rate of the lateral head.

Several studies have reported the effects of air humidity on sweat rate (Kuno 1956), a relationship between skin moisture and sweat rate (Candas et al. 1979), a variation in sweat rate depending on temperature and humidity (Jung 1994), and a linear relationship between skin temperature and sweat rate (Turrell and Gerking 1945 from Brebner et al. 1958). However, these studies rarely investigate to what extent the sweat rate in humans is directly influenced by air humidity. Berglund and Gonzalez (1977) found that sweating tends to increase following an increase in air humidity. Another study also showed that head sweating rate could be influenced by not only metabolic rate but also air humidity (O’Berien and

Cadarette 2013). On the other hand, Brebner et al. (1958) reported that air humidity below a critical value has a minimal effect on sweat rate, whereas above this critical value, small changes in humidity are associated with large changes in sweating. In other words, the results are not consistent among different studies, and the relationship between humidity and sweating on the head is rarely investigated.

Accordingly, the purpose of this study was to examine sweat distribution and ASGs on the head under different humidity conditions during passive heating. We hypothesized that in different humidities, sweat rates would be higher in a hot-dry environment (30%RH) than a hot-humid environment (85%RH), and sweat rates in the frontal region would be higher than those in the vertex region. Furthermore, if sweat rates and the number of sweat glands are measured simultaneously, we may determine the causes of regional sweat variation with the SGO.

Chapter2. Theoretical Background

2.1 Thermoregulation

Thermoregulation is an important role of homeostasis for human. In thermoregulation, body heat is generated mostly in the deep organs, especially the liver, brain, and heart, and in contraction of skeletal muscles (Guyton and Hall 2006). Humans have been adapted to a large variation of climates, including hot humid and hot dry environment. High temperatures cause grave stresses for the human body. For human, adaptation to varying climatic conditions includes both physiological mechanisms resulting from evolution and behavioral mechanisms resulting from conscious cultural adaptations (Harrison et al. 1988, Weiss and Mann 1985).

In a hot environment, eccrine sweat glands under the skin secrete, which move up using the sweat duct, through the sweat pore and onto the surface of the skin. Because this causes heat loss via evaporative cooling, a lot of essential water could be lost. However, when the environmental temperature is above core body temperature, sweating is the only physiological thermoregulation way for humans to lose heat.

2.2 Sweating and sweat distribution

What role does sweating play in thermoregulation? Evaporative heat loss through sweating is a very efficient way which means for balancing metabolic heat production and heat absorbed from surroundings by radiation and convection. Polk et al. (1995) reported that sweat secretes when the ambient temperature rises above

30-31°C, and/or when internal body temperature rises above 37 °C. Those who are physically fit or used to warm environments, show a better response of the sweating mechanism in response to exercise as sweating begins at a lower internal body temperature. Humans and a few other species sweat.

Sweating, also known as perspiration is the production of fluids secreted by the sweat glands in the skin of mammals (Mosher 1933). In human, sweating is primarily a means of thermoregulation, which is achieved by the water-rich secretion of the eccrine glands. Two types of sweat glands can be found in humans; eccrine glands and apocrine glands. The eccrine sweat glands are distributed over the entire body. It is provoked by variable causes such as high temperature, muscular exercise, sensory stimulations, emotion or mental stress, etc (Kuno, 1956) and it can be classified according to two types, the thermal stimulation and the mental or emotional stimulation. Thermal sweating appears over the whole body surface mostly from eccrine sweat glands and mental or emotional sweating appears conditionally on the palms, soles, and axillae (Kuno, 1956).

There are many studies in which regional distribution of thermal sweating has been measured from various sites. Ikeuchi and Kuno (1927) had reported sweat distribution during resting thermal loading, whereas, sweat distribution during exercising reported by Weiner (1945). Taylor et al. (2006) and Machado-Moreira et al. (20008) studied that although the volar surface of the hands and feet clearly respond to passive heating and have the highest glandular densities, these sites retain the lowest glandular flows during resting thermal stimulation. In compare to the torso sites (chest, back), they have about five times more sweat glands, however sweat gland output from the torso glands is approximately 7-15times greater. In addition, they found that there is a clear difference between the face and torso. The face secretes 4-7 times greater glandular flow relative to the palms and soles, but it has only half the glandular density. The comparison between face and other regions of the body have investigated in many studies; however there are not many studies about a comparison on the overall sweat distribution including hairy sites on the head.

Chapter3. Methods

3.1 Subjects

Eight young males participated in this study (mean ± SD: 23.6 ± 3.0 years in age, 178.2 ± 5.3 cm in height, and 90.1 ± 15.4 kg in weight). The head of all subjects was shaved completely prior to participation, and there were no naturally bald subjects. Subjects were instructed to abstain from alcohol or excessive exercise before their participation. The subjects were informed of the purpose of the study and procedures in advance. A written consent was obtained from all subjects. The Institutional Review Board of Seoul National University (IRB No. 1608/003-023) approved this study.

3.2 Measurements

Rectal temperature (T_{re}) was measured every 5 s using a data logger (LT-8A, Gram Corporation, Japan), which was inserted nearly 16 cm beyond the anal sphincter. Skin temperature (T_{sk}) was measured every 5 s using thermistor probes at seven body regions [the forehead, chest, forearm, hand, thigh, calf, and foot] (Fig. 2.1) and using the data logger at four regions on the left side of the head [the frontal, vertex, temporal, and occipital regions] (Fig. 2.2). Mean skin temperature ($\bar{T}_{sk}$) was calculated by the Hardy and Dubois 7-point formula (Hardy and Dubois 1938):

$$\bar{T}_{sk} = 0.07T_{\mathrm{forehead}} + 0.35T_{\mathrm{trunk}} + 0.14T_{\mathrm{arm}} + 0.05T_{\mathrm{hand}} + 0.19T_{\mathrm{thigh}} + 0.13T_{calf} + 0.07T_{foot} \quad \text{[Eq.3.1]}$$

To estimate the total sweat rate, subjects were weighed on a calibrated scale

(Resolution 1 g; ID2; Mettler-Toledo, Germany) before and after each trial. Local sweat rates were measured by two different methods: the absorption paper and the sweat capsule method. For the paper method, local sweat rates in four regions on the left side of the head (the frontal, vertex, temporal, and occipital regions) were estimated using moisture absorption papers ($2 \times 2\ cm^2$) by weighing the total mass before and after every trial on an electronic scale (AB204; Mettler Toledo, Switzerland). Local sweat rates were continuously measured in the same four regions using perspiration meters with sweat capsules (SKN-2000 Perspiration Meter; SKINOS, Japan). ASGs were measured by the iodine-impregnated paper method at eight regions on the right side of the head (two frontal, two parietal, two temporal, one occipital, and one vertex) using a 100% cotton paper. The cotton paper was cut into $3 \times 3\ cm^2$ pieces and preconditioned in a desiccator with solid iodine for 12 h. The number of ASGs was counted using "Ddamddami software". Skin hydration was measured using a skin hydrometer (MDD 4; Courage$^+$Khazaka Electronic GmbH, Germany). Heart rate was monitored and measured every 5 s using a portable chest belt and a wristwatch (Model RS 400/800; Polar, USA). The following subjective perceptions were recorded at rest and every 15 min after leg immersion: 9-point thermal sensation (4: very hot, 3: hot, 2: warm, 1: slightly warm, 0: neutral, -1: slightly cool, -2: cool, -3: cold, -4: very cold), 7-point thermal comfort (3: very comfortable, 2: comfortable, 1: a little comfortable, 0: neither, -1: a little uncomfortable, -2: uncomfortable, -3: very uncomfortable), 7-point sweat sensation (3: very dry, 2: dry, 1: a little dry, 0: neither, -1: a little wet, -2: wet, -3: very wet), and 7-point thirst sensation (0: not thirsty, 0.5, 1: a little thirsty, 1.5, 2: thirsty, 2.5, 3: very thirsty).

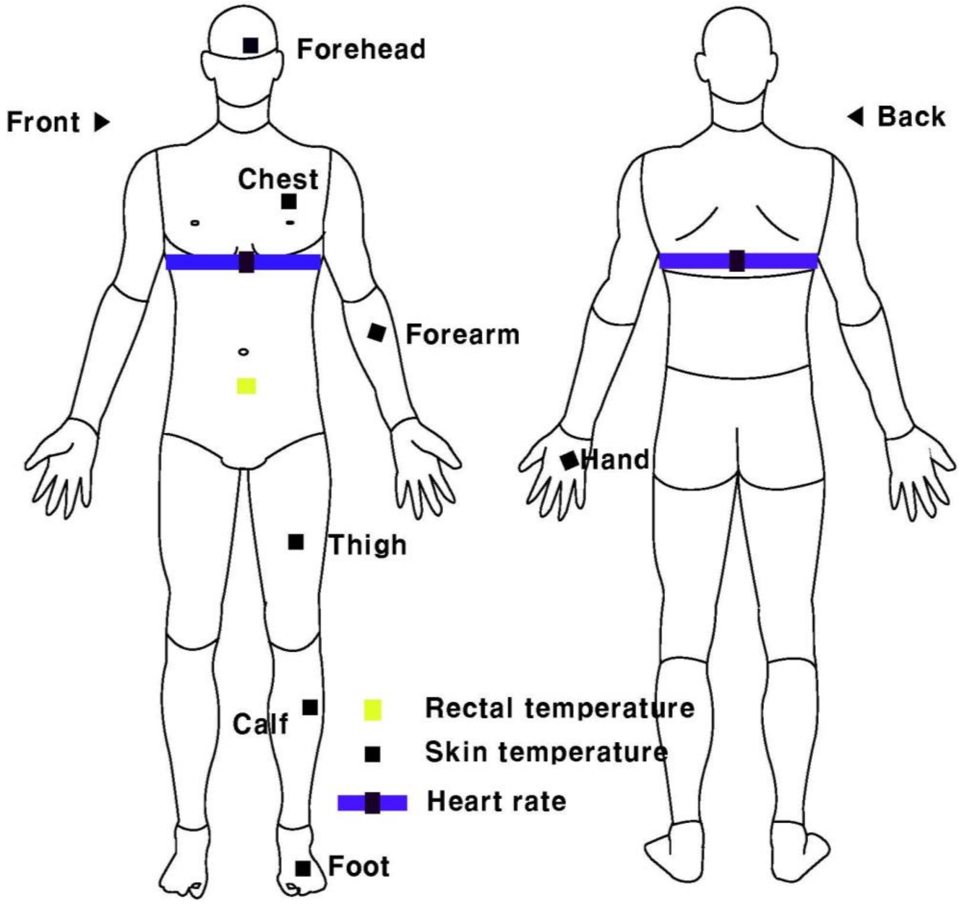


Fig. 3.1. A diagram of measurement in 7 regions of skin temperature (forehead, chest, forearm, hand, thigh, calf, foot), rectal (core) temperature, heart rate were measured at the body sites.

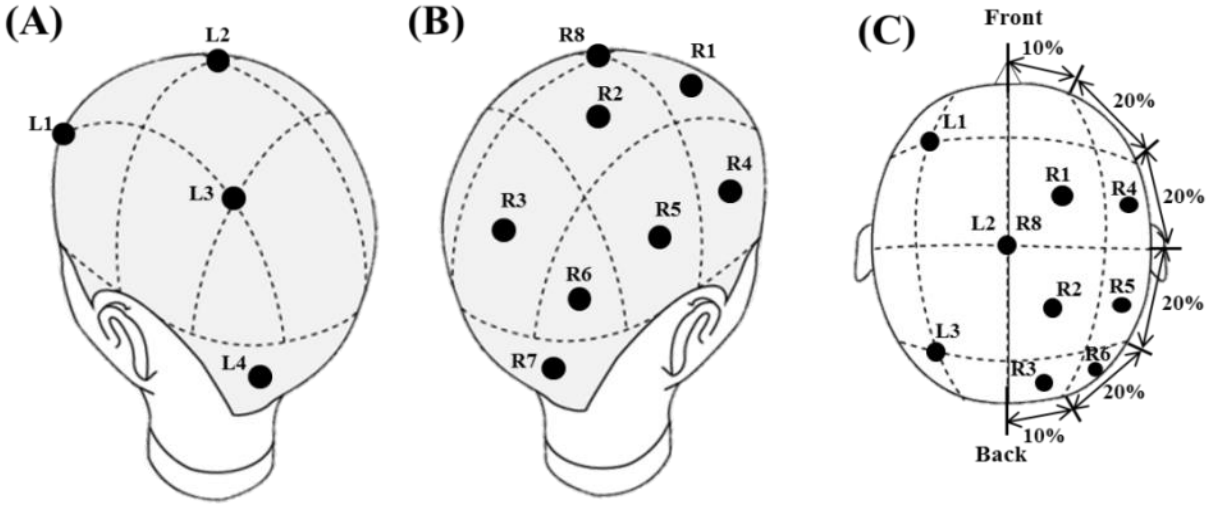
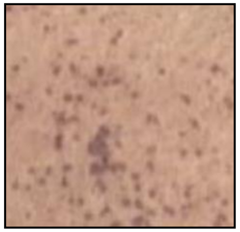
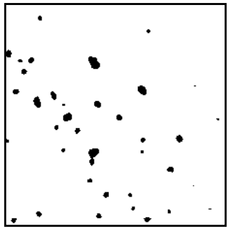
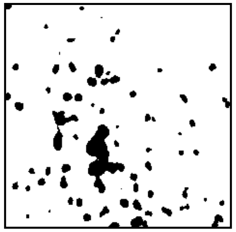
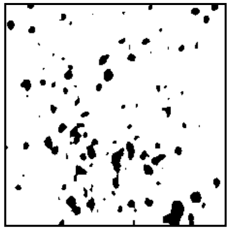


Fig. 3.2. A diagram of measurement regions on the scalp: four regions from L1 to L4 for skin temperature and local sweat rate, eight regions from R1 to R8 for active sweat glands. (A) Left back diagonal view, (B) Right back-diagonal view, and (C) Top view.

Table. 3.1. Time course of an example of active sweat glands on the head by using an idodine-impregnated method

	20min	**40min**	**60min**
Original			
Ddamddami Software			

3.3 Experimental environments and procedures

Environmental conditions were set at 32 ℃ and 30%RH (hot-dry environment, H30%) and at 32 ℃ and 85%RH (hot-humid environment, H85%). The experiments were conducted between July and August in Korea, which was in the middle of summer. When subjects arrived, they took a rest and changed into prepared underpants and short pants in a room with neutral air temperature (T_a of 23–25 ℃). After drinking 300 ml of water to ensure hydration, all experimental sensors were attached to the body of the subjects, and the absorption paper for assessing local sweat rates was set at the four regions of the head (Fig. 3.2A). Measurements were performed three times each pre-trial and post-trial to estimate the total sweat rate. As soon as subjects entered the climate chamber, sweat capsules for assessing local sweat rates were set up at the four regions of the head (Fig. 3.2A). During the leg immersion period, the ASGs in eight regions of the head were measured (Fig. 3.2B). A trial consisted of resting on a chair for 10 min followed by leg immersion in water (42 ℃) for 60 min (Fig. 3.3).

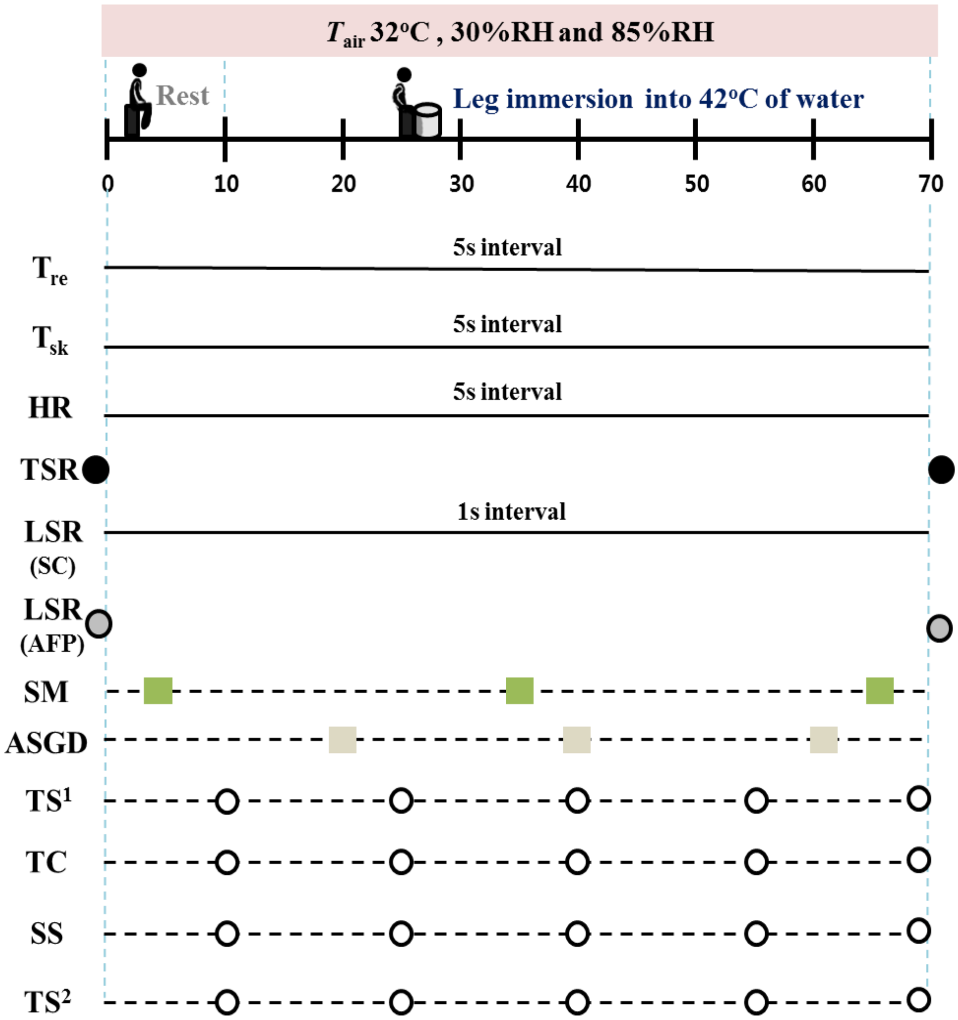


Fig. 3.3. Time course of an experiment and measurements. T_{re}: Rectal temperature, T_{sk}: skin temperature, HR: Heart rate, TSR: Total sweat rate, LSR (SC): Local sweat rate (Sweat capsule method), LSR (AFP): Local sweat rate (Absorption Filter Paper method), SM: Skin moisture, ASGD: Active sweat glands density, TS^1: Thermal sensation, TC: Thermal comfort, SS: Sweat sensation, TS^2: Thirst sensation.

3.4 Data analysis

All data are expressed as the mean ± SD, and chest temperature was considered as a reference for trunk temperature in this study. Statistical analysis was performed by paired t-test to determine significant differences between the H30% and H85% conditions. Repeated measures ANOVA and post-hoc tests were conducted to identify significant differences among the four or eight regions of the head. The significance was set at $P < 0.05$.

Chapter4. Results

4.1 Total sweat rates

Total sweat rates were calculated from the difference of body weight at before and after passive heat exposure. Total sweat rates were significantly greater for the H30% condition (179.4 ± 35.6g·h^{-1}) than the H85% condition (148.1 ± 27.2 g·h^{-1})(P<0.05) (Fig.3.1).

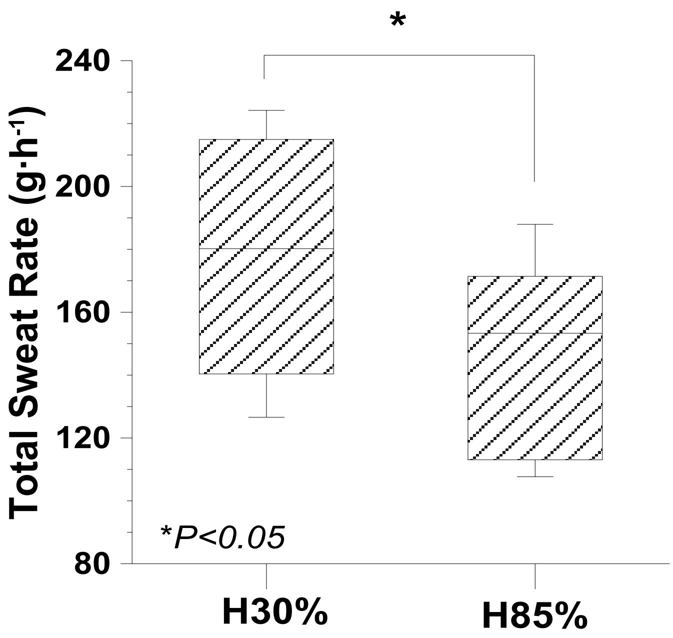


Fig. 4.1. Box-whisker plots of the total sweat rate during leg immersion in water (42 ℃) under dry (H30%) and humid (H85%) conditions at 32 ℃. *P refers to a significant difference between the H30% and H85% conditions at the 0.05 alpha level. Data are expressed as the mean ± SD.

4.2 Local sweat rates

Local sweat rates were measured on the frontal, vertex, temporal, and occipital sites by two different methods using an absorption filter paper (Paper method) and a perspiration meter with sweat capsules (Capsule method).

4.2.1 Local sweat rate: the absorption filter paper method

For the paper method, the total sum of local sweat rates from the four sites was greater under the H85% condition (484.5 ± 249.4 mg) than the H30% condition (420.6 ± 124.3 mg); however, the difference was not statistically significant (Table 4.1). Regional differences among the four sites were statistically significant only under the H30% condition (Table 4.1). The differences between the two conditions were dependent on the head region, with values greater in the frontal than the vertex region ($P < 0.05$).

Table 4.1. Local sweat rates of head regions during leg immersion in water at 42 ℃ using the absorption filter paper method

Unit: mg	Head region (N=7)				Total sum of the head	*P*-value
	Frontal	Vertex	Temporal	Occipital		
H30% (Hot & Dry)	162.3 ± 85.3[b]	61.3 ± 18.1[a]	88.4 ± 34.4[ab]	108.6 ± 69.9[ab]	420.6 ± 124.3	0.041
H85% (Hot & Humid)	158.1 ± 68.8	81.5 ± 38.8	103.5 ± 41.7	141.4 ± 153.7	484.5 ± 249.4	N.S.
P-value	N.S.	N.S.	N.S.	N.S.	N.S	

[a,b,] or [ab] showed significant differences among the four regions based on a post-hoc test at $P < 0.05$. 'N.S.' means 'not significant'. We excluded the local sweat rate of one subject because of unusual values (N = 7). Data are expressed as the mean ± SD. ….

4.2.2 Local sweat rate: the sweat capsule method

For the sweat capsule method, local sweat rates were significantly greater under the H85% condition (1.67 ± 0.55 $mg \cdot cm^{-1} \cdot min^{-1}$ for the last 5 min) than the H30% condition (0.33 ± 0.28 $mg \cdot cm^{-1} \cdot min^{-1}$ for the last 5 min) in the temporal region; however, the other three regions showed no differences between the two conditions (Fig. 4.2, Fig. 4.3). Among the four regions, the frontal region had the highest sweat rates under both the H30% and H85% conditions; however, there was no significant difference (Fig. 4.4).

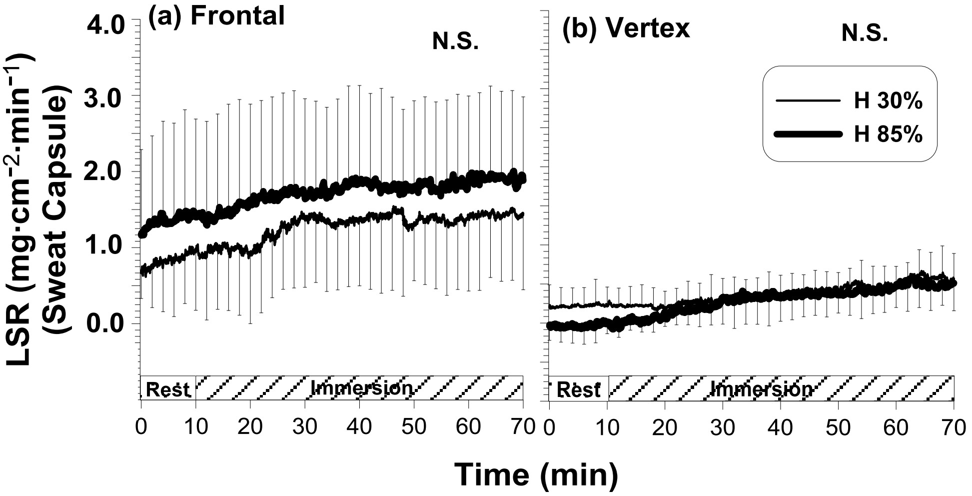


Fig. 4.2. Local sweat rates in the (a) frontal and (b) vertex regions of the head during leg immersion in water (42 ℃) at an air temperature of 32 ℃ in dry and humid environments (the sweat capsule method). **P* refers to a significant difference between the H30% and H85% conditions at the 0.05 alpha level. Data are expressed as the mean ± SD. 'N.S.' means 'not significant'.

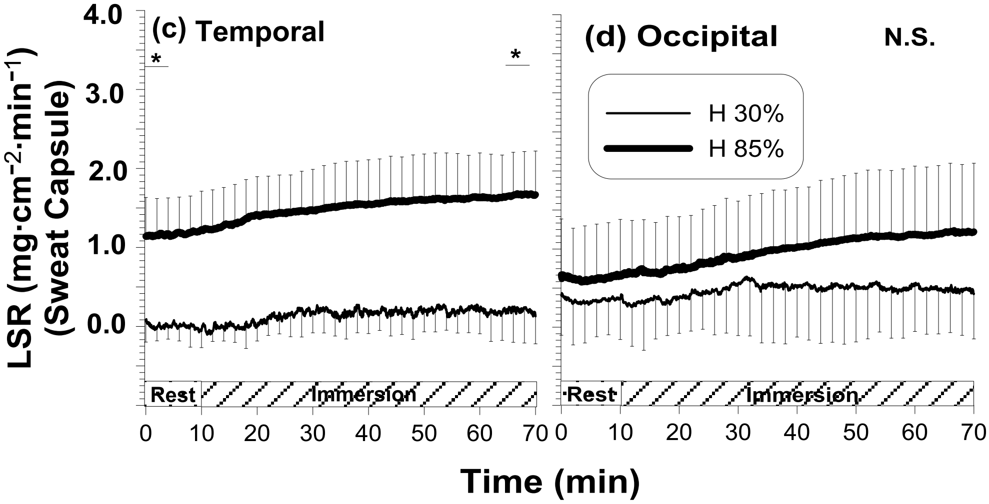


Fig. 4.3. Local sweat rates in the (c) temporal and (d) occipital regions of the head during leg immersion in water (42 ℃) at an air temperature of 32 ℃ in dry and humid environments (the sweat capsule method). **P* refers to a significant difference between the H30% and H85% conditions at the 0.05 alpha level. Data are expressed as the mean ± SD. 'N.S.' means 'not significant'.

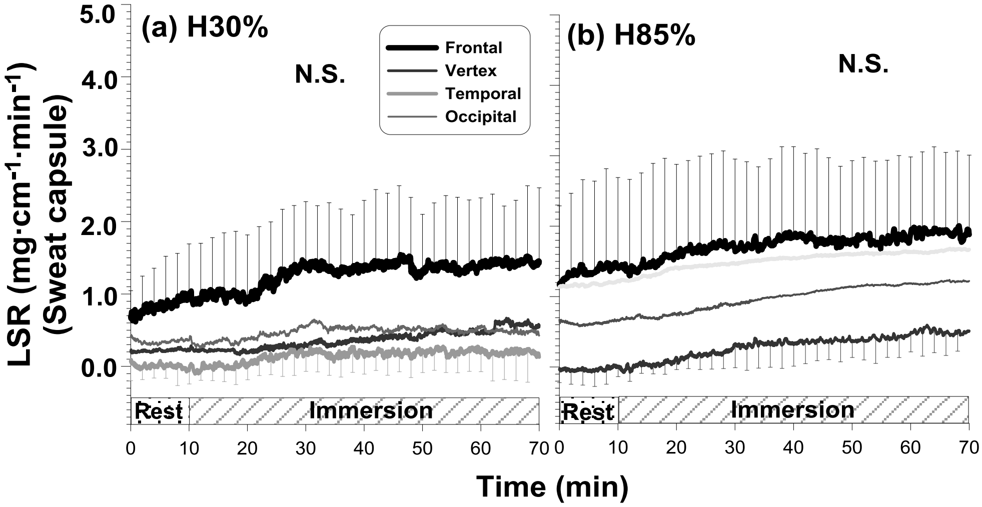


Fig. 4.4. Local sweat rates of the head during leg immersion in water (42 ℃) at an air temperature of 32 ℃ under the (a) H30% (dry) condition and (b) H85% (humid) condition (the sweat capsule method). Data are expressed as the mean ± SD. 'N.S.' means 'not significant'.

4.3 Head skin temperature

Skin temperatures in the frontal, temporal, and occipital regions were significantly higher under the H80% condition than the H30% condition ($P < 0.05$); however, the vertex showed no differences between the two conditions (Fig. 4.5). The change in vertex skin temperature was the smallest among the four head regions, which was only 0.2 ℃ in the vertex region. On the other hand, temperature changes ranged from 0.4~0.6 ℃ in the frontal, temporal, and occipital regions.

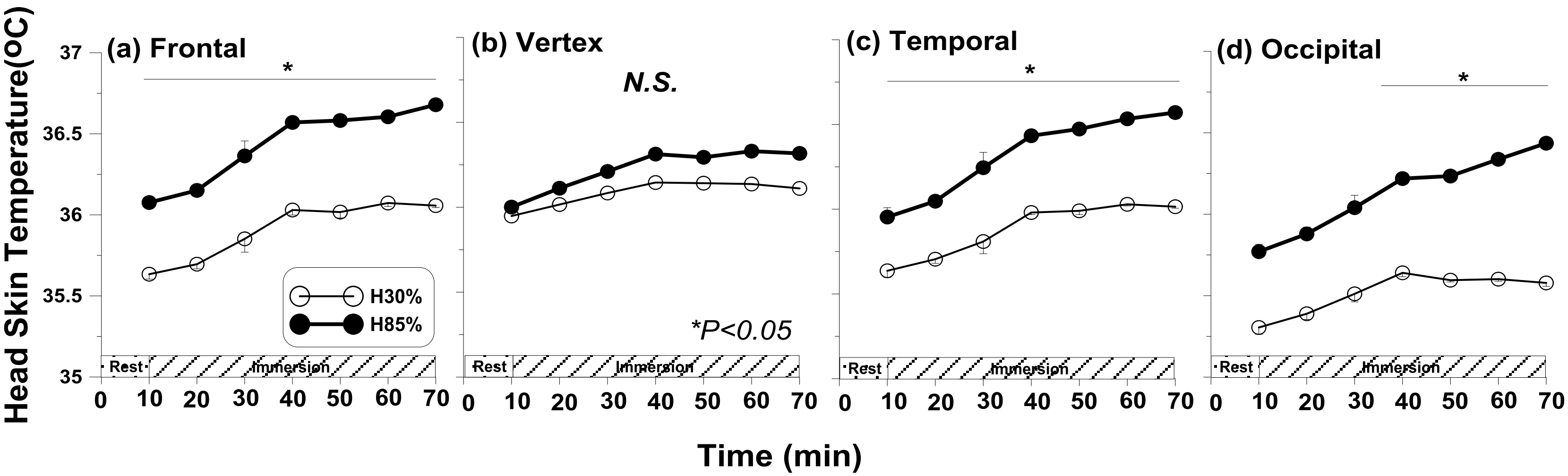


Fig. 4.5. Time course of skin temperature in the four head regions [(A) frontal, (B) vertex, (C) temporal, and (D) occipital]. **P* refers to a significant difference between H30% and H85% conditions at the 0.05 alpha level. Data are expressed as the mean ± SD. 'N.S.' means 'not significant'.

4.4 Active sweat glands (ASGs)

The numbers of ASGs, which were averaged from the eight regions, were significantly greater under the H85% condition (82 ± 13 spots·cm^{-2}) than the H30% condition (62 ± 17 spots·cm^{-2}) at the last stage of immersion (60th min) (P < 0.01) (Fig. 4.6). Regarding regional differences between the four regions, the occipital region had the greatest number of ASGs (88 ± 50 spots·cm^{-2} under the H30% condition and 104 ± 38 spots·cm^{-2} under the H85% condition), whereas the vertex region had the lowest number of ASGs (39 ± 25 spots·cm^{-2} under the H30% condition and 68 ± 23 spots·cm^{-2} under the H85% condition) (Table 4.2). However, regional differences were not significantly different.

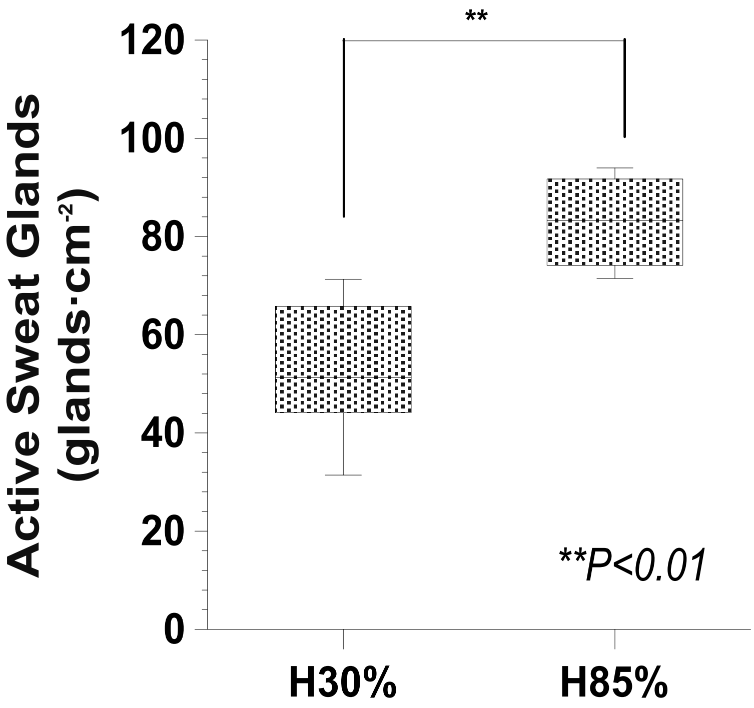


Fig. 4.6. The number of active sweat glands on the head during leg immersion in water (42 ℃) in a hot-dry environment (H30%) and hot-humid environment (H85%). **P* refers to a significant difference between the H30% and H85% conditions at the 0.01 alpha level. Data are expressed as the mean ± SD. ‘N.S.’ means ‘not significant’.

Table 4.2. The number of active sweat glands in eight regions on the right side of the head during leg immersion in water at 42 ℃ (glands·cm^{-2})

	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**Average**	**Total sum**	***P*-value**
H30% **(Hot & Dry)**	63 ± 35	39 ± 25	53 ± 27	81 ± 33	51 ± 13	68 ± 31	88 ± 50	52 ± 35	62 ± 17	494	N.S.
H85% **(Hot & Humid)**	81 ± 31	68 ± 23	90 ± 28	93 ± 34	76 ± 25	66 ± 17	104 ± 38	82 ± 37	82 ± 13	659	N.S.
***P*-value**									P = 0.002		

*Data were expressed as Mean ± SD. 'N.S.' means 'Not significant'.

4.5 Rectal temperature (T_{re}) and Mean skin temperature ($\bar{T}_{sk}$)

Rectal temperature was not significantly different between the two humidity conditions; however, the increase in temperature was greater under the H85% condition than the H30% condition (Fig. 4.7A). The increase in rectal temperature under the H85% and H30% conditions was around 0.34 ℃ and 0.22 ℃, respectively. Mean skin temperature was much higher under the H85% condition (36.0 ± 0.3 ℃) than the H30% condition (34.8 ± 0.7 ℃) during last 5 min of leg immersion (P < 0.05) (Fig. 4.7B).

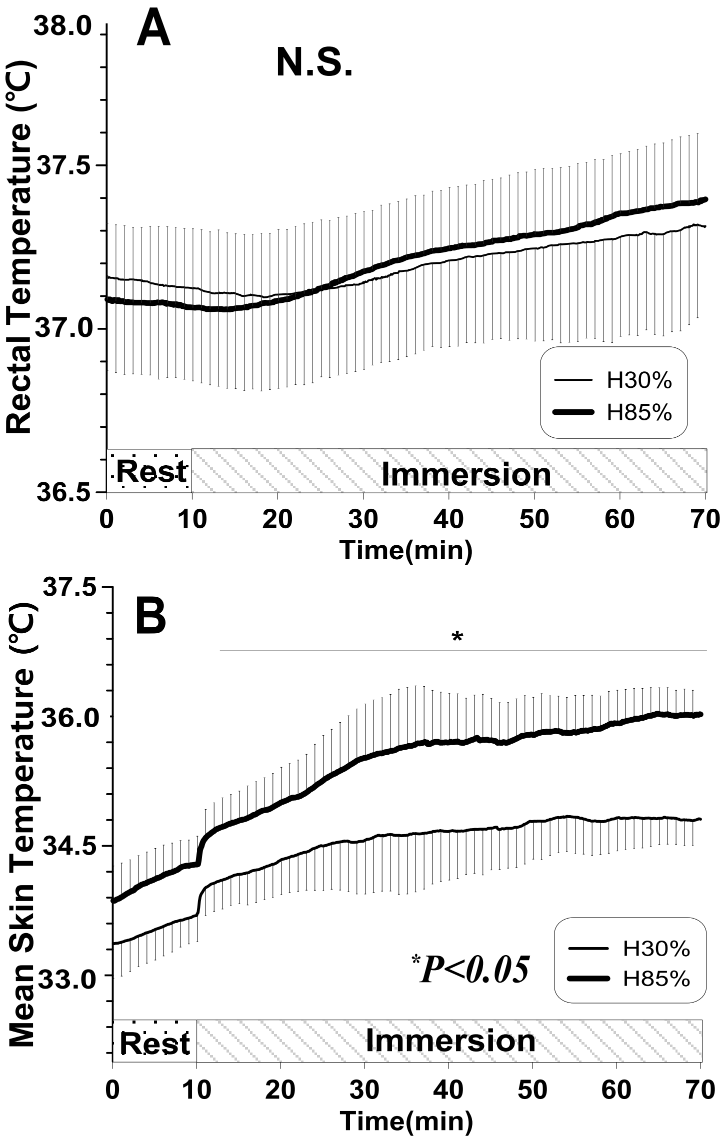


Fig. 4.7. Time course of (A) rectal temperature and (B) mean skin temperature during leg immersion in water (42 ℃) in a hot-dry environment (32 ℃ and 30%RH; H30%) and hot-humid environment (32 ℃ and 85%RH; H85%). **P* refers to a significant difference between the H30% and H85% conditions. 'N.S.' means 'not significant'. Data are expressed as the mean ± SD.

4.6 Heart rate (HR)

Heart rate at rest was 78.4 ± 8.7 and 78.9 ± 7.3 bpm under the H30% and H85% conditions, respectively, with no statistical difference. Although the heart rate was slightly increased after leg immersion, no significant differences were found between the two humidity conditions at the last stage of the 60-min immersion (85.9 ± 8.8 bpm under the H30% condition vs. 93.2 ± 7.6 bpm under the H85% condition) (Table 4.3).

Table 4.3. Heart rate under the H30% and H85% conditions at rest and after immersion in water at 42 ℃

		After immersion in water (42°C)		
	Rest	**10min**	**30min**	**50min**
H30%	78.4 ± 8.7	77.3 ± 8.0	83.9 ± 7.7	85.9 ± 8.8
H85%	78.9±7.3	77.5±6.7	84.7±7.7	93.2±7.6
P-value	N.S.	N.S.	N.S.	N.S.

4.7 Hydration of skin on the head

Skin hydration between the four regions of the head was significantly different at rest ($P < 0.05$). However, there was no difference after leg immersion in water at 42 ℃, and there was no significant difference between the H30% and H85% conditions during leg immersion because values increased rapidly up to the maximum levels under both conditions.

4.8 Subjective perception

Subjects felt hotter at the end of the rest period and after leg immersion for 60 min in the hot-humid environment. During leg immersion, subjects felt more thermally uncomfortable in the hot-humid environment than the hot-dry environment and had increased sweating over the whole body under the H85% condition compared with the H30% condition ($P < 0.05$). On the other hand, thirst sensation was not different between the two conditions (Fig. 4.8, Fig. 4.9).

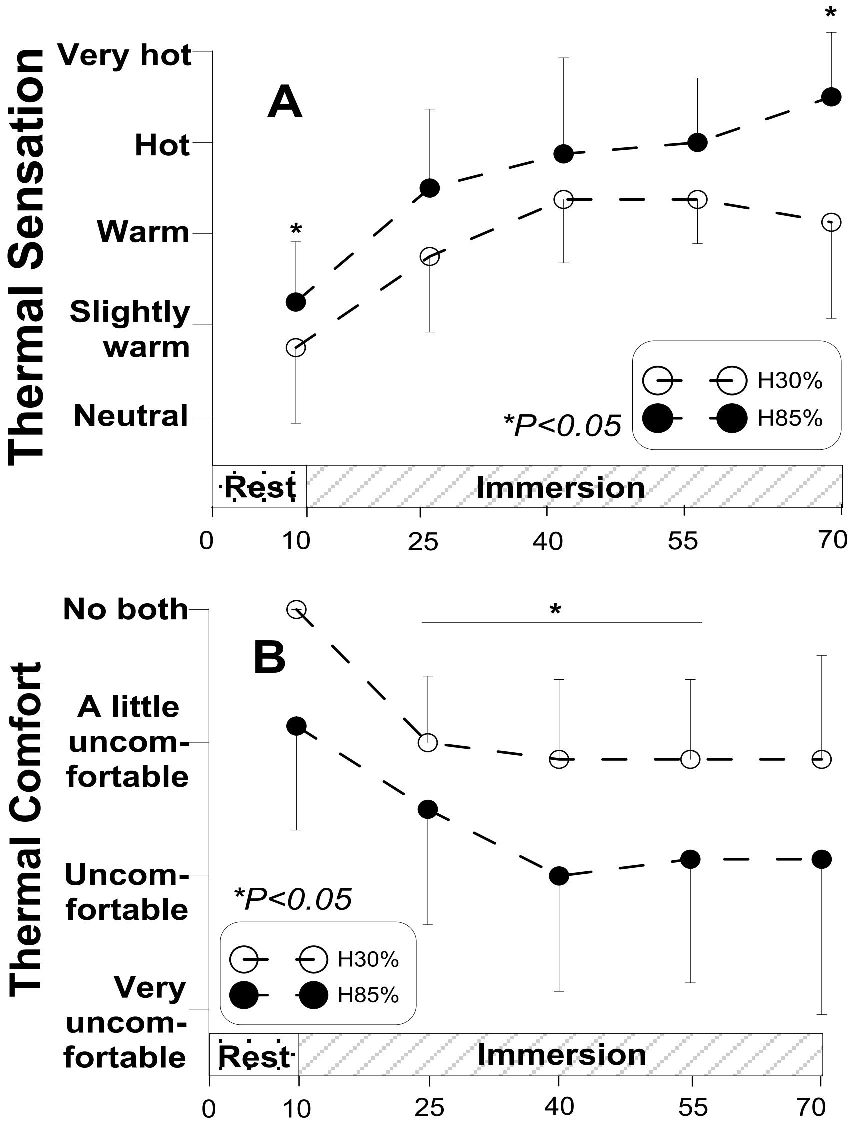


Fig. 4.8. Time course of overall (A) thermal sensation and (B) thermal comfort during leg immersion in water (42 ℃) at an air temperature of 32 ℃. **P* refers to a significant difference between the H30% and H85% conditions. 'N.S.' means 'not significant'. Data are expressed as the mean ± SD.

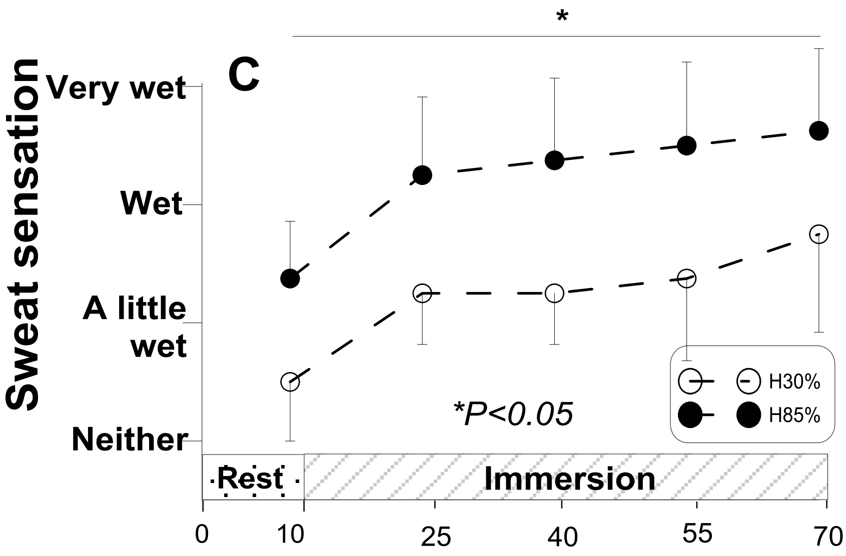


Fig. 4.9. Time course of overall (C) sweat sensation and (D) thirst sensation during leg immersion in water (42 ℃) at an air temperature of 32 ℃. **P* refers to a significant difference between the H30% and H85% conditions. 'N.S.' means 'not significant'. Data are expressed as the mean ± SD.

Table 4.4 Summary of the results in the study

Measurement items		**H30%**		**H85%**	***p-values***
Rectal temperature (℃)		Δ 0.22	≒	Δ 0.34	N.S.
Mean skin temperature, $_{last}$[a] (℃)		34.8	<	36.0	< 0.05
Head skin temperature, $_{last}$ (℃)	: Frontal	36.1	<	36.7	< 0.05
	: Vertex	36.1	≒	36.3	N.S
	: Temporal	36.0	<	36.6	< 0.05
	: Occipital	35.6	<	36.4	< 0.05
Total sweat rate ($g \cdot h^{-1}$)		179.4	>	148.1	< 0.05
LSR[b] on the head (paper method), $_{last}$ (mg)		420.6	≒	484.5	N.S
LSR (capsule method), $_{last}$ ($mg \cdot cm^{-2} \cdot min^{-1}$)	: Frontal	1.44	≒	1.90	N.S.
	: Vertex	0.57	≒	0.48	N.S.
	: Temporal	0.33	<	1.67	< 0.05
	: Occipital	0.55	≒	1.22	N.S.
Active sweat glands on the head, $_{last}$ ($glands \cdot cm^{-2}$)		62	<	82	< 0.05
Heart rate, $_{last}$ (bpm)		85.9	≒	93.2	N.S.
Overall thermal sensation, $_{last}$		Warm	<	Hot ~ very hot	< 0.05

Overall thermal comfort, $_{last}$	A little Uncomfortable	<	Uncomfortable	< 0.05
Overall sweat sensation, $_{last}$	A little wet ~ wet	<	Wet ~ very wet	< 0.05
Thirst sensation, $_{last}$	A little thirsty	≒	A little thirsty	N.S.

[a]'last' means the last 5 min or last stage of the measurement during leg immersion; [b]LSR: Local sweat rate.

Chapter5. Discussion

In the current study, sweat distribution on the entire non-glabrous skin surfaces of the scalp was measured during passive heating in a hot-dry environment (H30%) and hot-humid environment (H85%). To the best of our knowledge, the relationship between sweat rate and the effects of humidity on the head is rarely reported.

We made three important observations in our study. First, the total sweat rate was significantly higher in a hot-dry environment (H30%) than a hot-humid environment (H85%). Second, contrary to our expectation, the local sweat rates of the head in a hot-humid environment (H85%) were not significantly different from those in a hot-dry environment (H30%). Third, the frontal region (hairline area) secreted a large amount sweat, whereas the vertex region (the top of the head) secreted the least amount of sweat.

5.1 Effects of air humidity on the body

The total sweat rate was greater under the H30% condition than the H85% condition ($P < 0.05$). This difference in the total sweat rate may be attributed to the low humidity under the H30% condition that induces more sweat, and the increased sweat rate affects the skin surface by evaporative heat loss. Because of evaporative heat loss, the increase in mean skin temperature under the H30% condition was much lower than that under the H85% condition. Moreover, the difference in the total sweat rate between the H30% and H85% conditions was 31 $g \cdot h^{-1}$, which was not enough to cause a significant change in rectal temperature.

Considering that the whole-body water loss of an individual with a surface area of 1.8 m^2 ranges between 26~43 $g \cdot h^{-1}$ in the normal environment (Taylor and Machado-Moreira 2013), the difference observed in the hot environment is considered to be small.

5.2 Effects of air humidity on the head

The local sweat rate under the H85% condition appeared to be greater than that under the H30% condition; however, the difference was not significant. Jung (1994) and Nadel et al. (1970) reported that sweat rate can be affected by local skin temperature; accordingly, the pattern of body sweat rate corresponded to that in previous studies. On the other hand, the pattern of head sweat rate was different. If a higher skin temperature induces sweat, the sweat rate under the H85% condition should be higher than that under the H30% condition because the head skin temperature under the H85% condition was higher than that under the H30% condition ($P < 0.05$, except for the vertex) in this study. However, given that the local sweat rate of the head under the H85% condition was similar to that under the H30% condition, the sweat pattern of the head was different from that of the whole body. Furthermore, the number of ASGs on the head under the H85% condition was significantly greater than that under the H30% condition ($P < 0.01$). Despite the higher skin temperature and higher number of ASGs, the sweat rate of the head under the H85% condition was not significantly different compared with that under the H30% condition.

Several possibilities may explain the different sweat distribution pattern of the head. A few studies reported that the decline or suppression of sweating could be attributed to a nervous disorder (Wolkin, Goodman and Kelly 1944; Kuno 1956), glandular fatigue (Hancock, White house and Haldane 1930), excessive skin hydration of the sweat ducts (Collins and Weiner 1962), hydration of the keratin ring around the sweat gland (Peiss, Randall and Hertzman 1956), depressed irritability of receptors due to dilution of the chemical environment around the receptors (Hertig 1960) (from Peter and Wyndham 1966), or hidromeiotic suppression of sweating (Candas et al. 1980; Machado-Moreira et al. 2008b). Among these possibilities, hidromeiotic suppression of sweating (Candas et al. 1980) might be associated with the results of the present study because there was an increase in the number of ASGs and skin temperature.

Results such as skin temperature, local sweat rate, and the number of ASGs on the head should be considered to determine whether there was an absence or insufficient levels of evaporative heat loss around the sweat glands on the head in a hot-humid environment (H85%).

5.3 Why does the vertex region have the lowest sweat response?

In the present study, the sweat rates between regions of the head were not significantly different in different humidity conditions; however, we found a significant difference between the intra-regional sites of the head under the H30% condition. The sweat rate in the frontal region (162 ± 85.3 mg) was greater than that in the vertex region (61.3 ± 18.1 mg) under the H30% condition ($P < 0.05$). Under the H85% condition, the sweat rate was similar to that under the H30% condition with no significant differences. These results correspond to a previous study in which the vertex was found to secrete the least amount of sweat (Machado-Moreira et al. 2008b; Cabanac and Brinnel 1988). To elucidate the differences in sweating between different regions of the head, we could examine the relationship between skin temperature, thermal sensitivity, and sudomotor sensitivity.

When ambient conditions change, the skin thermoreceptors provide the first thermoregulatory input, giving rise to thermal sensations (Hammel 1968), and these thermal sensations lead to changes in the skin temperature. Local skin temperature changes may independently modify sudomotor and vasomotor responses (Bothorel et al. 1991; Nadel et al. 1971; Taylor et al. 1984). Moreover, sweat rate could be influenced by differences in sudomotor functions (Saad et al. 2001), and sweat could be secreted in proportion to the size and neuroglandular sensitivity of each gland (Sato et al. 1983, 1990). Similar to the current study, Machado-Moreira et al. (2008b) also found that the top of the head (the vertex) has reduced sudomotor sensitivity. In addition, Kim et al. (2017) reported that the vertex of the head is the most insensitive region to detect an increase in temperature. Our study found that the vertex showed the least change in skin temperature and ASGs, as well as the lowest sweat rate, when compared with other regions. We assume that the minimal change in skin temperature of the vertex could be associated with lower warmth and sudomotor sensitivity as well as the reduced development of ASGs. Therefore, the local sweat rate of the vertex could be the lowest compared with that of other regions of the head.

Nevertheless, why did the vertex have the lowest sweat response and why was it the most insensitive region among the other regions of the head? According to

Aisenson (1950), the top of the head is embryologically completed around the age of 2.5~3 in the process of human development. Furthermore, Kuno (1956) indicated that the total number of ASGs remains unchanged after the age of 2.5 years; nevertheless, the distribution of the glands in different regions over the body surface is variable between adults and children. In this regard, it is thought that because of the late completion of the head in the infantile stage, nerve distribution and blood vessels might be relatively less developed than those of other parts of the body. In addition, if other parts of the head secrete enough sweat to control body temperature effectively, the vertex may not have to sweat as much as other regions of the head such as the forehead or near the hairline area.

Chapter6. Limitations

In this study, the measured sweat responses in regions on the left side of the head and ASGs on the right side of the head were not exactly similar because the local sweat rate was measured using the sweat capsule and absorption filter paper only in four regions and the ASGs were measured in eight regions. However, the sweat pattern was consistent between the two measurements. The shape of the head is generally spherical. Therefore, although the amount of sweating in the frontal and occipital region is relatively large, there is no clear difference when comparing with the top part of the head (the vertex) because of the downflow of sweat in a hot-humid environment.

To apply the findings of this study to develop headgears, not only passive heating but also active heating should be considered because the wearer of a headgear usually generates some heat during work, sports, or general outdoor activities.

Chapter7. Conclusion

There are limited studies on the relationship between air humidity and head sweating, and there is little data on ASG distribution on the hairy sites of the head. In the present study, local sweat rates and ASGs in the eight regions of the head including the scalp were measured. The results revealed that head sweat rates and ASGs were increased by increasing air humidity, whereas total sweat rates in the humid environment were lower than those in the dry environment. Regarding regional differences, the vertex had the lowest sweat rate and lowest number of ASGs, whereas the frontal region, located near the boundary within the non-hairy site, had a greater sweat rate. Therefore, the sweat distribution pattern of the head can be considered different from that of the body. In particular, the vertex secreted the least amount of sweat and was insensitive toward changes in temperature. This study provides baseline data on head sweating and contributes to the development of advanced headgears. To improve the thermal comfort of headgears, they should be designed by adding a vent hole to the front and back for ventilation, and the top of headgears should be made of breathable material with enhanced durability.

Bibliography

Aisenson MR (1950) Closing of the anterior fontanelle. Pediatrics, 6(2): 223-226.

Berglund LG, Gonzalez RR (1977) Evaporation of sweat from sedentary man in humid environments. J Appl Physiol, 42: 767-772.

Brebner DF, Kerslake DM, Waddell JL (1958) The effect of atmospheric humidity on the skin temperatures and sweat rates of resting men at two ambient temperatures. J Physiol, 144: 299-306.

Bothorel B, Galeou M, Dewasmes G, Hoeft A, Candas V (1991) Leg skin temperature and thigh sweat output: possible central influence of local thermal inputs. Eur J Appl Physiol Occup Physiol, 62: 405-409.

Candas V, Libert JP, Vogt JJ (1980) Effect of hidromeiosis on sweat drippage during acclimation to humid heat. Eur J Appl Physiol Occup Physiol, 44: 123-133.

Collins KJ, Weiner JS (1962) Observations on arm-bag suppression of sweating and its relationship to thermal sweat-gland ‘fatigue’. J Physiol, 161: 538-556.

Cotter JD, Patterson MJ, Taylor NA (1995) The topography of eccrine sweating in humans during exercise. Eur J Appl Physiol Occup Physiol, 71(6): 549-554.

Filingeri D, Havenith G (2015) Human skin wetness perception: psychophysical and neurophysiological bases. Temperature, 2: 86-104.

Guyton AC, Hall JE (2006) Textbook of Medical Physiology (11th ed). Philadelphia: Elsevier Saunders. p. 890.

Hammel HT, Pierce JB (1968) Regulation of internal body temperature. Annual review of physiology, 30: 641-710.

Hertig BA (1960) Effects of immersion in water on thermal sweating (Doctoral dissertation, University of Pittsburgh).

Hirosawa TI, Dodo H, Hosokawa M, Watanabe S, Nishiyama K, Fukuchi Y (1984) Physiological Variations of Warm and Cool Sense with Shift of Environmental. Inter J Neur, 24: 281-288.

Havenith G, Fogarty A, Bartlett R, Smith CJ, Ventenat V (2008) Male and female upper body sweat distribution during running measured with technical absorbents. Eur J Appl Physiol 104: 245-255.

Harrison GA, Tanner JM, Pilbeam DR, Baker PT (1988) Human Biology: An introduction to human evolution, variation, growth, and adaptability. (3rd ed), Oxford: Oxford University Press.

Hardy JD, DuBois EF (1938) The technic of measuring radiation and convection. J Nutr, 15: 461-475.

Hertzman AB, Randall WC, Peiss CN, Seckendorf R (1952) Regional rates of evaporation from the skin at various environmental temperatures. Journal of applied physiology, 5: 153-161.

Inoue Y, Shibasaki M (1996) Regional differences in age-related decrements of the cutaneous vascular and sweating responses to passive heating. Eur J Appl Physiol Occup Physiol, 74: 78-84.

Ikeuchi K, Kuno Y (1927) On the regional differences of the perspiration on the surface of the human body. J Orient Med, 7: 106-107.

Jung Deog-Jo (1994) The difference of the sweat rate and skin temperature according to environments during submaximal exercise. J. Kor. Soc. Tan-Therm. Environ. Sys 1: 49-54.

Kenshalo DR, Holmes CE, Wood PB (1968) Warm and cool thresholds as a function of rate of stimulus temperature change. Attention, Perception, & Psychophysics, 3: 81-84.

Kondo N, Shibasaki M, Aoki K, Koga S, Inoue Y, Crandall CG (2001) Function of human eccrine sweat glands during dynamic exercise and passive heat stress. J Appl Physiol, 90(5): 1877-1881.

Kuno Y (1956) Human perspiration. Thomas.

Kerslake DM (1955) Factors concerned in the regulation of sweat production in man. The Journal of physiology, 127(2): 280-296.

Li GL, Li LP, Cai QE (2008) Motorcycle helmet use in Southern China: An observational study. Traffic injury prevention, 9(2): 125-128.

Liu X, Holmér I (1995) Evaporative heat transfer characteristics of industrial safety helmets. Appl Ergon, 26(2): 135-140.

Mosher HH (1933) Simultaneous Study of Constituents of Urine and Perspiration" (PDF). J Biol Chem, 99 (3): 781–790.

Moyen NE, Ellis CL, Ciccone AB, Thurston TS, Cochrane KC, Brown LE, ... , Judelson DA (2014) Increasing relative humidity impacts low-intensity exercise in the heat. Aviation, space, and environmental medicine, 85(2): 112-119.

Machado-Moreira CA, Smith FM, van den Heuvel AM, Mekjavic IB, Taylor NA (2008a) Sweat secretion from the torso during passively-induced and exercise-related hyperthermia. Eur J Appl Physiol, 104(2): 265-270.

Machado-Moreira CA, Caldwell JN, Mekjavic IB, Taylor NA (2008) Sweat secretion from palmar and dorsal surfaces of the hands during passive and active heating. Aviation, space, and environmental medicine, 79(11): 1034-1040.

Machado-Moreira CA, Wilmink F, Meijer A., Mekjavic IB, Taylor NA (2008b) Local differences in sweat secretion from the head during rest and exercise in the heat. Eur J Appl Physiol, 104(2): 257-264.

Nadel ER, Bullard RW, Stolwijk JA (1971) Importance of skin temperature in the regulation of sweating. J Appl Physiol, 31(1): 80-87.

O'Brien C, Cadarette BS (2013) Quantification of head sweating during rest and exercise in the heat. Eur J Appl Physiol, 113: 735-741.

Patel R, Mohan D (1993) An improved motorcycle helmet design for tropical climates. Appl Ergon, 24(6): 427-431.

Patterson MJ, Galloway SD, Nimmo MA (2000) Variations in regional sweat composition in normal human males. Experim Physiol, 85: 869-875.

Peiss CN, Randall WC, Hertzman AB (1956) Hydration of the skin and its effect on sweating and evaporative water loss. J Invest Derm, 26(6): 459-470.

Peter J, Wyndham CH (1966) Activity of the human eccrine sweat gland during exercise in a hot humid environment before and after acclimatization. J physiol, 187(3): 583-594.

Postow E, Polk C (1996) Handbook of biological effects of electromagnetic fields. Boca Raton: CRC Press.

Saad AR, Stephens DP, Bennett LAT, Charkoudian N, Kosiba WA, Johnson JM (2001) Influence of isometric exercise on blood flow and sweating in globrous and nonglabrous human skin. J Appl Physiol, 91(6): 2487-2492.

Skalkidou A, Petridou E, Papadopoulos FC, Dessypris N, Trichopoulos D (1999) Factors affecting motorcycle helmet use in the population of Greater Athens, Greece. Injury prevention, 5(4): 264-267.

Sato F, Owen M, Matthes R, Sato K, Gisolfi CV (1990) Functional and morphological changes in the eccrine sweat gland with heat acclimation. Journal of Applied Physiology, 69(1): 232-236.

Sato K, Sato F (1983) Individual variations in structure and function of human eccrine sweat gland. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 245(2): R203-R208.

Smith CJ, Ventenat V, Havenith G (2007) Regional sweat rates of the arms and hands in male squash players. Environmental Ergonomics XII, p. 285.

Taylor NA, Caidwell JN, Mekjavic IB (2006) The sweating foot: local differences in sweat secretion during exercise-induced hyperthermia. Aviation, space, and environmental medicine, 77(10): 1020-1027.

Taylor WF, Johnson JM, O'Leary DS, Park MK (1984) Modification of the cutaneous vascular response to exercise by local skin temperature. J Appl Physiol, 57(6): 1878-1884.

Taylor NA, Machado-Moreira CA (2013) Regional variations in transepidermal water loss, eccrine sweat gland density, sweat secretion rates and electrolyte composition in resting and exercising humans. Extreme physiology & medicine, 2(1): 4.

Weiner JS (1945) The regional distribution of sweating. J Physiol, 104: 32-40.

Weiss ML, Mann AE (1985) Human Biology and Behaviour: An anthropological perspective. (4th ed). Boston: Little Brown.

Wolkin J, Goodman JI, Kelley WE (1944) Failure of the Sweat Mechanism in the Desert: Thermogenic Anhidrosis. Journal of the American Medical Association, 124(8): 478-482.

초 록

본 연구는 더운 여름철 머리보호구 착용자들에게 서열부담과 불쾌감을 유발하는 헬멧 및 두건의 디자인을 개선하기 위해 고온저습(32℃, 30%RH)과 고온다습(32℃, 85%RH) 환경에서 발생되는 머리부위의 땀 분포 특성과 활성땀샘의 분포를 파악하고자 하였으며, 20대 젊은 남성의 하지 온욕을 통해 본 실험은 진행되었다. 수동적으로 가해진 온열 환경에서 머리부위 발한량은 다른 두 습도 조건에서 유의한 차이는 보이지 않았으나, 고온다습 환경에서 고온저습 환경보다 더 많은 경향을 보였다. 머리 부위별 발한량은 헤어라인 부근의 발한량이 정수리 부근의 발한량보다 월등히 많음을 보였으며(P<0.05), 이는 선생연구와 일치하는 결과를 보였다. 두 습도 조건 간 국소 발한량의 유의한 차이는 보이지 않은 반면, 정수리의 피부온도를 제외한 다른 부위는 고온다습 환경에서 유의하게 높은 피부온도를 보였다(P<0.05). 두 환경조건에서 모두 헤어라인 부근보다 정수리 부근의 발한량과 피부온도 변화량이 가장 적음을 확인하였다. 이는 정수리 부근의 피부 온열 민감도 낮음과 함께, 이 부분의 혈관 및 신경 분포가 엉성하다는 선행연구에 따라 두정은 상대적으로 환경의 영향을 덜 받고, 이로 인해 피부온도 변화가 적으며, 체온조절의 한 메커니즘인 발한도 적게 일어난다는 점에 주목할 만 하다.

따라서 머리보호구 디자인 시 환경 변화에 둔감한 정수리 부분은 통기성이 있는 소재를 사용하되 일차적인 목표인 보호를 위해 강화된 내구성 소재를 배치하고, 이마와 더불어 상대적으로 정수리보다 많은 발한량을 보였던 헤어라인(전두, 측두, 후두 모두)에는 땀 흡수를 효과적으로 할 수 있는 소재를 사용하며, 전면과 후면에 환기구멍을 뚫는 등의 디자인 개선에 본 연구를 적용할 수 있을 것으로 사료된다.

주요어: 국소발한량, 발한 분포, 땀, 총발한량, 능동땀샘
학　번: 2015-23101