

# Does the hair influence heat extraction from the head during head cooling under heat stress?

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**Abstract:** The purpose of this study was to investigate the effects of head hair on thermoregulatory responses when cooling the head under heat stress. Eight young males participated in six experimental conditions: normal hair (100–130 mm length) and cropped hair (5 mm length) with three water inlet temperatures of 10, 15, and 20°C. The head and neck of subjects were cooled by a liquid perfused hood while immersing legs at 42°C water for 60 min in a sitting position at the air temperature of 28°C with 30% RH. The results showed that heat removal from the normal hair condition was not significantly different from the cropped hair condition. Rectal and mean skin temperatures, and sweat rate showed no significant differences between the normal and cropped hair conditions. Heat extraction from the head was significantly greater in 10°C than in 15 or 20°C cooling ( $p < 0.05$ ) for both normal and cropped hair, whereas subjects preferred the 15°C more than the 10 or 20°C cooling regimen. These results indicate that the selection of effective cooling temperature is more crucial than the length of workers' hair during head cooling under heat stress, and such selection should be under the consideration of subjective perceptions with physiological responses.

**Key words:** Head hair, Cooling regimen, Heat strain, Liquid cooling garment (LCG), Subjective perception

## Introduction

Body cooling by liquid perfused garments has shown to reduce heat strain and improve thermal comfort of workers in heat or while wearing encapsulated protective clothing<sup>1,2</sup>. For example, there have been studies on the combination of body parts which improve cooling effectiveness<sup>3,4</sup>, the improvement of skin cooling effects without humidity issues<sup>5</sup>, and the comparison of cooling patch vs. water cooling system<sup>6</sup>. According to many previous studies<sup>3,4,7</sup>, it seems to be clear that the more effective and efficient body parts for cooling to alleviate heat strain

were body extremities such as the head, neck, hands or feet compared to the trunk parts. In particular, for workers who should wear protective helmets in hot environments, head cooling will be a convenient way to reduce the heat around the head using helmets.

Shitzer *et al.*<sup>8</sup>) compared the relative amounts of heat removed by a liquid cooling garment (LCG) at various regions of the body. They found that a relatively high percentage of the total heat removal by the suit came from the head. In particular, it was reported that the neck was the more efficient region for cooling than the face, showing 2.5 times greater heat extraction from the neck compared to that from the face<sup>9</sup>. When subjects did whole body immersion at 25°C for 30 min, regional heat flow was the greatest from the head, neck, and upper torso, while the lowest was in the hands and feet, among 12 body regions<sup>10</sup>. The reasons for heat removal from the

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head and neck being greater than other body parts would be as follows: the ratio of head blood flow to surface area is 4–10 times greater than those in the trunk and proximal limbs<sup>11</sup>), little or no head skin vasoconstriction in response to cold was found during cooling the head<sup>12</sup>), and the proximity of large blood vessels to the skin in the neck<sup>13</sup>).

While the convenience and efficiency of head cooling were reported, there are very few studies on the effect of head hair on heat removal from the head. The body hair is advantageous in cold environments, but the hair provides additional insulation to the body and impedes heat removal during heat stress. The thermal conductivity of the body surface for most mammals is reduced by fur. Heller<sup>14</sup>) reported that the heat loss from the glabrous skin (the face and palm) rises to values more than five times that of the nonglabrous skin (the upper back, lower back, abdomen, thigh, and upper arm) in humans over the course of exercise in hot environments. Many animal researchers have reported the effect of fur on body temperature regulation: impact of hair coat differences on rectal temperature, skin temperature, and respiration rate of cows<sup>15</sup>), the role of fur insulation in the heat balance of animals from cold environments<sup>16–18</sup>), red kangaroos in desert regions with short hair which was the result of adapting to a hot environment<sup>19</sup>), and different fur insulation in perameloid marsupials from various environments<sup>20</sup>). However, very few studies about the adverse or beneficial effects of head hair in humans on heat exchanges during cooling or heating the head were found.

Along with the head hair issue, the desired cooling temperature on the head is still in question. When the temperature of the head was kept cool, if core temperature increased by artificial manipulation, thermal comfort did not get worse and the sweat rate of the face decreased<sup>3, 4</sup>). It is evident that head cooling can alleviate heat stress and improve thermal comfort<sup>21–24</sup>). Head cooling temperatures vary from 7.5°C<sup>24</sup>), 10°C<sup>25</sup>), 13°C<sup>3</sup>), 20°C<sup>26</sup>), or ~30°C<sup>21</sup>), but there are studies reporting that mild cooling is more effective than intensive cooling<sup>27</sup>) or clinically similar to intensive cooling<sup>28</sup>).

The investigation of the effect of head hair and the optimal cooling temperature could be applicable to various safety and health research to alleviate heat strain of emergency workers, military, athletes and patients. In particular, head cooling using portable cooling hoods could be feasible and easier for persons who wear protective helmets. When evaluating the effects of liquid cooling hoods it is important to examine cooling capacity with/without hair on the head. The purpose of this study was to

explore the influence of hair while cooling the head with a liquid perfused hood on thermoregulatory responses and to investigate the most appropriate cooling temperature over the head during heat stress. We hypothesized that: 1) heat removal from the head during head cooling in heat stress would be greater for the cropped hair than the normal hair condition and 2) mild water temperature (15 or 20°C) would be preferred by subjects even though heat removal from the head would be greater at intensive water temperatures (10°C).

## Methods

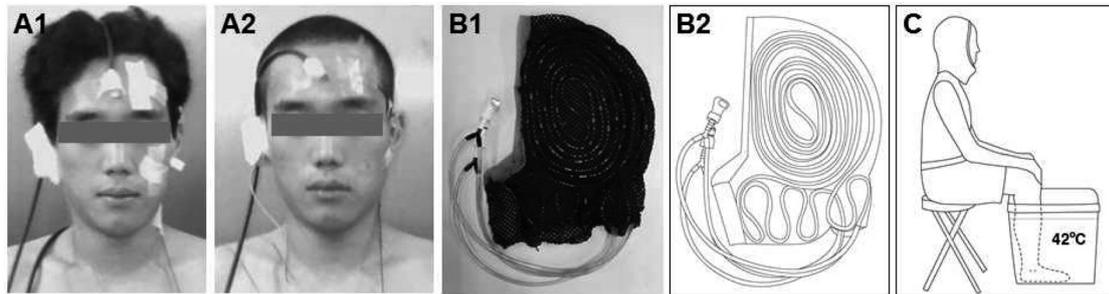
### *Subjects*

Eight male university students (mean  $\pm$  SD: age 21.0  $\pm$  1.9 yr, height 174.8  $\pm$  4.6 cm, body mass 78.3  $\pm$  16.4 kg, body surface area 2.0  $\pm$  0.2 m<sup>2</sup>, and body fat 16.7  $\pm$  6.4%BF) participated in this study. Subjects abstained from alcohol and strenuous exercise 48 h before any scheduled experiments. They were informed of the experimental procedures with possible risks and informed consent forms were obtained from subjects prior to their participation. This study was approved by the Institutional Review Boards of Seoul National University [IRB No. 1408/001-011].

### *Experimental design and procedures*

All subjects participated in this study six times on different days: normal and cropped hair conditions with water temperatures ( $T_{wi}$ ) of 10, 15, and 20°C. For the normal hair condition, subjects maintained their own natural hair style of about 100–130 mm hair length, whereas for the cropped hair condition subjects cut their own hair below 5 mm length (Fig. 1). The mass of the hair cut for the cropped hair condition was 29  $\pm$  10 g (mean  $\pm$  SD) for eight subjects. Because of the hair cut, all subjects participated in the normal hair condition first, followed by the cropped hair condition, while the order of the three water temperatures were randomized for all subjects. Subjects participated in their six experiments at the same time of day and consecutive experiments of a subject were separated by a minimum of 48 h.

Upon arriving at an experimental site, subjects drank 300 ml of water first and they wore only undershorts and shorts. They were weighed on a scale before and after each experiment to estimate total sweat rate (TSR). After equipping all measurement sensors on the body, subjects entered an experimental chamber maintained at an air temperature of 27.6  $\pm$  0.4°C and 31  $\pm$  6% relative humidity (RH). An experimental protocol consisted of 10-min rest in a sitting



**Fig. 1.** A picture of a subject (A), a liquid perfused hood (B) and a leg immersion at 42 °C water (C).  
**A1:** Normal hair condition, **A2:** Cropped hair condition, **B1:** A liquid perfused hood in this study, **B2:** Illustration of the hood, **C:** Illustration of the leg immersion to the knee level.

position followed by 60-min leg immersion (knee level) in hot water of 42°C using a water bath (LH-300, LIMHO Industry Co., Ltd., Korea). A liquid cooling hood, which was laboratory-made, was fully activated only during the 60-min leg immersion. Water in the liquid perfused hood was circulated by a water pump with a control function of water temperature (RW-0525G, JEIO TECH, Korea, a resolution of 0.1°C). Inlet and outlet water temperatures ( $T_{wi}$  and  $T_{wo}$ ) were continuously recorded. The liquid perfused hood was constructed of two flexible polyester mesh fabrics with tubing (335 g in total mass with water filled) and covered the head and neck except for the face (515 cm<sup>2</sup> in net surface area) (Fig. 1). The hood was fastened on the front of the neck with Velcro. A total of 8.05 m of PVC tubing (inside diameter 4.0 mm and outside diameter 6.0 mm) was inserted into the small holes of the outer mesh layer. The water chiller was connected to supply the hood with circulated water (540 ml·min<sup>-1</sup> in water flow rate). To estimate heat dissipation from the hood to the ambient air (28°C, 30%RH), heat flow was measured from the cooling hood that shaped with nothing inside the hood. The half of the total heat flow was considered as heat dissipation to the ambient air outside the hood.

#### Measurements

Prior to the experiment, the urine specific gravity of subjects were examined (PAL-10S, ATAGO, Japan) to confirm their hydration status. Urine specific gravity was averaged at  $1.018 \pm 0.010$  d (mean  $\pm$  SD) with no dehydration. Rectal temperature ( $T_{re}$ ), auditory canal temperature ( $T_{ac}$ ), and skin temperatures ( $T_{sk}$ ) were recorded every second using thermistors (LT-8A, Gram Corporation, Japan). Rectal temperature was measured by a thermistor probe inserted 16 cm beyond the anal sphincter of the rectum according to Lee and colleagues<sup>29</sup>. A sensor to measure  $T_{ac}$  was equipped with a silicon mold to fit into the right ear.

The sensor was gently introduced into the right ear canal and covered with gauze for insulation. Skin temperature were measured on the center of the forehead, left side of the cheek, chest, abdomen, back of the neck, upper back, upper arm, forearm, dorsal hand, middle finger, thigh, and calf. For the neck temperature, the sensor was kept on the midpoint of the back of the neck not to be contacted by the tube of the cooling hood. Mean skin temperature (mean  $T_{sk}$ ) was estimated from a modified Hardy and Du-Bois' equation: Modified mean  $T_{sk} = 0.07T_{head} + 0.35T_{(chest + abdomen + back)/3} + 0.14T_{arm} + 0.05T_{hand} + 0.19T_{thigh} + 0.2T_{leg}$ . Heart rate (HR) was measured every second throughout the experiment using a HR monitor (RS400, Polar Electro, Finland). Local sweat rates were continuously recorded on the upper back every second (SKN-2000, Nishizawa Electric Meters Manufacturing Co., Ltd, Japan). Total sweat rate (TSR) was determined by differences between body masses before and after the experiment using a body scale (F150S, Sartorius, Germany, resolution 1 g). Sweat that was absorbed in experimental clothing was determined by weighing the experimental clothing before and after each experiment.

Thermal sensation, thermal comfort, sweat sensation, and thirst sensation over the whole body and the head were evaluated using categorical scales combined with visual analog scales every 10 min starting from the 6<sup>th</sup> min for the 70 min trial. The length of each scale was 17.4 cm and all scales were presented in a horizontal direction. Any point between consecutive categories was able to be selected on a touch screen and the results were automatically recorded by pointing at the portable touch screen (ATIV Tab3-XQ300TZC, Samsung Electronics, Korea; <http://comfortlab.cu.cc/>). Thermal sensation scales were constructed with nine categories (very cold, cold, cool, slightly cool, neutral, slightly warm, warm, hot, and very hot), thermal comfort with seven categories (very uncom-

fortable, uncomfortable, a little uncomfortable, not both, a little comfortable, comfortable, and very comfortable), sweat sensation with seven categories (very dry, dry, a little dry, neither, a little wet, wet, and very wet), and thirst sensation with four categories (no thirst, slightly thirsty, thirsty, and very thirsty). Perceived skin wettedness ( $W_p$ ), which was perceived as a wetted body surface area, was recorded based on Lee and colleagues' study<sup>30</sup>.

#### Data analysis

Heat flow (HF) through the liquid perfused hood was calculated by the following heat flow equation (Eq. 1). The heat flow was converted to watts (1 kcal = 1.163 watts).

$$\text{HF (kcal}\cdot\text{h}^{-1}) = h_w \cdot C_w (T_{wi} - T_{wo}) \text{ ————— <Eq. 1>}$$

Where,  $h_w$  refers to water flow rate ( $\text{l}\cdot\text{h}^{-1}$ )

$C_w$ : water specific heat  $1 \text{ kcal}\cdot\text{kg}^{-1}\cdot\text{C}^{-1}$

$T_{wi}$ : inlet water temperature

$T_{wo}$ : outlet water temperature.

All data were expressed as mean and standard error (mean  $\pm$  SE). Values for the first 10 min (Rest) and for the last 10 min (leg immersion) were averaged as baseline and last values, respectively. Statistical analyses were done using SPSS v. 21 (IBM SPSS Statistics, USA). Testing for normality of the data was assessed with a Shapiro-Wilk test. Paired *t*-test was used to compare the difference between the normal and cropped hair conditions. One-way ANOVA with repeated measures was used to establish significant differences between the three experimental conditions of 10°C, 15°C, and 20°C. A Tukey's post hoc analysis was conducted to compare values among the three conditions. *p*-value of 0.05 was used to determine statistical significance.

## Results

#### Heat flow

No significant differences were found in heat flow between the normal and cropped hair conditions at all water temperatures, whereas significant differences between three water temperatures were found for both normal and cropped hair conditions ( $p < 0.001$ , Table 1). Heat removal from the head was approximately twice greater for the 10°C cooling than for the 20°C cooling ( $p < 0.001$ ). We measured heat flow from the hood alone at the air temperature of 28°C and air humidity of 30%RH. The heat extraction from the hood to the atmosphere were 52, 35, and  $17 \text{ W}\cdot\text{h}^{-1}$  at  $T_{wi}$  of 10, 15 and 20°C, respectively. We did not consider these values when calculating heat extraction from the head to avoid possible confusion when

comparing values from previous studies.

#### Rectal, auditory canal and skin temperatures ( $T_{re}$ , $T_{ac}$ and $T_{sk}$ )

$T_{re}$  was significantly lower in the cropped hair ( $37.4 \pm 0.1^\circ\text{C}$ ) than in the normal hair condition ( $37.6 \pm 0.1^\circ\text{C}$ ) during heat exposure when  $T_{wi}$  was 10°C ( $p = 0.025$ ). For the  $T_{wi}$  of 15°C and 20°C, no significant differences were found in  $T_{re}$  between the normal and cropped hair conditions (Fig. 2A). There were also no differences in auditory canal temperatures ( $T_{ac}$ ) between the normal and cropped hair conditions, but the increase in  $T_{ac}$  ( $\Delta T_{ac}$ ) during heat exposure was smaller for  $T_{wi}$  of 10°C than 20°C for both normal and cropped hair conditions ( $p < 0.05$ , Fig. 2B).

Mean skin temperature mean  $T_{sk}$  (o) had no significant differences between the normal and cropped hair conditions or  $T_{wi}$  of 10, 15, and 20°C. There were no significant differences in cheek temperatures by water temperature and normal/cropped hair. However, forehead temperature ( $T_{forehead}$ ) was significantly lower in  $T_{wi}$  of 10°C than in  $T_{wi}$  of 20°C ( $p < 0.05$ ) for the normal hair condition (Fig. 3A). Neck temperature ( $T_{neck}$ ) was significantly lower in  $T_{wi}$  of 10°C than in  $T_{wi}$  of 20°C ( $p < 0.05$ ) for both normal and cropped hair conditions (Fig. 3B).

#### Sweating responses

Total sweat rate showed a tendency of being lower for the cropped hair ( $122 \pm 5 \text{ g}\cdot\text{h}^{-1}$ ) than for the normal hair condition ( $161 \pm 21 \text{ g}\cdot\text{h}^{-1}$ ) at the  $T_{in}$  of 15°C ( $p = 0.056$ ), but no differences were found among the three water temperatures. On average, total sweat rate during the 60-min leg immersion ranged from 122 to  $161 \text{ g}\cdot\text{h}^{-1}$ . Local sweat rate on the upper back showed significantly lower sweat rate in the cropped hair ( $0.72 \pm 0.06 \text{ mg}\cdot\text{min}^{-1}$ ) than in the normal hair condition ( $0.94 \pm 0.11 \text{ mg}\cdot\text{min}^{-1}$ ) during heat exposure when  $T_{in}$  was 20°C ( $p = 0.085$ ).

#### Heart rate (HR)

Heart rate during heat exposure significantly increased by  $8 \pm 2$ ,  $5 \pm 1$ , and  $5 \pm 2 \text{ beat}\cdot\text{min}^{-1}$  for the haired when  $T_{in}$  was 10, 15, and 20°C, respectively, and by  $7 \pm 2$ ,  $5 \pm 2$ , and  $3 \pm 2 \text{ beat}\cdot\text{min}^{-1}$  for the cropped hair when  $T_{in}$  was 10, 15, and 20°C, respectively. However, there were no significant differences in HR between the normal and cropped hair conditions, or among  $T_{in}$  of 10, 15, and 20°C. Cooling the head had no significant effects on restraining the increase of HR. On average, HR was maintained around 74 to  $81 \text{ beat}\cdot\text{min}^{-1}$  at rest and around 82 to  $84 \text{ beat}\cdot\text{min}^{-1}$  during heat exposure.

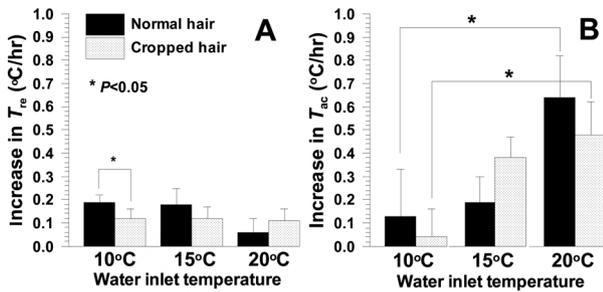


Fig. 2. Increases in rectal temperature ( $T_{re}$ ) (A) and in auditory canal temperature ( $T_{ac}$ ) (B) for the normal and cropped hair conditions while cooling the head at 10, 15, or 20°C water during heat stress (All data were expressed as mean  $\pm$  SE).

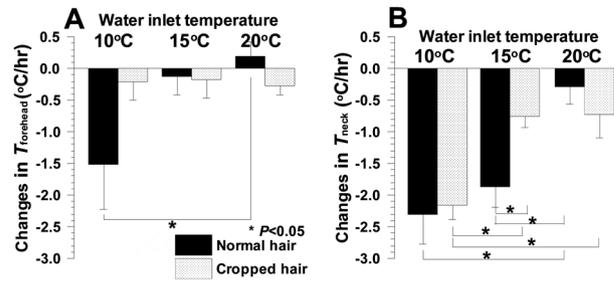


Fig. 3. Changes in forehead temperature ( $T_{forehead}$ ) (A) and neck temperature ( $T_{neck}$ ) (B) for the normal and cropped hair conditions while cooling the head at 10, 15, or 20°C water during heat stress. ( $T_{wi}$  represents inlet water temperature of the hood. All data were expressed as mean  $\pm$  SE).

Table 1. Heat removal through a liquid perfused hood with 10, 15, and 20°C water circulated during heat stress  $W \cdot h^{-1}$

	Water temperature circulated through a liquid perfused hood ( $T_{wi}$ )			<i>p</i> -value
	10°C	15°C	20°C	
Normal hair	132 $\pm$ 3	91 $\pm$ 2	60 $\pm$ 2	<0.001
Cropped hair	129 $\pm$ 5	91 $\pm$ 3	62 $\pm$ 2	<0.001

$T_{wi}$ , water inlet temperature; Data were expressed as mean  $\pm$  SE.

### Subjective perceptions

For overall subjective perceptions, subjects felt less warmer, less uncomfortable, less humid, and less thirsty during the cropped hair condition than for the normal hair condition at the  $T_{in}$  of 15°C, whereas there were no significant differences between the normal hair and cropped hair conditions at the  $T_{in}$  of 10°C or 20°C (Table 2,  $p < 0.1$ ). In particular, there were significant differences in thermal comfort and sweat sensation on the head. Subjects expressed a more thermally comfortable feeling ( $p = 0.001$ ) and decreased feeling of sweat ( $p = 0.052$ ) on the head in the cropped hair condition when compared to the normal hair condition. For the perceived skin wettedness ( $W_p$ ), no significant differences were found between the normal hair and cropped hair or among  $T_{in}$  of 10, 15, and 20°C, showing about 37 to 46% BSA on average.

### Discussion

Our hypotheses were that 1) heat removal from the head during head cooling in heat would be greater for the cropped hair than the haired condition and 2) less cooler water temperature (15 or 20°C) would be preferred to cooler temperature (10°C) even though heat removal from the head would be greater at intensive water temperature

of 10°C. To the best of our knowledge, effects of hair length on head cooling under heat stress have not been previously reported. We did not find significant influences of the hair on thermal responses. Thus, the first hypothesis has been rejected. For the second hypothesis, we found that 10°C head cooling was more effective in alleviating physiological heat strain than 20°C head cooling, while 15°C head cooling was preferred more for alleviating subjective heat strain than 10 or 20°C head cooling. Thus, the second hypothesis has been accepted.

### Effect of head hair on thermoregulation

Thermoregulatory effects of the hair or fur in mammals have been proven<sup>15–20</sup>). The present study indicates that the 29  $\pm$  10 g of total hair shaved from the head did not result in any meaningful impact on heat removal as well as thermoregulatory responses during head cooling in heat stress. Shaving more hair from the head could induce significant influences on heat extraction through liquid cooling hoods. Cabanac and Brinnetl<sup>31</sup>) compared beards and baldness in terms of thermoregulation<sup>26</sup>) and found that the evaporation rate through sweating from bald scalps was 2 to 3 times greater than those from the hairy scalp during light hyperthermia. However, because the liquid cooling hood in the present study was activated at the start

**Table 2. Subjective perceptions on the body overall at the end of leg immersion in 42 °C water while cooling the head**

Variable	Condition	Water temperature into a liquid perfused hood ( $T_{wi}$ )			<i>p</i> -value
		10°C	15°C	20°C	
Thermal sensation	Normal hair	0.99 ± 0.21	1.52 ± 0.49	1.16 ± 0.27	0.333
	Cropped hair	1.05 ± 0.22	0.91 ± 0.34	1.42 ± 0.21	0.164
	<i>p</i> -value	0.801	0.036*	0.401	
Thermal comfort	Normal hair	-0.70 ± 0.12	-1.18 ± 0.27	-0.68 ± 0.35	0.092 <sup>a</sup>
	Cropped hair	-0.58 ± 0.28	-0.52 ± 0.29	-0.68 ± 0.33	0.860
	<i>p</i> -value	0.574	0.059 <sup>a</sup>	0.951	
Wet sensation	Normal hair	1.15 ± 0.09	1.59 ± 0.18	1.26 ± 0.12	0.105
	Cropped hair	1.06 ± 0.09	1.06 ± 0.15	1.26 ± 0.17	0.645
	<i>p</i> -value	0.526	0.029*	1.000	
Thirst sensation	Normal hair	0.64 ± 0.21	0.95 ± 0.27	0.63 ± 0.21	0.321
	Cropped hair	0.58 ± 0.20	0.50 ± 0.17	0.53 ± 0.17	0.600
	<i>p</i> -value	0.787	0.091 <sup>a</sup>	0.398	
Subjective wetness, Wp (%BSA)	Normal hair	40 ± 9	46 ± 9	37 ± 10	0.502
	Cropped hair	42 ± 9	40 ± 9	43 ± 10	0.682
	<i>p</i> -value	0.365	0.213	0.442	

Data were expressed as mean ± SE. \* $p < 0.05$  and <sup>a</sup> $p < 0.1$  indicates a significant difference between haired and cropped hair conditions or among 10, 15 and 20°C. Categorical scales in subjective perceptions are as follows: thermal sensation (-4 very cold, -3 cold, -2 cool, -1 slightly cool, 0 neither, 1 slightly warm, 2 warm, 3 hot, 4 very hot), thermal comfort sensation (-3 very uncomfortable, -2 uncomfortable, -1 a little uncomfortable, 0 neither, 1 a little comfortable, 2 comfortable, 3 very comfortable), wet sensation (-3 very dry, -2 dry, -1 a little dry, 0 neither, 1 a little wet, 2 wet, 3 very wet), thirst sensation (0 no thirst, 1 a little thirsty, 2 thirsty, 3 very thirsty).

of heat exposure and restrained sweating on the head to some extent, it is not appropriate to discuss the effect of sweating from the head. A key route for heat exchanges on the head was by conduction, not evaporation. In addition, because there was no genetic baldness among subjects in this study, whereas Cabanac and Brinnetl<sup>31)</sup> recruited genetically inherited bald males, it is difficult to compare the present results to Cabanac and Brinnetl<sup>31)</sup>.

#### Heat removal from the head

As summarized in Table 3, heat extracted from cooling hoods ranged from 17 to 179 W·h<sup>-1</sup> by water inlet temperature, water flow rate, and activity levels. The cooling hood used in the present study can be evaluated as being effective and efficient when compared to other cooling hoods (Table 3). As heat removal of most liquid cooling garments (whole body) ranges from approximately 250 to 450 W<sup>32, 33)</sup>, the heat removal capacity of the cooling hood amounts to almost half of the garments. Such high effectiveness in heat removal from the head could be related to the unique traits of the head itself, showing that a rich superficial vascular supply and the apparent lack of vasoconstrictive innervation in the scalp of the head,

which results in the blood vessels being continuously dilated even under cold environments. Furthermore, most cooling hoods cover the neck as well as the head and the neck is very effective region for cooling. It seems that our results coincide with other findings that the head is more convenient and effective body area for heat removal when compared to other body parts<sup>34)</sup>.

In this study subjects were exposed to passive heat stress for an hour, but if a subject (78.3 kg in body mass, the average in the present study) was exposed to a neutral environment, the amount of heat removed from the head could decrease body temperature by 1.7°C per hour. When assuming specific heat capacity of the human body as 0.83 kcal·°C<sup>-1</sup>·kg<sup>-1</sup>, approximately 65 kcal is required to decrease 1°C of body temperature for the subject. Heat removal of 132 W, thus, is accountable for the decrease of 1.7°C in body temperature. However, due to the heat in-flowed through the legs during passive heat stress, rectal temperatures of subjects increased by approximately 0.1–0.2°C even though the head cooling is to be sufficient for decreasing body temperature. Total heat flow into the body through leg immersion at 42°C water is much greater than 132 W when considering evaporative heat loss from the

**Table 3. Water inlet temperature ( $T_{wi}$ ), water flow rate, and heat extraction from liquid cooling hoods**

Heat stress	Activity	$T_{wi}$ (°C)	Water flow rate ( $l \cdot \text{min}^{-1}$ )	Heat extraction by liquid ( $W \cdot h^{-1}$ )	Reference
$T_{air}$ 50°C	Exercise	7.5	0.8	179	Shvartz <sup>22)</sup>
No description	Exercise	5~7	0.75	140	Nunneley <i>et al.</i> <sup>20)</sup>
No description	Exercise	10~22	0.36	17-63	Nunneley <i>et al.</i> <sup>20)</sup>
$T_{air}$ 46°C	Exercise	20	0.9	No description	Kissen <i>et al.</i> <sup>24)</sup>
$T_{air}$ 35°C	Exercise	15.5	0.8	No description	Nunneley & Maldonado <sup>2)</sup>
$T_{air}$ 50°C	Sitting	12	0.06	34	Epstein <i>et al.</i> <sup>34)</sup>
$T_{air}$ 40°C	Exercise	13	1	Approx. 50-95	Cohen <i>et al.</i> <sup>1)</sup>
		10	0.54	132	
42°C water (leg immersion)	Sitting	15	0.54	91	The present study
		20	0.54	60	(The normal hair)
		10	0.54	129	
42°C water (leg immersion)	Sitting	15	0.54	91	The present study
		20	0.54	62	(The cropped hair)

The significant figure of each value in  $T_{wi}$ , water flow rate, and heat extraction follows the significant figure in its original article.

skin (Total sweat rate was recorded from 122 to 161  $g \cdot h^{-1}$  in the present study, which could be converted to evaporative heat loss of 83~108 W when assuming water evaporative heat loss as 0.58 kcal·kg<sup>-1</sup>).

Therefore, to avoid increasing body temperature using head cooling during heat stress, it needs to increase by 7~14 W in heat removal. In practice, this can be achieved by air ventilation around the body. Shaving head hair could be another solution, but the present results do not support this because no significant influences of the hair were found. Another alternative solution would be to increase the water flow rate of the hood. The water flow rate of the liquid perfused hood in the present study was 0.54  $l \cdot \text{min}^{-1}$ , which was not different from the flow rates in cooling hoods of previous studies (Table 3). At 10°C head cooling, the increases of 30~60  $ml \cdot \text{min}^{-1}$  in water flow rate is attributed to the increases of 7~14 W in body heat removal, which is able to restrain the increase of 0.1~0.2°C·h<sup>-1</sup> in body temperature. Increasing water flow rate is feasible by improving tubing distribution, size of the tube, or inlet/outlet construction. In theory, more heat extraction from the head is able to be achieved through much lower water temperature and higher water flow rate, but those treatments are not recommended because such a large heat extraction may cause thermal discomfort and risks to the circulatory system. The water temperature and flow rate should be decided according to the levels of activity and heat stress to avoid excessive heat removal and thermal discomfort.

#### *Finding the optimum temperature for head cooling*

The optimum temperature for head cooling needs to be distinguished from that of cooling the whole body. For

whole body cooling, the Apollo LCG suit used three levels of water temperatures at 6.7, 15.5, and 22°C<sup>32)</sup> and in Waligora and Michel's study<sup>35)</sup>, the most comfortable inlet temperature from 4.4 to 15.5°C was 10°C and the subjects were overly cooled at 4.4°C and 6.7°C inlet temperatures. Water inlet temperatures used in liquid cooling vests ranged from ice water to 25°C, while for liquid cooling hoods water inlet temperatures ranged from 5 to 22°C (Table 3). Kissen *et al.*<sup>26)</sup> and Greenleaf *et al.*<sup>25)</sup> used a water cooled helmet liner with 20 and 10 °C inlet temperature, respectively. An interesting finding is that subjects preferred much cooler water while cooling the head than while cooling the torso. Subjects favored the lowest water inlet temperature during the neck and face cooling (8.4°C), while they favored cooling the thighs and feet at 12.5°C<sup>9)</sup>. Shvartz<sup>24)</sup> reported that the favored water inlet temperature varied between 6 and 10°C for the hood and 8 and 14°C for the hood and suit at an air temperature of 50°C.

When cooling the human body, a physiological principle is that heat extraction through the vessel network in the 'vasomotor zone' is limited by changes in the rate of blood flow due to vessel vasoconstriction/vasodilation, whereas outside of the 'vasomotor zone', biological heat flow is consistent and conforms to the physical process of heat transfer only by tissue conductivity<sup>36)</sup>. In this regard, the human body does not cool down efficiently at very low temperatures, which suggests that a mild cooling regimen could be more effective than intensive cooling. With this background knowledge, we compared the effectiveness in heat removal of three coolant temperatures at 10, 15, and 20°C. From a physiological viewpoint, 10°C inlet temperature was more effective in alleviating physiologi-

cal heat strain in  $T_{ac}$ ,  $T_{neck}$ , and  $T_{forehead}$  than 15 or 20°C inlet temperatures. In addition,  $T_{ac}$  was a more sensitive and valid index to reflect body heat storage during head cooling under heat stress when compared to  $T_{re}$  because  $T_{ac}$  increased by heating the legs but the increases were suppressed by cooling the head, whereas  $T_{re}$  was relatively less affected by head cooling. However, the validity of auditory canal temperature as a heat storage index may be uncertain when wearing the cooling hood. It needs to be verified through further studies on body regional cooling studies. For subjective perceptions such as thermal comfort, thermal sensation, sweat sensation, and thirst sensation, subjects preferred a mild cooling regimen (15°C) than an intensive cooling regimen (10°C). The 20°C cooling regimen was not desired for head cooling. These results indicate that physiological heat strain does not always correspond with subjective heat strain during heat exposure. Further, the desired temperature for head cooling should be individually modified with the levels of metabolic heat production and thermal environments.

## Conclusion

To the best of our knowledge, the present study is the first trial to explore the effect of head hair on heat removal during head cooling under heat stress. We found no significant influences of the hair on heat extraction during head cooling, but further studies removing more hair are required to confirm the present results. To improve the effectiveness of the liquid cooling hood, increasing water flow rate or decreasing somewhat water temperature is more feasible than shaving the hair on the head. Among 10, 15, and 20°C, the desired temperature for head cooling under heat stress was 10°C to alleviate physiological heat strain, but subjects preferred 15 to 10°C in terms of subjective responses, such as thermal sensation or thermal comfort. The 20°C water inlet temperature was recommended for neither physiological nor subjective heat alleviation. From a technical viewpoint, cooling hoods have advantages in terms of total mass, battery durability, mobility, and usability when compared to cooling vests or jackets. The present results are applicable for workers, especially who wear protective helmets, in extreme hot environments.

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