생활과학석사학위논문

Evaluation of Heating Protocols and Body Regions with Graphene Heater for Cold Protective Clothing

방한복 보온성 향상을 위한 면상 그래핀 히터 가온 프로토콜 개발 및 최적의 가온 부위 평가

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이 논문을 생활과학석사학위논문으로 제출함

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2016 년 12 월

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Abstract

Evaluation of Heating Protocols and Body Regions with Graphene Heater for Cold Protective Clothing

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The purpose of this study was to evaluate the effects of intermittent and continuous heating protocols using graphene heated clothing and identify the more effective body region for heating in a cold environment. The current study consisted of three parts.

First, we examined the permissible temperature of graphene heater on the chest, upper back, respectively for human application. Two young males participated in two experiments consisted of chest heating and upper back heating at an air temperature of 0.4°C with 41%RH. The temperature of graphene heater was increased by controlling the voltage. The permissible temperature of graphene heater for human application was decided to be around 45°C considering pain sensation, subjective perceptions and the prevention of skin burn injury.

Second, we developed intermittent heating protocol according to electric power consumption. Electric power was set at 0.18, 0.71, 1.61, and 2.86 W with the voltage of 5, 10, 15, and 20 V per graphene heater, respectively. Tests were conducted at an air temperature of 30ºC with 10%RH. Five intermittent heating protocols were developed with different electric power consumptions. For the continuous heating protocol (CP), 20 V during 60 min generated an electric power of 8.58 W from three graphene heaters. For the intermittent heating protocols, electric power was 5.28, 5.49, 2.49, 5.10, and 2.94 W for IP-1, IP-2, IP-3, IP-4, and IP-5, respectively. The results showed that the electric power consumption of the IP-3 (2.49 W) was conserved by 71% compared to the continuous protocol (8.58 W). Based on the results, IP-3 was selected for the following human wear trials.

Lastly, we evaluated in the following five graphene heating protocols in human wear trials: no heating, continuous heating the chest, continuous heating the back, intermittent heating the chest, and intermittent heating the back. Eight males participated in the experimental protocol consisting of 10 min rest on a chair at an air temperature of 25ºC with 28%RH and 60 min cold exposure at an air temperature of 0.6ºC with 40%RH. Rectal temperature, cardiovascular and respiratory responses showed no significant differences among the five heating conditions while heating the back showed more beneficial effects on skin temperatures than heating the chest. In summary, to keep a balance between saving electric power and minimizing thermal discomfort in cold environments, intermittent heating the back is recommended.

Keywords: Cold protective clothing, graphene heater, body heating, heating protocol, electrically heated clothing

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List of Abbreviations

BP	Blood pressure
CB	Continuous-back heating
CC	Continuous-chest heating
CP	Continuous protocol
CVD	Chemical vapor deposition
DBP	Diastolic blood pressure
GHT	Graphene heater temperature
HF	Heat flux
HR	Heart rate
IB	Intermittent-back heating
IBML	Insensible body mass loss
IC	Intermittent-chest heating
IP	Intermittent protocol
MAP	Mean arterial pressure
NH	No heating
PET	Polyethylene-terephthalate
RIE	Reactive ion etching
SBP	Systolic blood pressure
$\bar{T}_b$	Mean body temperature
TC	Thermal comfort
T_{re}	Rectal temperature

TRT	Thermal release tape
TS	Thermal sensation
T_{sk}	Skin temperature
$\bar{T}_{sk}$	Mean skin temperature
TT	Thermal tolerance
VO_2	Oxygen consumption
WCI	Wind chill index

Chapter 1. Introduction

Body cooling that accompanies discomfort impairs physical and mental performance in various ways (Raatikka et al., 2007). Physiological responses to cold include body temperature falling, the strain on the heart and respiratory system, shivering, etc. Psychological responses include arousal, reduced memory capacity, dull perception and changes in mood and personality. Extreme or prolonged cold can cause a range of cold injury and illness, including cracked skin, frostbite, hypothermia and trench foot. Individuals who work in refrigeration units or outside in cold weather, such as agricultural and fishery workers, cold storage workers, reindeer herders and soldiers in military training or operations, are vulnerable to cold injuries (Degroot et al., 2003; Ervasti et al., 1990; Mäkinen et al., 2009).

Workers who are exposed to cold environments require cold protective clothing, which is selected based on the specific requirements of activity and air temperature, to protect against cold-related hazards (Holmer, 2005). There are two main methods used to increase thermal insulation of clothing: passive heating and active heating. A passive heating method is used to increase thermal insulation without the aid of any electric power, which is done by increasing the air layer of clothing using down filler, multi-layered clothes or heating textiles such as moisture-absorbing heat release, far-infrared, solar or chemically-heated textiles (Choi et al., 2004; Park et al., 2006; Sarier and Onder, 2007; Shim and McCullough, 2000; Song et al., 2015). However, most passive heating applications increase the weight of clothing. The increase of weight raises the energy consumption of wearers by 3% per clothing kilogram (Dorman and Havenith, 2009). In addition, friction between clothing layers hinders the movement and deteriorates physical, manual performance (Dorman and Havenith, 2009; Duggan, 1988; Scott, 1988). The heating textiles slightly increase the thermal insulation value (Jin et al., 2012; Lee et al., 2015; Shim et al., 2009). On the other hand, active heating can be defined by providing extra heat with the aid of electric power using electrically-heated materials and systems. One of the advantages of the active heating systems is that the thermal effect is greater than those from the passive heating system. Electric heating materials increase over 10^{o}C from the base temperature (Kang and Lee, 2015). However, improvements are still needed for practical application in terms of power consumption, the size for ergonomic design of the system, total weight, etc.

To meet the requirements of the active heating system, a graphene heater was chosen in this study. Graphene is one atom thick, two-dimensional material, light weight (Geim and Novoselov, 2007), flexible (Güneş et al., 2009), transparent (Nair et al., 2008) and also has high conductivity (Prasher, 2010). A graphene heater with those advantages could substitute for electric heating wires planted in clothing. For example, the feature of two-dimensional materials contributes to even temperature distribution, while the electric heating wires provide uneven distribution in surface temperature. The flexible and lightweight qualities will provide comfort and mobility to wearers. A thin form of graphene could contribute to designing supremacy when applied to clothing. The high thermal conductivity of graphene enables the development of more effective heating protocols due to the quick responses in temperatures. There is advanced research regarding the applicability and improvement of graphene heaters and the improvement of heating performance (Bae et al., 2010), improving electrical properties and heating performance (Kang et al., 2011; Kang et al., 2015). To the best of our knowledge, however, no research has been found that evaluated the practical implications of graphene heaters for humans in cold environments.

One of the strengths when using graphene heaters is that the surface temperature of graphene heaters can be controlled automatically or manually. To reduce the weight of the active heating unit in wearable clothing systems, the weight of the battery should be minimized which requires minimum electrical consumption of the system with an identical thermal insulation. An intermittent heating protocol using the graphene heater can save power consumption. In addition, the intermittent protocol may have advantages in terms of psychological comfort of wearers. Continuous heating on the human skin can diminish thermal comfort for wearers (Zhang, 2003) and transient thermal environments can provide higher levels of thermal comfort than stable environments (Arens et al., 2006; de Dear, 2011). Therefore, we assumed that intermittent heating protocols using graphene heaters would be more advantageous for electric energy efficiency and psychological comfort of wearers when compared to continuous heating protocols. The purpose of this study was to explore the practical applicability of graphene heaters for humans in cold environments. We hypothesized that: 1) an intermittent heating protocol would bring warmer sensations when compared to a continuous heating protocol applied, and 2) the upper back would be more effective for maintaining body temperature than the chest on the trunk of the human body.

Chapter 2. Theoretical Background

2.1. Graphene and graphene heater

A graphene is a new form of carbon materials that was discovered 2004 (Novoselov et al., 2004) which is a one-atom-thick sheet of carbon atoms arranged laterally in a honey-comb lattice, two-dimensional material (Bodenmann and MacDonald, 2007). Also, graphene is light weight (Geim and Novoselov, 2007), flexible which showed no change in sheet resistance with a 90^{o}C bending angle (Güneş et al., 2009), transparency of 97.7% (Nair et al., 2008) and also has high conductivity than copper (Prasher, 2010). Seol et al. Reported that graphene in contact with silicon dioxide (SiO_2) has a thermal conductivity of ~600$Wm^{-1}K^{-1}$.

Because of its thinness, lightness, and flexibility, graphene heater is well suited as a heater for garments and can be applied without affecting the design, materials, and color of the garment due to its transparency. In addition, due to the high conductivity, it is possible to develop an intermittent heating protocol. Intermittent heating protocols reduce power consumption and can increase battery efficiency, so there is a need for research on an intermittent heating protocol to achieve both efficiency and effectiveness.

However, previous studies related to electrically heated garment have lowered the power consumption by setting the maximum heating temperature low or by reducing the heating area (Table A.1). This is presumably due to the difficulties in developing a heating protocol because existing heaters do not show immediate temperature rise and fall response by voltage regulation. However, since graphene heater has high conductivity, it shows the instantaneous temperature change according to the voltage regulation, and it is possible to develop the user's desired temperature protocol. For this reason, graphene heater which can be applied to clothes and capable of developing heating protocol has been selected.

2.2. Necessity of electric heated cold protective clothing

In cold environments, people usually wear bulky and heavy multilayer clothing. Fabric with low thermal conductivity and the air layer between the clothes reduces the loss of heat by conduction (Morris et al., 1985). Lee (1981) studied the effects of air layers between fabrics on the thermal insulation value and the result showed the air layer thickness and the heat transfer coefficient were proportional to the total thickness of the air layer within 15 mm. Lee (1984) also presented the similar results that the air layer between the human body and clothing was desirable to increase the thermal insulation and the maximum thermal insulation occurred when the thickness of the air layer was 16 mm. However, it restricts the wearer’s physical activity (Scott, 1988) and if the critical thickness for the optimal thermal insulating power of clothing does not provide sufficient thermal insulation, electrically heated clothing will be a desirable and effective alternative.

2.3. Intermittent heating protocol

The dynamic characteristics of thermoreceptors affect thermal sensation and thermal comfort. A thermoreceptor adapts to the thermal environment, when the ambient environment changes abruptly, it is strongly stimulated at first, sending impulses at a high frequency. However, this stimulation fades rapidly after a minute of temperature change and then it reaches a steady level progressively and slowly. Therefore, a person feels much colder or warmer when the skin temperature drops or rises rapidly than when the temperature remains at the same level. The strong thermal sensation when entering a cold pool or a hot tub can be explained by this phenomenon (Arens and Zhang, 2006).

Based on the characteristics of the thermoreceptor, it can be assumed that the intermittent protocol could arouse more positive response than the continuous protocol when cooling or warming the human body. Therefore, in this study, we tried to verify the hypothesis through experiments and developed and evaluated an intermittent heating protocol.

2.4. Optimal body region for heating

Considering the weight of heating clothes, battery capacity, it is crucial to find the optimal body region for heating in order to maximize the heating effect. The point to be considered is whether the heater can be closely contacted with the human body, whether the heater is not obstructive to the performance, or can minimize the heat emission to the external environment. From a physiological point of view, it would be reasonable to examine whether the body part plays an important role in thermoregulation or the thermal sensitivity by region.

In this study, chest and upper back were selected as a body region suitable for wearing multiple layers of clothes, not the curved surface for the heater contact, less influenced by the chimney effect and bellow effect. These two body parts were also suitable from a physiological point of view, according to the advanced research, the head and the torso has a higher sensitivity over the body and the extremities has the lowest due to the reduction in the distribution of thermoreceptors towards the extremities (Lee and Tamura 1995). Also, the warming of the central part of the body was relatively more efficient due to higher core temperature (Wang et al., 2010). For these reasons, we chose the chest and upper back for this study and investigated the more effective area between the chest and upper back through the experiment.

2.5. Factors affecting cold responses

Cold responses may be modified by the number of factors, including acclimatization to cold, cold resistance, the amount of body fat, cold exposure time, metabolic rate, clothing (insulation and moisture permeability), the environmental condition including wind speed, posture, age, sex and etc.

Significant overall effect of gender was identified when compared male and female thermal sensation to a $40^{o}c$ stimulus and sensations magnitude as females provided a warmer sensation score than male (4.7 ± 1.8 vs 3.6 ± 2.2, $p<0.05$, respectively) (Gerrett et al., 2014). Lautenbacher and Strian (1991) also found that females were more sensitive to a warm stimulus than males at the hand.

In this study, the effects of age and sex difference were controlled by selecting male subjects in their twenties, and cold exposure time, clothing, environmental condition, posture were also controlled by the experimental conditions.

Chapter 3. Materials and Methods

This study was comprised of three parts. We first examined the permissible temperature of graphene heater on the chest, upper back, respectively for human application. Second, we developed the intermittent heating protocol. Finally, we evaluated in the following graphene heating protocol in human wear trials: no heating (NH), continuous-chest heating (CC), continuous-back heating (CB), intermittent-chest heating (IC), intermittent-back heating (IB) (Figure 3.1).

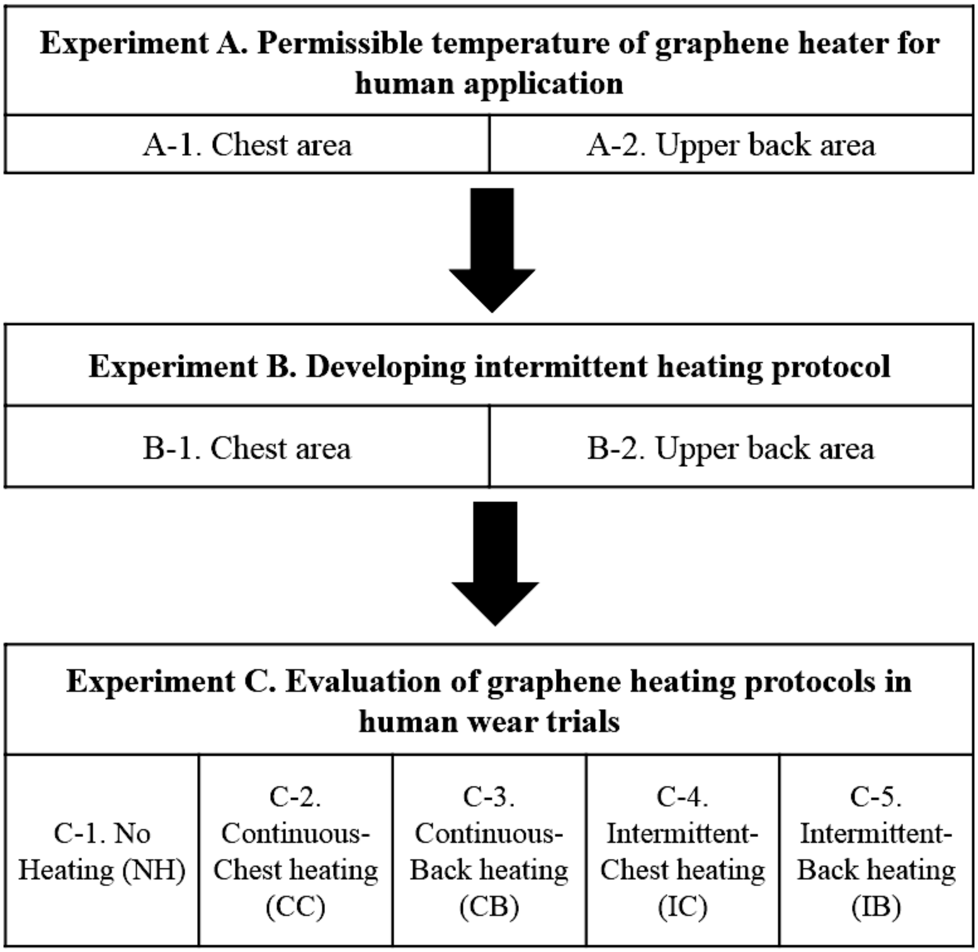

Figure 3.1. Schematic view of the present study.

3.1. Production of electrothermal graphene thin film

We followed the identical method for the synthesis of graphene as the chemical vapor deposition (CVD) method which uses hydrogen (15 sccm) and methane (150 sccm) gases with a Cu foil in vertical CVD to create a large size of graphene (Bae et al., 2010). The Cu foil was inserted into the vertical CVD and heated to 970°C under H_2 (g). Then, CH_4 (g) was injected into the outer tube to grow a monolayer graphene for 30 min. The outer tube was cooled down to room temperature with H_2 (g). The one side of graphene on Cu foil was removed by reactive ion etching (RIE) and thermal release tape (TRT, Jinsung Ins., Korea) was placed on the other side of the graphene film by lamination. The Cu foil was eliminated by Cu etchant (0.1 M ammonium persulfate, Sigma-Aldrich). The graphene on the TRT above a clean Polyethylene-terephthalate (PET) substrate was inserted between soft rollers. Finally, the TRT could be easily released after a rolling process at 110°C.

To manufacture a graphene heater, we carried out multiple stacking and n-doping processes according to previous research (Kang et al., 2011). After doping with nitric acid (HNO_3 60%, Samchun), the graphene on PET carried out the multiple stacking processes by the roll-to-roll method. After attaching Cu tape on two edges of rectangular graphene film, we laminated the graphene heater on the PET substrate. Electrothermal graphene film was composed of four layers of graphene. The weight was 5.8 ± 0.4 g, the size of the heaters was (5.7 ± 0.4 cm) × (10.5 ± 0.5 cm) and the thickness were 0.05mm. Voltage was supplied by a DC power supply (M8812, Maynuo Electronics, China) at T_a of 27.9 ± 0.5°C and H_a of 54 ± 3% (RH), the surface temperature of graphene heater was recorded every 5 s on the center of the film (LT-8A, Gram Corporation, Japan, resolution 0.01°C). The surface temperature distribution was characterized by an infrared thermography camera (T650sc, FLIR, Sweden) (Figure 3.2). The heating rate of the graphene heaters was examined with the voltage of 5, 10, 15, 20 and 25 V under the electric resistance of 83, 123 and 141 Ω. Lower resistance produced a higher heating rate and maximum temperature at the same voltage. When 25 V was supplied to 83 Ω graphene heater, the surface temperature was over 70°C (Table 3.1).

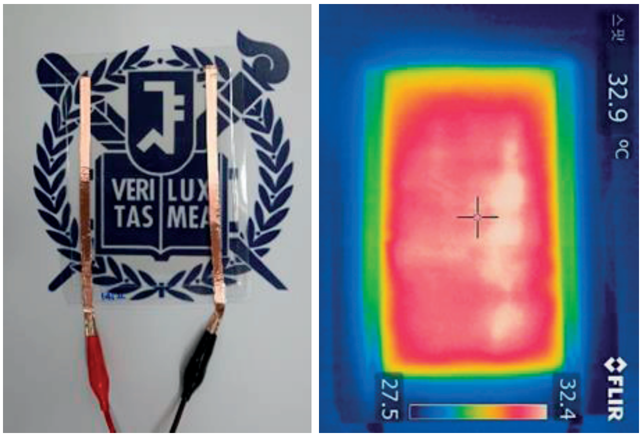

Figure 3.2. A graphene heater and thermographic image of the heater.

Table 3.1. Heating rate and maximum temperature of graphene heater according to the resistance

Voltage	Heating rate of graphene heater (°C·min^{-1})			Maximum temperature of graphene heater (°C)		
	83 Ω	123 Ω	141 Ω	83 Ω	123 Ω	141 Ω
5 V	0.4	0.2	0.1	30.2	29.2	28.9
10 V	1.5	0.8	0.8	37.8	33.3	32.9
15 V	2.4	1.4	1.3	50.0	40.4	39.4
20 V	3.1	1.5	1.6	65.7	49.4	47.4
25 V	-	2.2	1.5	Over 70	59.9	55.0

3.2. Permissible temperature of graphene heater for human application

3.2.1. Subjects

Two young males (mean ± SD: 24.0 ± 4.2 yr in age, 176.5 ± 3.5 cm in height, and 70.2 ± 9.3 kg in body mass) participated in this test. Subjects abstained from alcohol, smoking and strenuous exercise for the previous 24 h and were prohibited from taking any food for 2 h prior to their scheduled tests. Informed consent was obtained from the subjects. The experimental protocol was approved by the Institutional Review Boards of Seoul National University [IRB No. 1508/001-017].

3.2.2. Experimental design and procedures

The experiment consisted of two conditions: chest heating and upper back heating. Subjects participated in two conditions on different days in a random order to avoid the order effect.

Upon arriving on an experimental site, subjects drank 300 ml water first and wore only undershorts and shorts. They were weighed on a body scale before and after each experiment to estimate the insensible body mass loss. After equipping all measurement sensors on the body, subjects changed into experimental clothing (about 1.37 clo): under shorts, thermal underwear top and bottom, shirts, pants, coat, leather gloves, socks, and running shoes. The thermal underwear top had pockets on the chest and upper back parts so as to locate graphene heaters (Figure 3.3). The pockets were tight-fitting shaped to prevent lowering the heat conductivity due to air layer between fabrics. The textile of pockets was cotton 100% and thermal conductivity and thickness of the pocket fabric were 2.2669 × 10^{-5} $W \cdot cm^{-1} \cdot {}^{o}C^{-1}$ and 0.352 mm. Two pieces of graphene heaters were put in the pockets of the thermal underwear top.

Subjects entered an experimental chamber maintained at an air temperature (T_a) of 0.4 ± 0.5°C with an air humidity (H_a) of 41 ± 1%RH and an air velocity of 1.3 ± 0.4 $m \cdot s^{-1}$ (Wind Chill Index, WCI: -1.0°C). Voltage was controlled by a DC power supply (M8812, Maynuo Electronics, China) and was increased by 5 V every 10 min starting from 10 V. After 20 V, the voltage was increased by 1 V for safety. Subjects kept a standing posture until the end of the experiment. The experiment was terminated during the following cases: skin temperature under the graphene heater increased up to over 44°C, or subjects felt too hot and/or thermal pain due to the graphene heater.

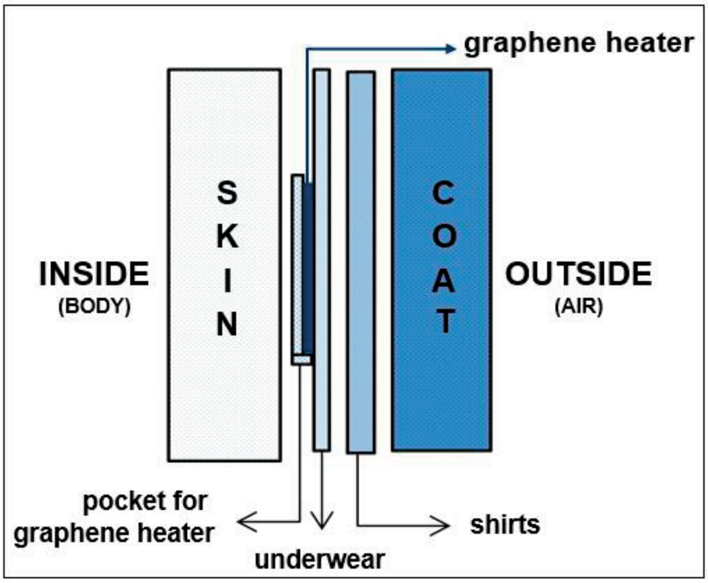

Figure 3.3. Schematic illustration of clothing layers and location of graphene heater.

3.2.3. Measurements

During the whole trial, skin temperatures on the left side of the chest and upper back and surface temperature of the graphene heaters were monitored every 5 s using a data logger (LT-8A, Gram Corporation, Japan) (Figure 3.4). Subjective perceptions were evaluated every 10 min with the following scales: thermal sensation (-4: very cold, -3: cold, -2: cool, -1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, 3: hot, 4: very hot) and thermal comfort (-3: very uncomfortable, -2: uncomfortable, -1: a little uncomfortable, 0: not both, 1: a little comfortable, 2: comfortable, 3: very comfortable). Values for the first 10 min (initial) and for the last 10 min (voltage stopped) were averaged as a baseline and the last value, respectively.

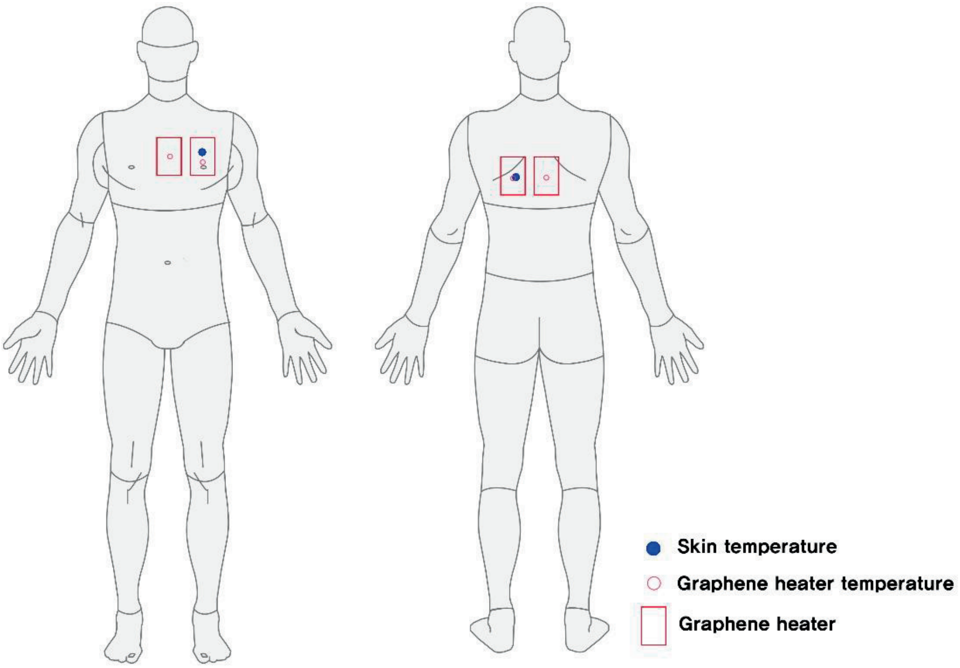

Figure 3.4. A diagram of measurement sites where skin temperature and graphene heater temperature were measured and locations of graphene heater.

3.3. Developing intermittent heating protocol

Electric power was set at 0.18, 0.71, 1.61, and 2.86 W with the voltage of 5, 10, 15, and 20 V per graphene heater, respectively. These values were derived from a voltage supply experiment at the graphene heater resistance of 140 Ω. If a graphene heater had a resistance value lower the 140 Ω, resistors were added to have the same temperature in accordance with the voltage. Tests were conducted at T_a 30ºC and H_a 10%RH (clothing microclimate in winter). 20 V was selected as a maximum voltage for human trials. Intermittent heating protocols were developed in various forms according to electric power consumption. The total duration of protocols was 60 min.

3.4. Evaluation of graphene heating protocols in human wear trials

3.4.1. Subjects

Eight young males (mean ± SD: 24.3 ± 2.1 yr in age, 175.5 ± 2.7 cm in height, 72.5 ± 9.8 kg in body mass and 23.6 ± 3.3 $kg \cdot m^{-2}$ in BMI) participated in this study. Subjects followed the same preparation procedures and the experimental protocol was approved by the identical IRB as mentioned in chapter 3.2.

3.4.2. Experimental design and procedures

Eight subjects participated in five experimental conditions (No Heating (NH), Continuous-Chest heating (CC), Continuous-Back heating (CB), Intermittent-Chest heating (IC), and Intermittent-Back heating (IB)) and a total of 40 experiments were conducted. Experimental conditions were randomly distributed to avoid any order effect. Each visit of a subject was separated by at least 48 h.

Upon arriving on an experimental site, subjects drank 300 ml water first and wore only undershorts and shorts. They were weighed on a body scale before and after each experiment to estimate the insensible body mass loss. After equipping all measurement sensors on the body, subjects changed into experimental garments which were the same as mentioned in chapter 3.2. Subjects rested 10 min in a sitting position on a stool at T_a of 25 ± 4°C and H_a of 28 ± 15 %RH with an air velocity 0.01 ± 0.02 $m \cdot s^{-1}$. After inserting three pieces of graphene heaters into the pockets on the left, middle, and right side of the chest (or upper back), subjects entered the experimental chamber at T_a of 0.6 ± 0.5°C and H_a of 40 ± 3 %RH with an air velocity of 1.4 ± 0.4 $m \cdot s^{-1}$ (Wind Chill Index, WCI: -0.9°C). At the chamber, subjects kept a standing posture for 60 min (Figure 3.5). Electric power was supplied to the graphene heaters by a DC power supply (M8812, Maynuo Electronics, China). Graphene heaters were not inserted for the condition NH. Intermittent heating protocol-3 (IP-3) among the five intermittent protocols was selected for IC and IB.

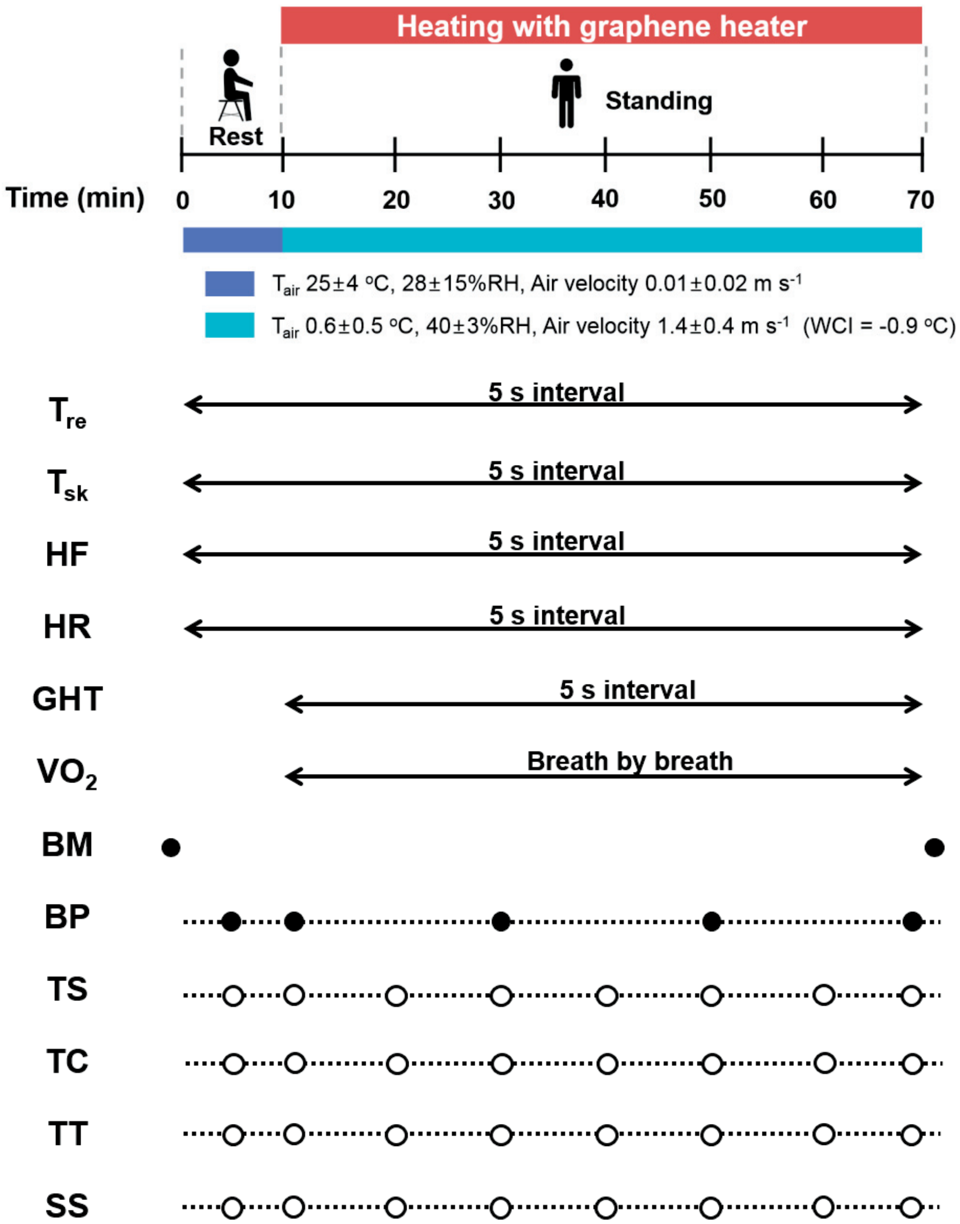

Figure 3.5. The time course of an experiment and measurements (T_{re}: rectal temperature, T_{sk}: skin temperatures, HF: heat flux, HR: heart rate, GHT: graphene heater temperature, VO_2: oxygen consumption, BM: body mass, BP: blood pressure, TS: thermal sensation, TC: thermal comfort, TT: thermal tolerance, SS: sweat sensation).

3.4.3. Measurements

Thermal, cardiovascular, respiratory responses and subjective perceptions were measured during the experiments (Figure 3.6).

During the whole trial, rectal temperature (T_{re}), skin temperatures (T_{sk}) and the surface temperature of the three pieces of graphene heaters were recorded every 5 s using a data logger (LT-8A, Gram Corporation, Japan). Rectal temperature was measured by a thermistor probe that was inserted 16 cm beyond the anal sphincter of the rectum (Lee et al., 2010). Skin temperatures were measured on the following body regions: the forehead, chest (the left, middle and right side under the three pieces of graphene heaters), front shoulder, abdomen, upper back (the left, middle and right side under the three pieces of graphene heaters), back shoulder, forearm, hand, finger, thigh, calf, foot and toe. Surface temperatures over the three graphene heaters on the chest or upper back were measured. Mean skin temperature ($\bar{T}_{sk}$) was estimated from a modified Hardy and DuBois' equation (Hardy and DuBois, 1938):

$$\bar{T}_{sk} = 0.07T_{forehead} + 0.35(T_{chest1} + T_{chest2} + T_{chest3} + T_{front\ shoulder} + T_{abdomen} + T_{upper\ back1} + T_{upper\ back2} + T_{upper\ back3} + T_{back\ shoulder})/9 + 0.14T_{forearm} + 0.05T_{hand} + 0.19T_{thigh} + 0.13T_{calf} + 0.07T_{foot} \quad \text{[Eq. 3.1]}$$

Heat flux was recorded every 5 s on the following four body parts: the left side of the chest, front shoulder, upper back, back shoulder (MCV-4V, T&D Corp., Japan). Heart rate (HR) was measured every 5 s using an HR monitor (RS400, Polar Electro, Finland). The insensible body mass loss was determined by differences between body masses before and after the experiment using a body scale (F150S, Sartorius, Germany). Oxygen consumption (VO_2) was continuously recorded by an indirect calorimetry throughout the experiment (Quark CPET, Cosmed, Italy). Each 5 min average during the rest and recovery periods were used as a representative value of each phase. Blood pressure (BP) was measured every 20 min on the right arm on the level of the chest in a standing position (HEM-7200, Omron Healthcare, Japan). Mean arterial pressure (MAP) were calculated from the equation:

$$MAP = DBP + 0.33\ (SBP - DBP) \qquad \text{[Eq. 3.2]}$$

Subjective perceptions were evaluated every 10 min by rating of thermal sensation (-4: very cold, -3: cold, -2: cool, -1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, 3: hot, and 4: very hot), thermal comfort (-3: very uncomfortable, -2: uncomfortable, -1: a little uncomfortable, 0: not both, 1: a little comfortable, 2: comfortable, and 3: very comfortable) and thermal tolerance (0: perfectly tolerable, 1: slightly difficult tolerable, 2: fairly difficult to tolerable, 3: very difficult to tolerable, and 4: intolerable). Subjects expressed shivering onset whenever shivering occurred, and the occurring time and body regions of the shivering were recorded.

3.4.4. Data analyses

All data were expressed as the mean and standard deviation (mean ± SD). Values for the last 5 min at rest and 15 ~ 20, 35 ~ 40, 55 ~ 60 min after entering the experimental chamber were averaged. Changes in skin temperature at 20, 40 and 60 min after cold exposure were calculated the difference between the rest and 15 ~ 20, 35 ~ 40, 55 ~ 60 min values, respectively. Statistical analyses were done using SPSS v. 21 (IBM SPSS Statistics, USA). One-way ANOVA and Tukey's HSD test were used to identify differences among the five experimental conditions. Significance was accepted at $p < 0.05$.

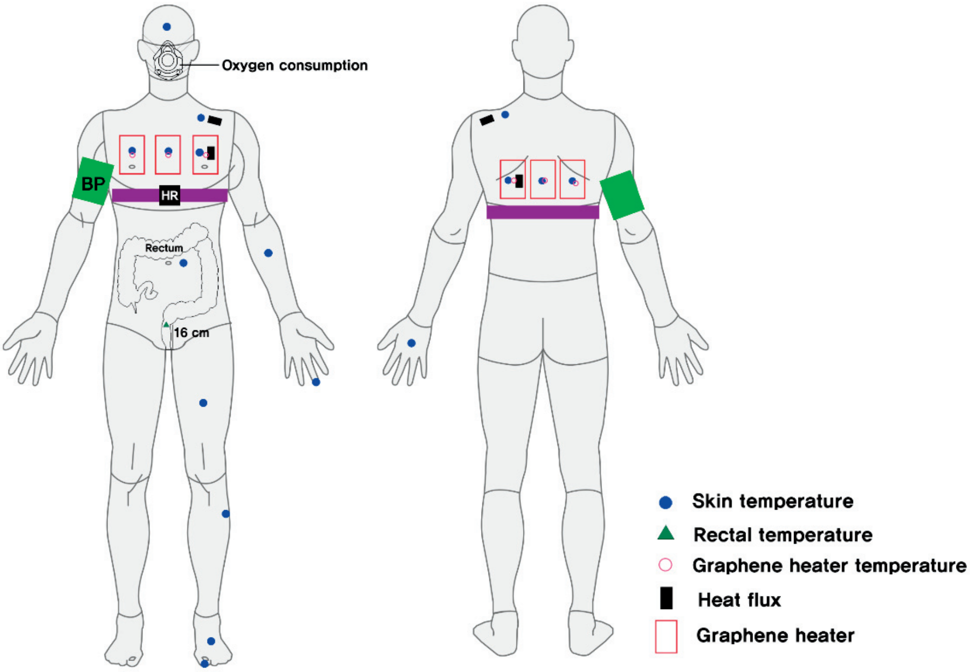

Figure 3.6. A diagram of measurement sites where skin temperatures, rectal temperature, graphene heater temperature, heat flux, oxygen consumption, heart rate (HR), blood pressure (BP) and locations of graphene heater.

Chapter 4. Results

4.1. Permissible temperature of graphene heater for human application

Subjects felt warm or hot sensation and also felt irritated when the skin temperature was over 36°C and the graphene heater temperature was around 45°C. Therefore, the permissible temperature of the graphene heater for human application was decided to be around 45°C considering pain sensation, subjective perceptions and the prevention of skin burn injury (Moritz, 1947) (Table 4.1).

Table 4.1. Permissible temperatures of graphene heaters and skin temperature when heating was terminated on the chest and back

Body region	Subject	Permissible temp. of graphene (Left side) (°C)	Permissible temp. of graphene (Middle side) (°C)	Skin temp. under the permissible temperature of graphene (°C)	Voltage stopped (V)
Chest	A	45.2	41.5	38.1	20
	B	49.7	59.8	38.5	24
Back	A	45.6	42.9	41.5	20
	B	43.7	39.5	36.3	20

For subject B in the chest heating condition, graphene temperature was higher (49.7°C and 59.8°C) than subject A but chest temperature maintained at a moderate level (38.5°C), which was because the graphene heaters were not tight on the body because of the subject's crouched posture.

Thermal sensations on the chest and/or back were improved by an approximate score of 1.5 ~ 2.0 because of the chest and/or back heating. Interestingly, chest and/or back heating improved the thermal sensation of the opposite non-heated trunk part by a score of 0.5 ~ 1.0. Heating the upper back improved overall thermal sensation by a score of 1.5 whereas chest heating did not cause any improvement of overall thermal sensation (Figure 4.1).

Thermal comfort on the chest and/or back were maintained at a level of between 'Not both' ~ 'A little comfortable' though the temperature of graphene heater was increased. Overall thermal comfort was improved by an approximate score of 0.5 ~ 1.0 because of the chest and/or back heating (Figure 4.1). This showed improving local thermal comfort more than a certain level had some limitations during the whole body exposed to cold environments by local heating, but local heating was able to relieve overall thermal discomfort according to the temperature of graphene heater was increased.

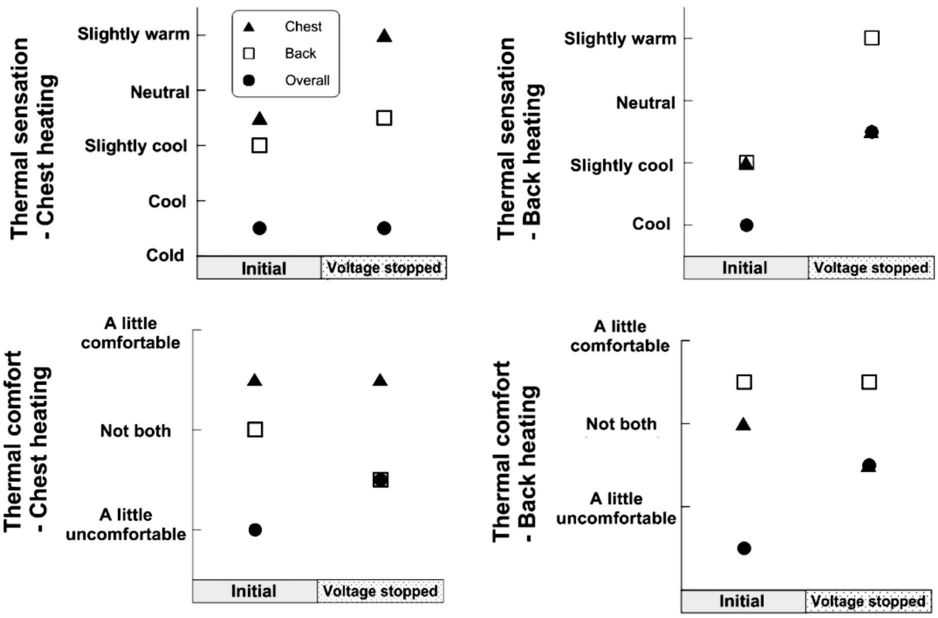

Figure 4.1. Subjective perceptions during chest heating and upper back heating, respectively.

4.2. Intermittent heating protocols

Five intermittent heating protocols were developed with different electric power consumptions (Figure 4.2). For the continuous heating protocol (CP), 20 V during 60 min generated an electric power of 8.58 W from three graphene heaters. For the intermittent heating protocols, electric power was 5.28, 5.49, 2.49, 5.10, and 2.94 W for IP-1, IP-2, IP-3, IP-4, and IP-5, respectively. IP-3 was the most efficient among the five IPs and 3.4 times more efficient when compared to CP (2.49 W vs. 8.58 W) (Table 4.2). During the heating, the surface temperature of the graphene heaters was on average 40.4, 42.1, 37.1, 41.6, 38.5, and 49.7°C for IP-1, IP-2, IP-3, IP-4, IP-5 and CP at T_a of 32.1 ± 0.6°C, H_a of 26 ± 1%RH. Based on the results, IP-3 was selected for the following human wear trials.

Table 4.2. Comparing intermittent heating protocols and continuous heating protocol

	IP-1	IP-2	IP-3	IP-4	IP-5	CP
Electric power (W)	1.76	1.83	0.83	1.70	0.98	2.86
Mean temperature of graphene heaters (°C)	40.4	42.1	37.1	41.6	38.5	45.0
Mean absolute temperature of graphene heaters (K)	313.59	315.21	310.30	314.76	311.61	318.15
K W^{-1}	178.2	172.2	373.9	185.2	318.0	111.2
Energy efficiency compared to CP (times)	1.6	1.5	3.4	1.7	2.9	1.0

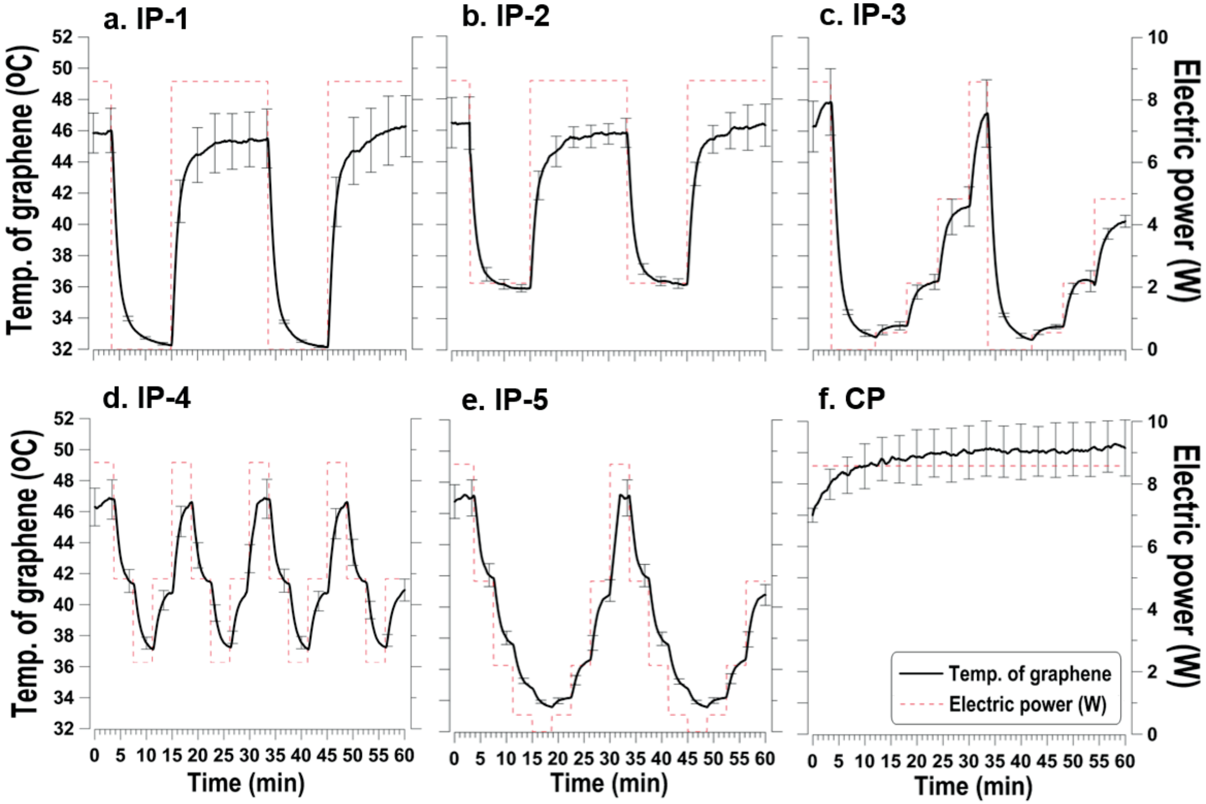

Figure 4.2. Averaged surface temperature and electric power of three pieces of graphene heaters according to continuous and intermittent heating protocols for 60 min (mean ± SD).

4.3. Evaluation of heating protocols in human wear trials

4.3.1. Temperature distribution of graphene heaters

Averaged surface temperatures of three pieces of graphene heaters during 60 min were 47.7 ± 3.9, 47.7 ± 7.4, 36.4 ± 4.7 and 35.7 ± 4.9 for the continuous heating the chest (CC), continuous heating the upper back (CB), intermittent heating the chest (IC), and intermittent heating the upper back (IB), respectively ($p < 0.001$). Graphene heaters that were inserted into the middle region showed significantly higher temperatures than heaters on the right or left side for continuous heating protocols ($p < 0.05$). For the back, in particular, 55.7 ± 7.7°C in the middle region was found while 43.5 ± 1.0°C on the right and 44.1 ± 4.0°C on the left ($p < 0.001$). However, intermittent protocols did not show any significant differences among the three locations of graphene heaters (Table 4.3).

Table 4.3. Temperature of graphene heaters by experimental conditions and by location of graphene heaters

Location of graphene	CC	CB	IC	IB
Right side	45.6 ± 2.6^{a}	43.5 ± 1.0^{a}	36.6 ± 0.8	35.7 ± 1.1
Middle	50.4 ± 3.2^{b}	55.7 ± 7.7^{b}	36.2 ± 1.4	36.0 ± 1.7
Left side	47.0 ± 3.3^{ab}	44.1 ± 4.0^{a}	36.4 ± 0.6	35.7 ± 1.0
p-value	0.014	<0.001	0.771	0.821

Note: Letters a, b represent significantly identical groups among three graphene location which were distinguished by Tukey HSD test (a < b).

4.3.2. Thermoregulatory, cardiovascular and respiratory responses

No differences were found in rectal temperature (T_{re}) among the five conditions while mean skin temperature ($\bar{T}_{sk}$) showed the lowest temperatures for the no heating condition (31.7 ± 1.0°C) and the highest for the intermittent heating on the chest (33.0 ± 0.9°C) at the initial stage of cold exposure (1 ~ 5th min of cold exposure) ($p < 0.05$) (Figure 4.3a) (Table 4.4). Chest temperature increased by 5.6 ± 1.8°C for CC and 2.4 ± 1.3°C for IC conditions, but decreased by 1.1 ~ 1.7°C for NH, CB and IB ($p < 0.001$) (Figure 4.3b) (Figure 4.4). Upper back temperatures increased by 1.3 ± 1.9°C for CB and decreased by -0.09 ± 1.2°C for IB conditions, but decreased by 2.5 ~ 3.1°C for NH, CC and IC ($p < 0.001$) (Figure 4.3c) (Figure 4.5). Heat gain on the chest from the graphene heaters in CC condition was approximately 179 ± 118, 176 ± 111, 169 ± 153, and 158 ± 125 W·m^2 greater than values in NH, CB, IC and IB condition (Figure 4.3d). No significant differences were found in heat flux on the upper back among the five conditions.

Heart rate maintained during the 60-min cold exposure and had 72 ± 7, 73 ± 6, 71 ± 7, 72 ± 9, and 72 ± 8 bpm for NH, CC, CB, IC, and IB, respectively, at the 60th min without any differences among the five conditions. Oxygen consumption also showed no group differences (6.90 ± 1.22, 7.18 ± 1.61, 6.69 ± 1.15, 6.33 ± 1.51, and 6.40 ± 1.36 ml·min·kg^{-1} for NH, CC, CB, IC and IB, respectively) Insensible body mass loss showed no group differences and the values were in the normal range of 140 ~ 170 g for 2 hours (Table 4.5). Blood pressure increased over time during cold exposure without any differences among the five conditions (Table 4.6).

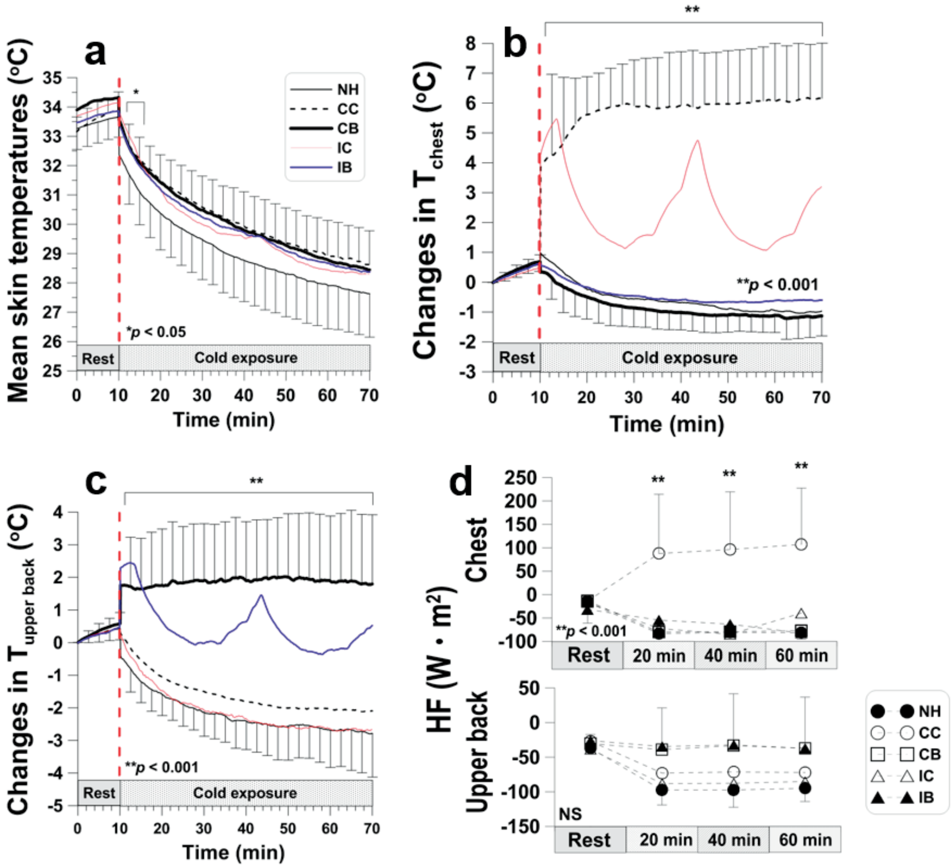

Figure 4.3. Mean skin temperature (a), changes in chest temperature (b), changes in upper back temperature (c), and heat flux on the chest and upper back (d). Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

Table 4.4. Summary of mean skin temperature of the five conditions during 11 ~ 15 min

	NH	CC	CB	IC	IB	*p*-value
11 min	32.24 ± 0.99^{a}	33.39 ± 0.67^{b}	33.40 ± 0.40^{b}	33.67 ± 0.69^{b}	33.25 ± 0.72^{ab}	0.004
12 min	31.96 ± 0.94^{a}	33.03 ± 0.67^{b}	32.98 ± 0.47^{ab}	33.32 ± 0.79^{b}	32.91 ± 0.70^{ab}	0.008
13 min	31.68 ± 1.01^{a}	32.72 ± 0.67^{ab}	32.62 ± 0.51^{ab}	33.01 ± 0.80^{b}	32.59 ± 0.67^{ab}	0.015
14 min	31.45 ± 1.07^{a}	32.47 ± 0.67^{ab}	32.37 ± 0.53^{ab}	32.73 ± 0.82^{b}	32.32 ± 0.68^{ab}	0.026
15 min	31.20 ± 1.10^{a}	32.30 ± 0.71^{ab}	32.18 ± 0.56^{ab}	32.37 ± 0.85^{b}	32.07 ± 0.73^{ab}	0.041

Note: Letters a, b represent significantly identical groups among five conditions which were distinguished by Tukey HSD test (a < b).

NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

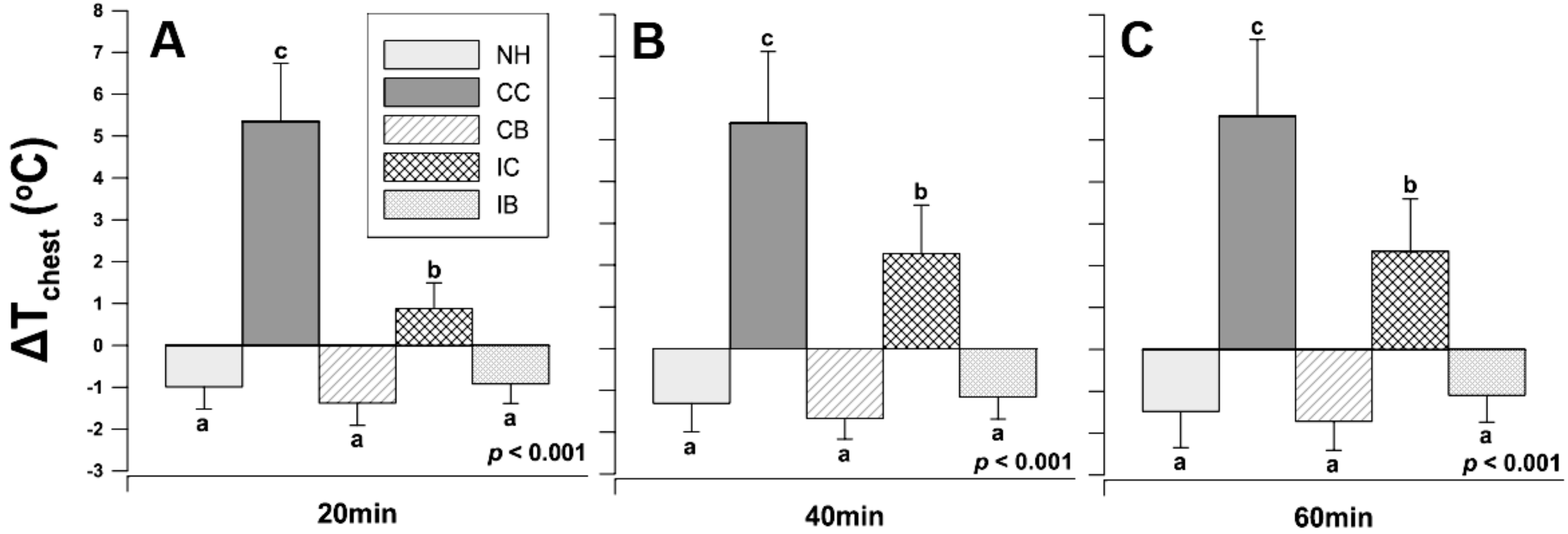

Figure 4.4. Changes in chest temperature at 20, 40 and 60 min after cold exposure.

Note: Letters a, b, c represent significantly identical groups among five conditions which were distinguished by Tukey HSD test (a < b < c).

NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

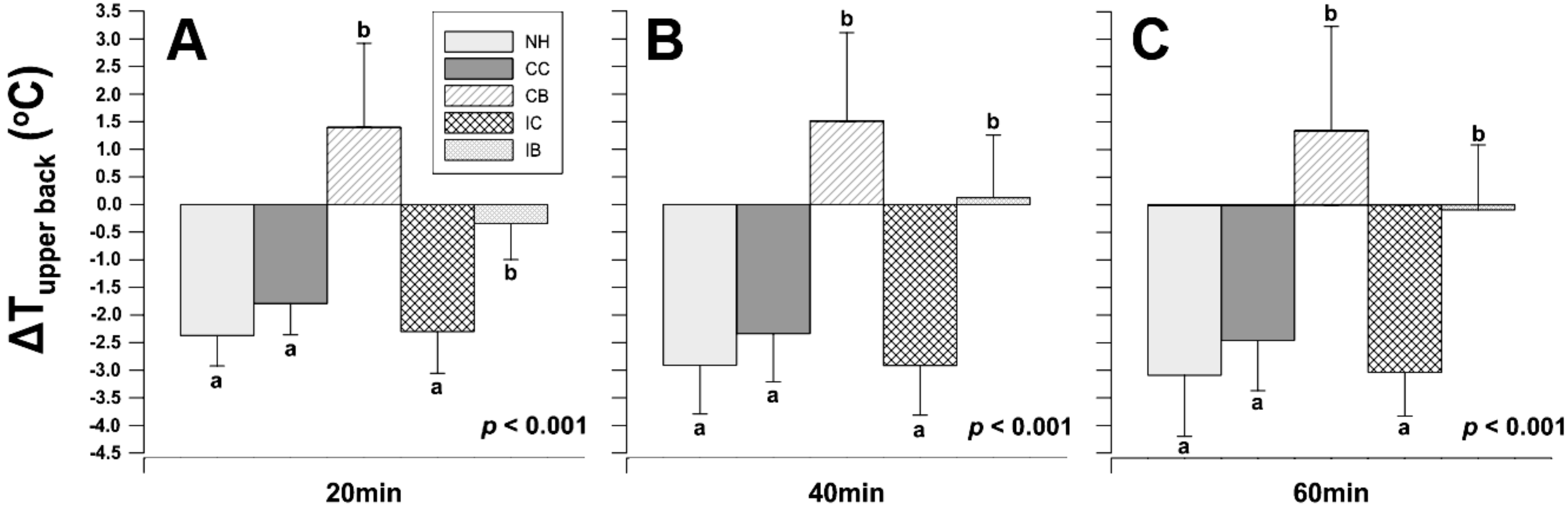

Figure 4.5. Changes in upper back temperature at 20, 40 and 60 min after cold exposure.

Note: Letters a, b represent significantly identical groups among five conditions which were distinguished by Tukey HSD test (a < b).

NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

Table 4.5. Summary of heart rate (HR), VO_2 and Insensible body mass loss of the five conditions

		NH	CC	CB	IC	IB	*p*-value
HR (bpm)	Rest	75 ± 8	74 ± 7	75 ± 9	76 ± 9	74 ± 9	0.986
	20 min	74 ± 9	76 ± 11	73 ± 8	74 ± 10	76 ± 11	0.947
	40 min	73 ± 9	73 ± 9	71 ± 9	73 ± 9	73 ± 10	0.987
	60 min	72 ± 7	73 ± 6	71 ± 7	72 ± 9	72 ± 8	0.985
VO_2(mL·min·Kg^{-1})		6.90 ± 1.22	7.19 ± 1.61	6.69 ± 1.15	6.33 ± 1.51	6.40 ± 1.36	0.728
Insensible body mass loss (g·2h^{-1})		150 ± 50	160 ± 50	170 ± 50	150 ± 50	140 ± 50	0.814

Table 4.6. Summary of blood pressure (BP) of the five conditions at rest, 20, 40, 60 min after cold exposure

BP (mmHg)		NH	CC	CB	IC	IB	*p*-value
Systolic pressure	Rest	122 ± 10^{a}	121 ± 8^{a}	123 ± 8	120 ± 9^{a}	122 ± 10^{a}	0.946
	0 min	127 ± 9^{ab}	126 ± 11^{ab}	122 ± 9	122 ± 10^{ab}	126 ± 9^{a}	0.798
	20 min	131 ± 7^{ab}	132 ± 9^{ab}	126 ± 9	130 ± 8^{ab}	128 ± 9^{a}	0.680
	40 min	133 ± 5^{ab}	135 ± 9^{b}	131 ± 11	134 ± 11^{ab}	134 ± 9^{a}	0.948
	60 min	136 ± 8^{b}	136 ± 8^{b}	132 ± 14	134 ± 12^{b}	136 ± 11^{a}	0.960
	p-value	0.012	0.009	0.2	0.014	0.045	
Diastolic pressure	Rest	79 ± 7^{a}	76 ± 8^{a}	79 ± 6^{a}	77 ± 6^{a}	78 ± 6^{a}	0.874
	0 min	86 ± 7^{ab}	82 ± 11^{ab}	81 ± 7^{ab}	80 ± 8^{ab}	81 ± 6^{ab}	0.551
	20 min	87 ± 7^{ab}	89 ± 8^{ab}	85 ± 6^{ab}	86 ± 7^{ab}	83 ± 7^{ab}	0.545
	40 min	88 ± 5^{ab}	89 ± 9^{ab}	88 ± 7^{ab}	89 ± 7^{b}	88 ± 6^{b}	0.988
	60 min	90 ± 7^{b}	91 ± 10^{b}	91 ± 11^{b}	90 ± 8^{b}	89 ± 8^{b}	0.996
	p-value	0.039	0.015	0.027	0.003	0.007	
Mean arterial pressure	Rest	94 ± 8^{a}	91 ± 8^{a}	93 ± 5^{a}	91 ± 7^{a}	92 ± 6^{a}	0.892
	0 min	100 ± 7^{ab}	97 ± 11^{ab}	95 ± 8^{a}	94 ± 8^{ab}	96 ± 6^{ab}	0.643
	20 min	101 ± 7^{ab}	103 ± 9^{ab}	99 ± 7^{a}	101 ± 7^{ab}	98 ± 6^{ab}	0.557
	40 min	103 ± 5^{ab}	104 ± 8^{b}	102 ± 8^{a}	104 ± 8^{b}	103 ± 7^{b}	0.978
	60 min	105 ± 7^{b}	106 ± 9^{b}	105 ± 12^{a}	104 ± 9^{b}	105 ± 9^{b}	0.998
	p-value	0.022	0.010	0.046	0.003	0.007	

4.3.3. Psychological responses

For thermal sensation on the chest, subjects felt the most warmth in CC and the least warmth in NH. Intermittent heating the chest had an insignificant effect on the improvement of chest thermal sensation because of great individual variations (Figure 4.6a). For thermal sensation on the back, similar results as the chest thermal sensation were obtained. Subjects felt the most warmth on the back in CB but intermittent heating the back had an insignificant effect on the improvement of back thermal sensation (Figure 4.6b). For thermal comfort on the chest (Figure 4.6c) and/or back (Figure 4.6d), similar results as thermal sensation were obtained from both chest and back.

No significant differences were found in thermal tolerance among the five conditions. However, thermal tolerance was significantly increased over time for all conditions (p<0.001). On average, thermal tolerance was maintained around 0 (perfectly tolerable) at rest and around 1.5~2.25 (1: slightly difficult tolerable ~ 2: fairly difficult to tolerable) at 60 min after cold exposure (Table 4.7).

On average, shivering onset time was 20.9 min ± 12.8 min and shivering was subjectively perceived as 5.6 ± 3.4 times during the 60 min cold exposure (Table 4.8). The total numbers of shivering were 43, 29, 40, 43, and 48 times for NH, CC, CB, IC and IB during the 60-min cold exposure (Table 4.9).

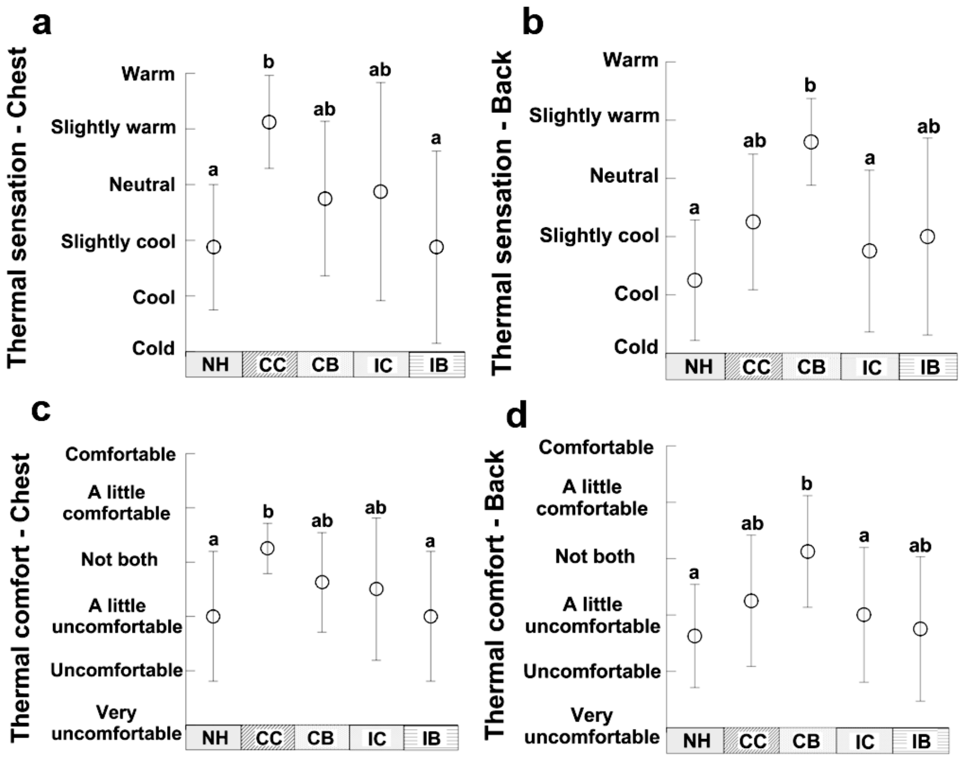

Figure 4.6. Thermal sensation on the chest (a) and the back (b); thermal comfort on the chest (c) and the back (d) in the five conditions at the 60th min during the cold exposure. Note: Letters a, b represent significantly identical groups among five conditions which were distinguished by Tukey HSD test (a < b). NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

Table 4.7. Summary of thermal tolerance of the five conditions at rest, 20, 40, 60 min after cold exposure

	NH	CC	CB	IC	IB	*p*-value
Rest	0.13 ± 0.35^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.13 ± 0.35^{a}	0.13 ± 0.35^{a}	0.736
0 min	0.38 ± 0.52^{a}	0.13 ± 0.35^{a}	0.00 ± 0.00^{a}	0.25 ± 0.46^{a}	0.25 ± 0.46^{a}	0.426
20 min	1.00 ± 0.76^{ab}	0.75 ± 0.46^{ab}	0.50 ± 0.53^{ab}	0.75 ± 0.71^{ab}	1.13 ± 0.64^{ab}	0.329
40 min	1.50 ± 0.76^{bc}	1.50 ± 0.93^{b}	1.13 ± 0.83^{bc}	1.63 ± 1.06^{bc}	1.63 ± 1.06^{b}	0.817
60 min	2.25 ± 0.89^{c}	1.75 ± 1.16^{b}	1.50 ± 1.20^{c}	2.00 ± 1.07^{c}	2.00 ± 0.76^{b}	0.655
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	

Table 4.8. Summary of number of subjects who felt shivering, onset time and frequency

	NH	CC	CB	IC	IB	*p*-value
Number of subjects who felt shivering (n)	7	6	8	7	8	-
Onset time after cold exposure (s)	1354 ± 783	983 ± 629	1625 ± 782	1087 ± 945	1144 ± 685	0.538
Frequency (times)	6.1 ± 3.2	4.8 ± 1.9	5.0 ± 5.0	6.1 ± 1.7	6.0 ± 4.0	0.915

Table 4.9. Summary of number of shivering in each body part of the five conditions

CC (total number: 29)	
trunk (12)	chest (8), back (2), trunk (1), upper back (1)
leg (8)	thigh (5), leg (2), shin (1)
whole body (5)	-
arm (3)	both arm (1), left upper arm (1), left arm (1)
neck (1)	back neck (1)
NH (total number: 43)	
trunk (24)	chest (10), back (5), shoulder (4), trunk (3), upper back (1), side (1)
leg (6)	leg (5), thigh (1)
arm (6)	arm (4), upper arm (2)
whole body (4)	-
head (1)	-
hand (1)	-
mouth (1)	-
CB (total number: 40)	
trunk (18)	trunk (7), back (4), chest (4), shoulder (2), waist (1)
leg (8)	leg (4), thigh (3), calf (1)
arm (7)	arm (5), both arm (1), left arm (1)
neck (3)	back neck (3)
whole body (2)	-
head (1)	-
hand (1)	-
IB (total number: 48)	
trunk (31)	trunk (8), chest (6), back (5), side (4), trapezius muscle (2), upper chest (2), upper back (2), shoulder (1), lower back (1)
leg (6)	leg (5), thigh (1)
arm (7)	arm (4), both arm (2), upper arm (1)
whole body (3)	-
neck (1)	-
IC (total number: 43)	
trunk (23)	Chest (13), back (4), upper back (3), trunk (2), upper body (1)
whole body (6)	-
arm (6)	both arm (2), arm (2), left upper arm (1), both upper arm (1),
neck (4)	neck (3), back neck (1)
leg (4)	Leg (3), knee (1)

Note: (N) represents the number of shivering each value occurs in each body part.

Chapter 5. Discussion

5.1. Advantages in intermittent heating protocol

5.1.1. Advantage 1: Electric power saving

In this study, electric power consumption was able to be conserved up to 71% by using an intermittent heating protocol. In previous studies related to electrically heated clothing, electric power was conserved up to 50% or more by adjusting maximum heating temperature or reducing heated body region (Kukkonen et al., 2001; Wang, 2010; Wang and Lee, 2010). The present results are original as the previous studies did not report the effects of intermittent heating. In the case of cooling, there were several previous studies on intermittent cooling that identified battery efficiency and the cooling effect (Cadarette et al., 2006; Cheuvront et al., 2003; Davey et al., 2013). Davey et al. (2013) studied the cooling effects of continuous air perfusion and intermittent air perfusion. Total air flow during intermittent perfusion was half of the continuous perfusion but intermittent perfusion was more effective on thermal comfort and temperature sensation. Cheuvront et al. (2003) reported that intermittent regional cooling protocols which were a half of cooling and a quarter of cooling was 164 ~ 215% more efficient than a continuous protocol and had positive physiological effects. Cadarette et al. (2006) showed that the whole body liquid cooling garment in a pattern of 2 min on-off reduced heat strain as much as continuous cooling for exercising male subjects wearing US Army chemical protective clothing. Even though it is hard to find studies about intermittent heating, the effect and efficiency of an intermittent heating protocol could be predicted with the above studies. In this regard, the present study explored the effects of intermittent heating protocols.

The biggest advantage of the intermittent heating protocol is to save electric power consumption along with obtaining psychologically-positive responses. In order to save power consumption apart from the intermittent protocol, heating areas should be small or thermal resistance of the heater should be low. However, the small heating area is not effective in terms of physiological or psychological thermoregulation. Lowering resistance is technically challenging. In this light, an intermittent heating protocol was regarded as the optimal way to achieve an equilibrium between electric power saving and thermal comfort of wearers. The intermittent heating protocol is advisable for the case of requiring low electric power consumption with maintaining heating effects. In addition, the graphene heater with intermittent heating protocol could alter the heating temperature immediately due to the high conductivity of the graphene.

5.1.2. Advantage 2: Uniformity of heated skin temperature

Three pieces of graphene heaters were placed on the left, middle, and right side of the chest and/or upper back. The temperature of the middle graphene heater on the back in CP showed a tendency of being higher (55.7 ± 7.7°C) than for the left (44.1 ± 4.0°C) and right heater (43.5 ± 1.0°C), while the differences in surface temperatures among the three regions ranged only from 0.2 to 0.4°C for IP. The result is predictable due to the interference effect of heat and the curved shape of the upper back. That is, the left and right side have projecting scapula but the middle area on the back formed a recessed shape which contains a layer of air. In this study, graphene heaters did not closely adhere to the skin during the whole experiment. T_{chest} and $T_{upper\ back}$ under the graphene heaters maintained at the range of 38.2 ~ 40.5°C. However, if subjects changed their posture or move their body during the experiment, graphene heaters would tightly attach to the skin and skin temperature would rise. In the present study, the surface temperature of the middle graphene heater during continuous heating was high enough to cause skin burn injuries. The intermittent heating protocol attains superiority over the continuous protocol in regards to preventing skin burn injuries.

5.2. Advantages of heating the back than the chest

5.2.1. Preventing skin temperature drop rather than increasing skin temperature

In the present study, the increments of T_{chest} during chest heating were higher than the increments of $T_{upper\ back}$ during back heating. This could be related to greater decrement in back temperature (3.1 ± 1.1°C) than in chest temperature (1.5 ± 0.9°C) during cold exposure in NH condition. The chest (33.9 ± 1.2°C) and upper back temperature (33.9 ± 1.2°C) were similar to each other at rest ($p > 0.05$), but $T_{upper\ back}$ lowered more quickly to cold exposure than chest temperature. However, a couple of previous researchers showed T_{chest} was lower than T_{back} (Huizenga et al., 2004; Wagner et al., 1974). Zhang (2003) reported chest temperature was 30.9°C while the back temperature was 32.4°C at T_a 15.6°C for 2 h, Webb (1992) showed left chest anterior was higher (30.1 ± 2.0°C) than right chest posterior (30.7 ± 0.9°C) during cold exposure for 2 h.

We propose that the lower back temperature in the present study was because of the forced ventilation in clothing induced by an air velocity of over 1.3 $m \cdot s^{-1}$ in this study. Subjects' skin fold thickness of the chest and upper back were similar (11.6 ± 7.9 and 14.9 ± 8.1 mm, respectively, $p > 0.05$). Radiative heat transfer coefficient and regional surface area on the chest and back were similar (de Dear et al., 1997). Taken together, it seems that the wind in cold environments is an important factor in deciding temperature distribution between the chest and back in terms of forced ventilation in clothing. Heating the upper back would be more effective in the windy environment to prevent excessive drop in skin temperature. That is, a heating protocol for wearers in cold environments should be designed to prevent skin temperature drop rather than to increase skin temperature. This is reasonable in that people feel cold when skin temperature drops.

5.3. Heating effects on psychological responses

The present results were contrary to expectations. We hypothesized that intermittent heating would show positive effects on subjective responses compared to continuous heating because the human skin is adapted to continuous thermal stimuli. However, intermittent heating did not induce significantly-positive influences on thermal sensation or thermal comfort, which might be relevant to great individual variations. Among the five experimental conditions, a significant improvement on psychological responses was only shown with continuous heating. Standard deviations among the subjects tended to be greater for the intermittent heating condition compared to the continuous heating condition.

The changes in body heat content (S) during NH condition experiment was calculated by a modified Burton's equation (Burton, 1935):

$$S\,(\mathrm{W}) = \Delta \bar{T}_b\, \mathrm{m}\, \mathrm{C} / \mathrm{t}\ 1000 \qquad \text{[Eq. 5.1]}$$

Where, $\Delta \bar{T}_b$ refers to the difference in $\bar{T}_b$ (°C)

m: body mass (kg)

C: heat capacity (kJ kg^{-1} $°C^{-1}$)

(used 3.47 kJ kg^{-1} $°C^{-1}$ which is identical to 0.8 kcal kg^{-1} $°C^{-1)}$

t: duration of the experimental trial (s).

The ranges were 94 ~ 220 W. Heat loss varied according to subjects and the maximum difference was 2.3 times. When considering the differences in self-identified cold tolerance among subjects as well as the great individual variations in subjective responses, the present results suggest that it is required to develop various intermittent heating protocols and a self-controlling system enabling wearers to choose their own preferred method of continuous heating and intermittent heating for the active heating clothing system with graphene heater in the future.

Chapter 6. Limitations and Suggestions

In this study, we selected a protocol that uses the lowest power consumption compared to the continuous heating protocol. However, the intermittent heating protocol can be developed in a myriad of cases such as a protocol that simply turns on/off at 1 minute or 2 minutes intervals, including the other four types of the protocol developed in this study. In order to reduce the interference effect of the individual differences and to find out the clear psychologically positive effect of the intermittent heating protocol, various protocols should be developed and evaluated.

If the related studies continue, researchers will be able to propose specifications for the temperature of heater and temperature range depending on environmental temperature, clothing microclimate, voltage pulse generation. As a result, consumers will enable to easily develop customized heating protocols. It is anticipated that the development and application of personalized heating protocol will result in positive physiological and psychological results as well as reduced power consumption.

For the further research, studies on the thermal conductivity of the heater pocket fabric, the minimization of the heat dissipation of the heater using the radiant barrier and etc. can be suggested as a way to increase the thermal efficiency of the heater.

Chapter 7. Conclusions

We evaluated the applicability of graphene heaters manufactured by a roll-to-roll method used for the human body exposed to a cold and windy environment. Intermittent and continuous heating protocols with graphene heated clothing were applied to the chest and/or upper back for heating. To maintain psychological comfort in the cold and windy environment, the upper back heating was more effective than the chest heating. The intermittent heating protocol had advantages in the following areas: 1) conserving electric power as much as 71% compared to continuous heating as thermoregulatory, respiratory and psychological responses maintained at a similar level, and 2) preventing low-temperature burns due to overheating. For continuous heating protocols, the surface temperature in the middle space between connected graphene heaters increased up to 55°C, which may induce low-temperature burns if the local heating prolonged. Some subjects felt warmer and more comfortable when intermittent heating protocols were applied, even though thermal sensation and comfort did not show any significant differences between intermittent and continuous heating protocols. Further studies are required to develop and evaluate an individualized control system with various intermittent heating protocols.

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Appendix

Table A.1. Heating power (W), heating body region from electrically heated clothing

Heater type	Heating power (W)	Heating body region	Reference
Gloves	13.4 ± 3.4 per a glove	Hand	Wang, 2010
Gloves	19 per a glove	Hand	Scott, 1988
Gloves	12 per a glove	Hand	Scott, 1988
Gloves – High voltage	5 per a glove	Hand / Back	Risikko and Anttonen, 1998
Gloves – Low voltage	1 per a glove	Fingers	Risikko and Anttonen, 1998
Socks	9.8 ± 2.4 per a sock	Foot	Wang, 2010
Socks	8 per a sock	Foot	Scott, 1988
Socks	1 per a sock	Toes	Risikko and Anttonen, 1998
Insole	12 per a insole	Sole	Scott, 1988
Vest	~11.3	Torso	Wang, 2010
Vest	13.05	Torso	Wang and Lee, 2010
Vest	9, 13.9, 24.7	Torso	Wang and Lee, 2010
Vest	5, 13	Torso	Wang and Lee, 2010
Vest	16.3	Upper back	Lee and Jeong, 2010
Vest	10.1	Upper back, lower back	Lee and Jeong, 2010
Vest	17.8	Abdomen, upper back	Lee and Jeong, 2010
Undershirts	32, 64	Arms, upper body	Rantanen, 2001

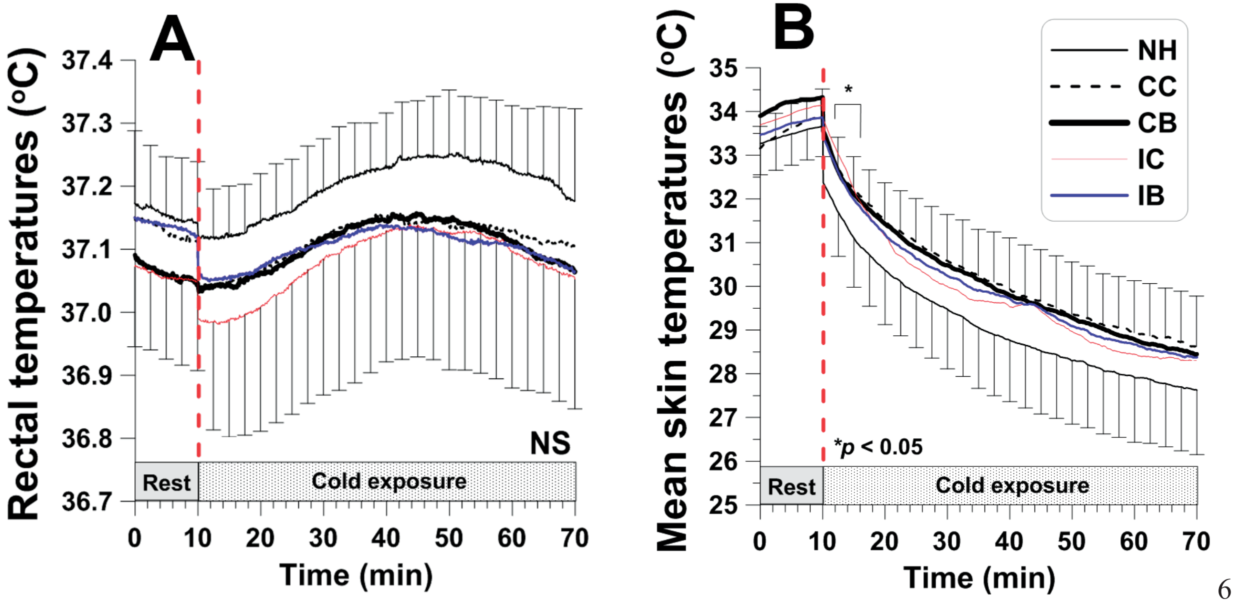

Figure A.1. Rectal temperature (A) and mean skin temperature (B) in the experiment evaluating the five heating protocols. Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

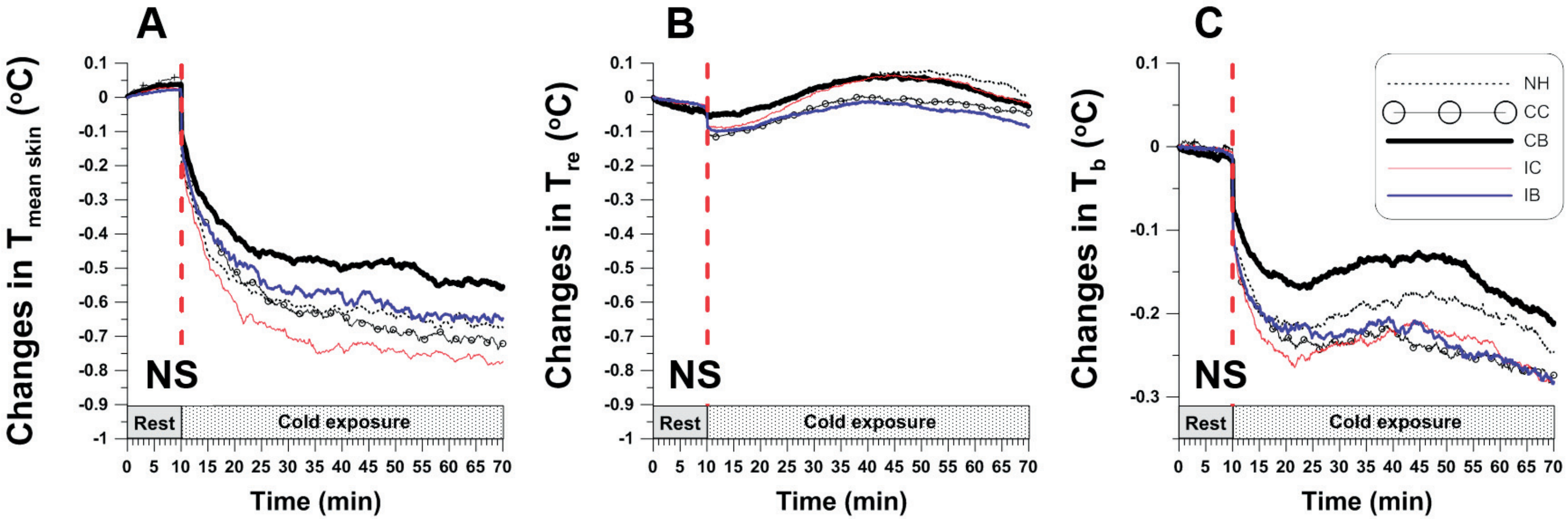

Figure A.2. Changes in mean skin temperature (A), changes in rectal temperature (B) and changes in mean body temperature (C) in the experiment evaluating the five heating protocols. Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

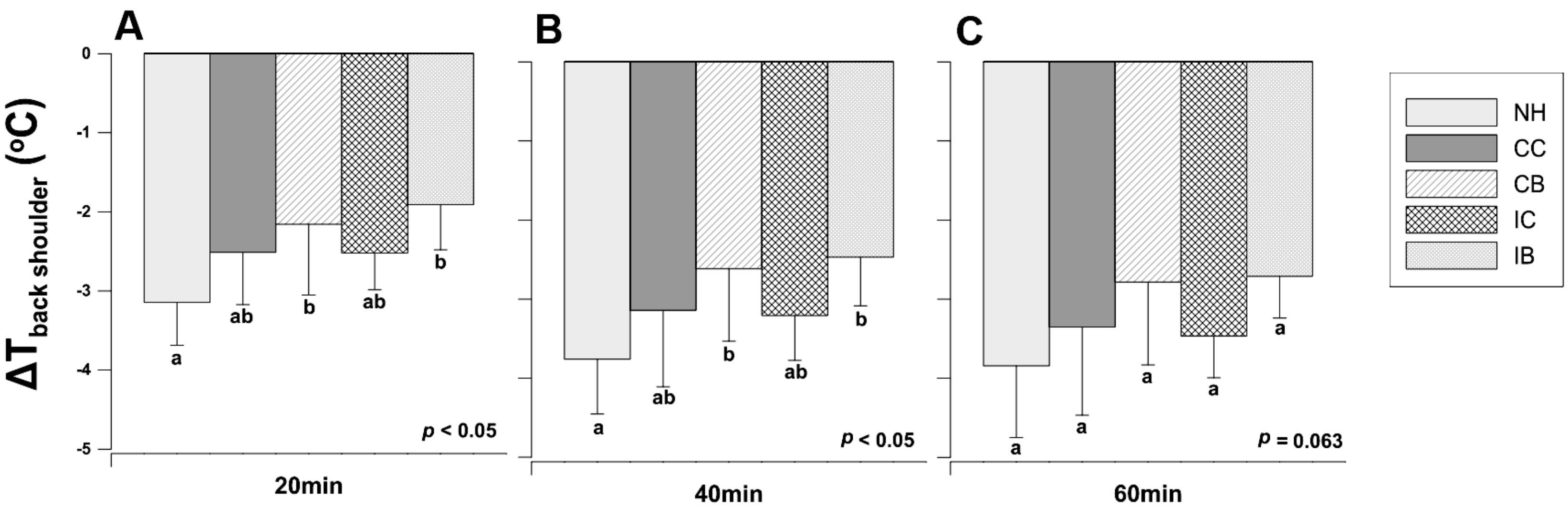

Figure A.3. Changes in back shoulder temperature at 20, 40 and 60 min after cold exposure in the experiment evaluating the five heating protocols.

Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

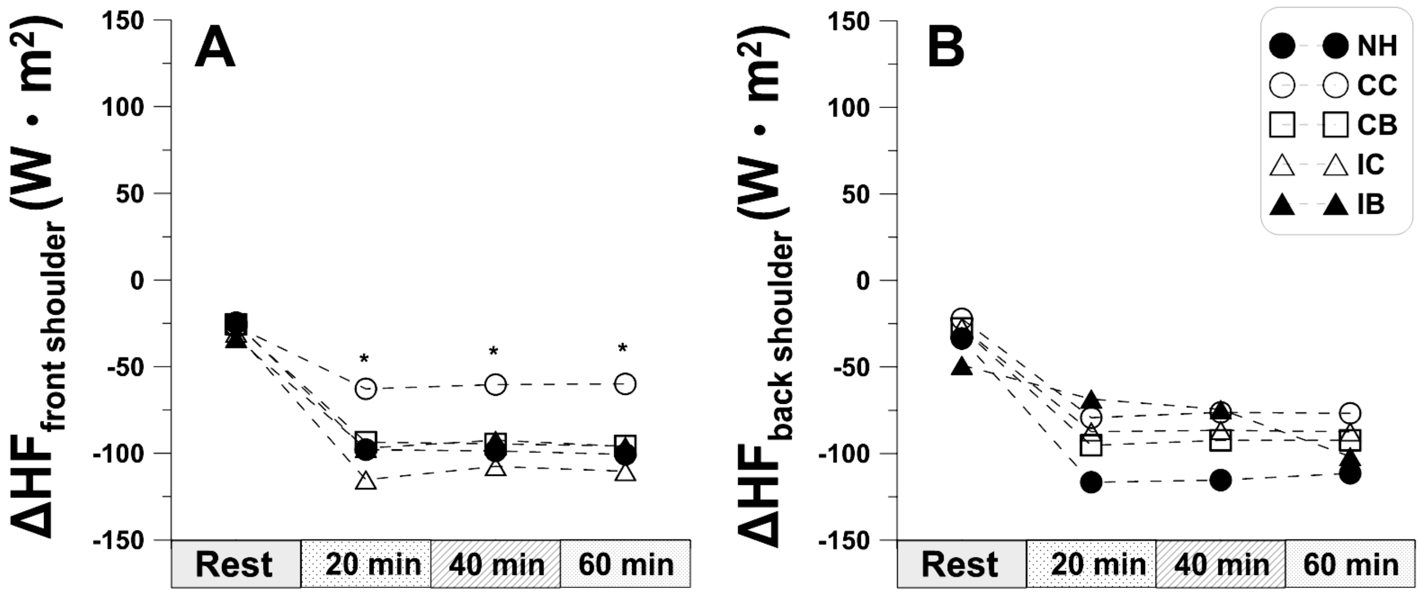

Figure A.4. Heat flux on the front shoulder (A) and back shoulder (B) in the experiment evaluating the five heating protocols. Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

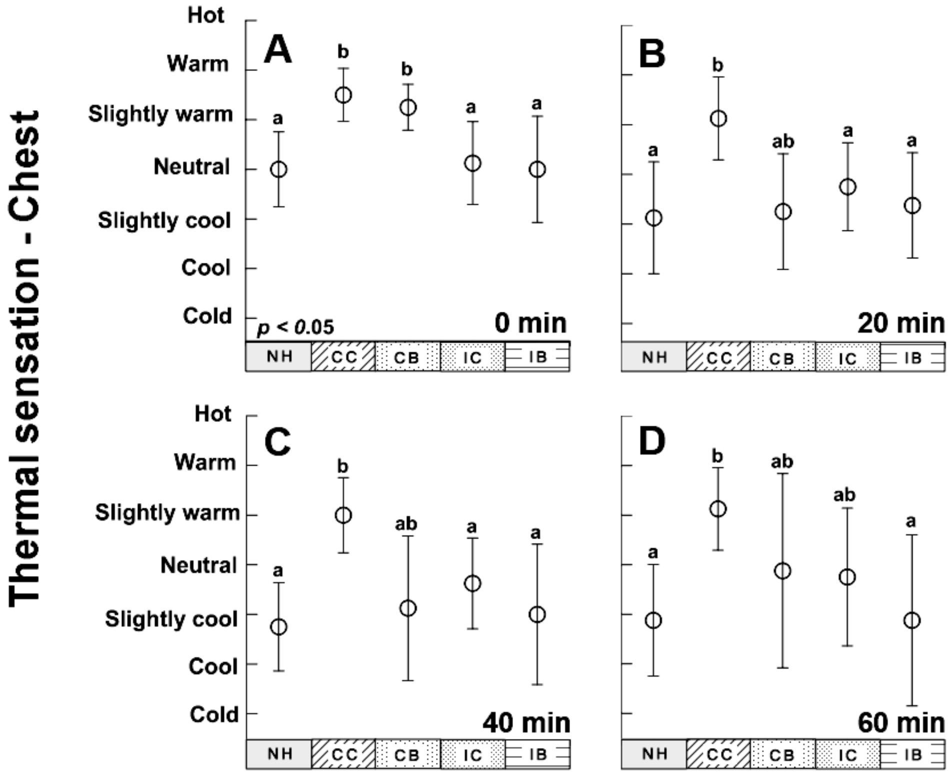

Figure A.5. Thermal sensation on the chest at 0, 20, 40 and 60 min after cold exposure in the experiment evaluating the five heating protocols. Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

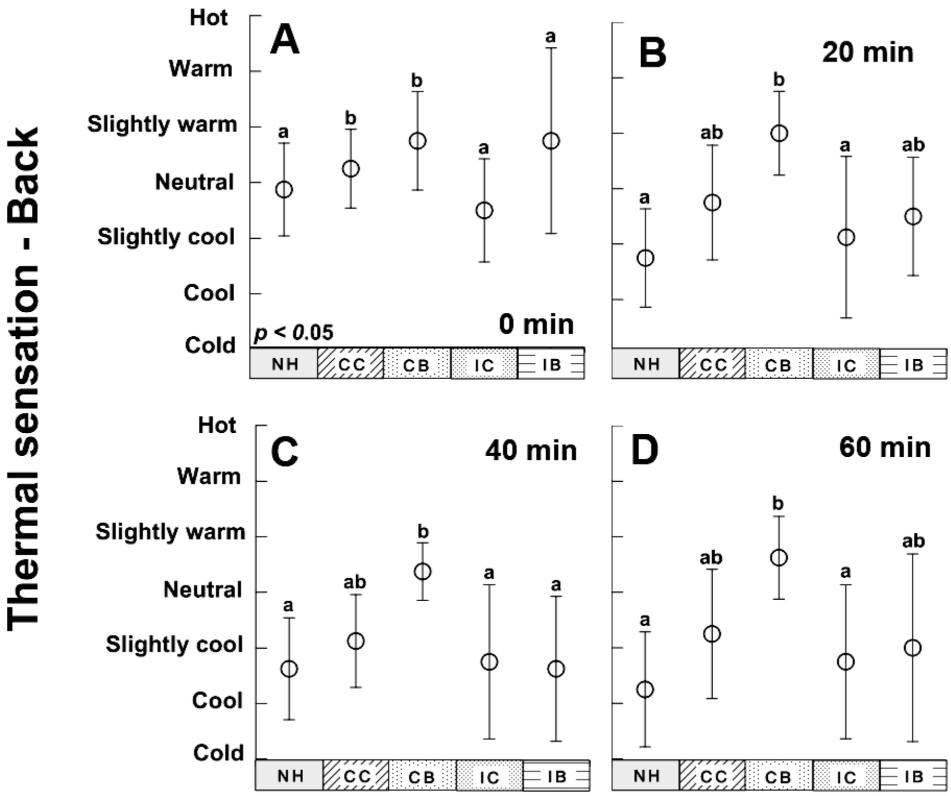

Figure A.6. Thermal sensation on the back at 0, 20, 40 and 60 min after cold exposure in the experiment evaluating the five heating protocols. Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

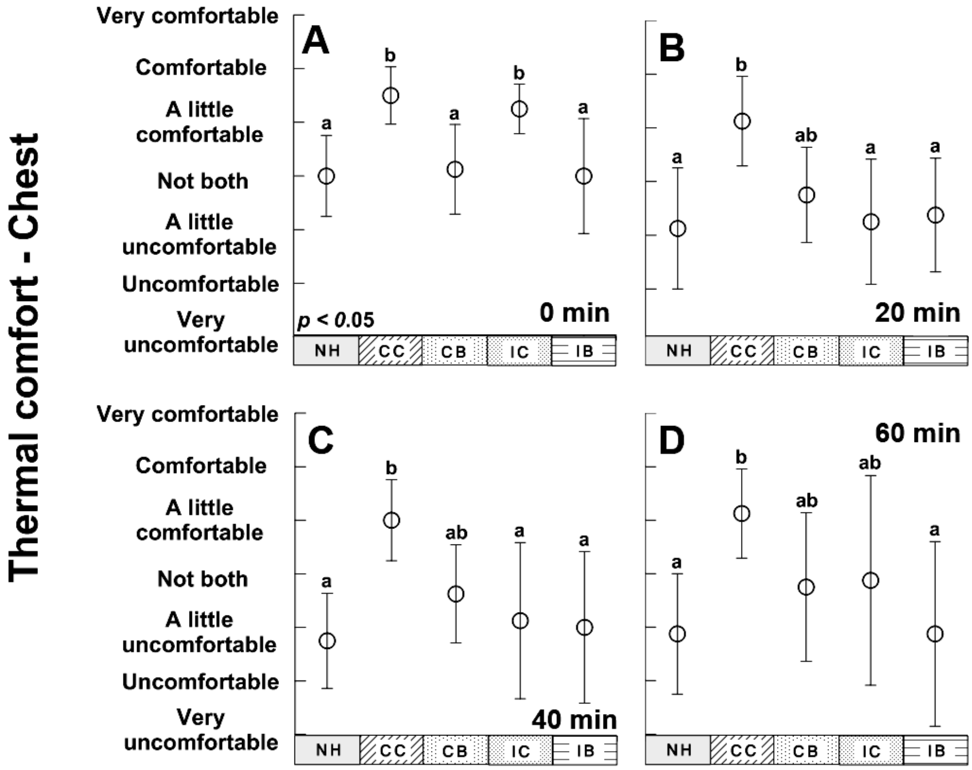

Figure A.7. Thermal comfort on the chest at 0, 20, 40 and 60 min after cold exposure in the experiment evaluating the five heating protocols. Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

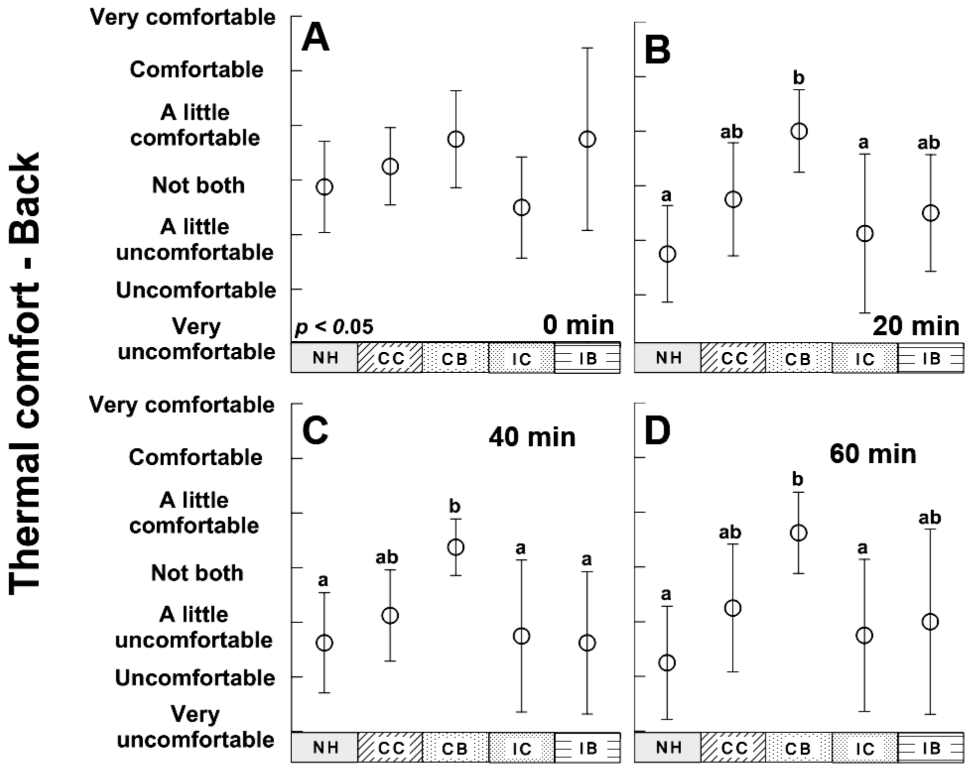

Figure A.8. Thermal comfort on the back at 0, 20, 40 and 60 min after cold exposure in the experiment evaluating the five heating protocols. Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

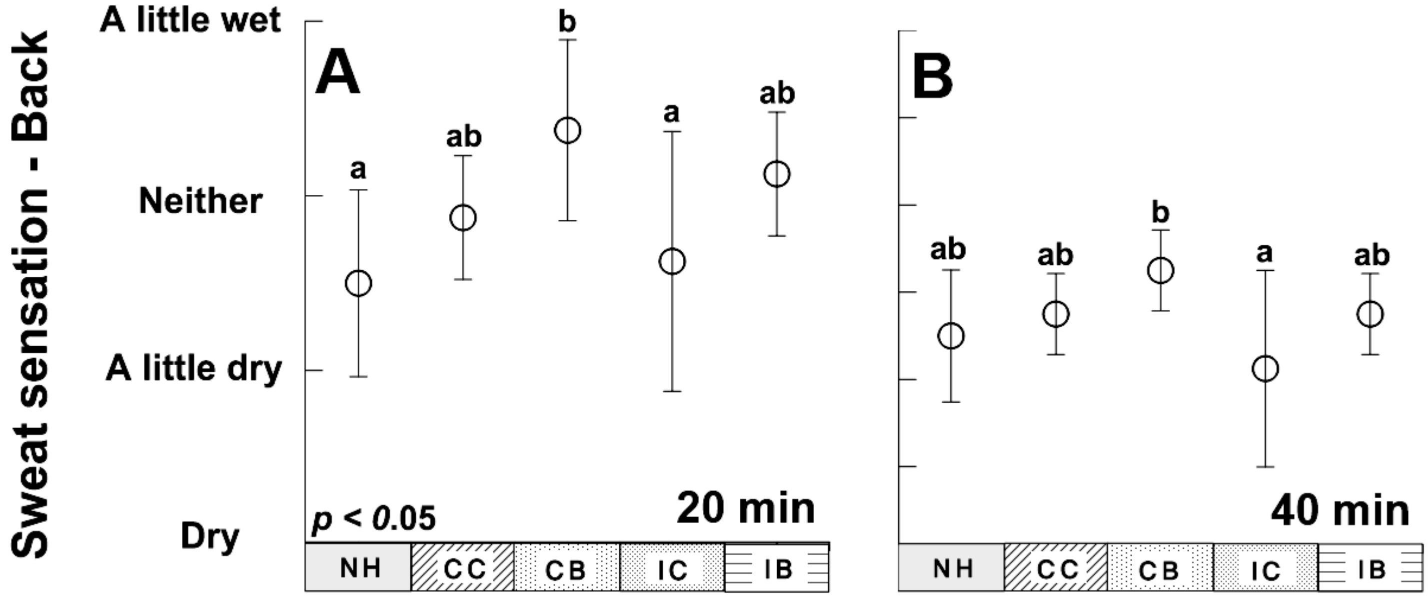

Figure A.9. Sweat sensation on the back at 20, 40 min after cold exposure in the experiment evaluating the five heating protocols. Note: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back).

초　　록

본 연구는 균일한 열 분포를 가지는 그래핀 (graphene) 면상 발열체를 동절기 의복에 적용하여 생리적 주관적 체온조절 효과는 유지하면서 소비전력량을 최소화 할 수 있는 가온 프로토콜을 찾기 위해 수행되었다. 또한, 가온 시스템 추가를 통한 의복 중량 증가를 최소화하기 위해 최적의 가온 부위를 찾고자 하였으며 다음과 같은 단계를 거쳐 수행되었다.

첫째, 면상 그래핀 히터를 의복에 적용했을 시 가온 부위 별 히터의 최대 온도를 알아보았다. 건강한 성인 남자 두 명이 피험자로 참여하였으며, 실험 조건은 가슴 가온, 등 가온으로 총 두 조건 이었다. 실험은 환경온 0.4°C, 상대습도 41%RH 에서 진행되었으며, 그래핀 히터의 온도는 히터에 가해지는 전압을 조절함으로써 상승시켰다. 실험결과 그래핀 히터의 최대가온온도는 통증감, 주관감, 피부 화상의 위험 등을 고려하여 가슴과 등 부위 모두 45°C 로 결정되었다 (전압 20 V).

둘째, 최대 가온 온도 45°C 를 기준으로 소비전력량을 고려하여 간헐적 가온 프로토콜을 개발하였다. 면상 그래핀 히터 한 개에 5, 10, 15 그리고 20 V 가 가해졌을 시, 전력은 각각 0.18, 0.71, 1.61 그리고 2.86 W 였다. 실험은 환경온 30°C, 상대습도 10%RH 에서 진행되었다. 각기 다른 소비전력량을 가진 다섯 개의 간헐적 가온 프로토콜 (IP1~5)이 개발되었고, 연속 가온 프로토콜이 세 개의 그래핀에 적용되었을 시 8.58 W 의 전력을 소모하는 반면, IP-1, IP-2, IP-3, IP-4, 그리고 IP-5 는 각각 5.28, 5.49, 2.49, 5.10, 그리고 2.94 W 의 전력을 소비하였다. 연속 가온 프로토콜 대비 소비전력량을 71% 절감한 IP-3 이 인체착용평가를 위해 선택되었다.

마지막으로, 인체착용평가를 통해 다음과 같은 다섯 개의 가온 프로토콜을 평가하였다: NH (no heating), CC (continuous heating the chest), CB (continuous heating the back), IC (intermittent heating the chest), and IB (intermittent heating the back). 건강한 성인 남자 여덟 명이 피험자로 참여하였으며, 실험은 환경온 25°C, 상대습도 28%RH 에서 10 분간 의자에 앉아 안정 후, 환경온 0.6°C, 상대습도 40%RH 의 추운 환경에 60 분간 노출하는 것으로 구성되었다. 직장온, 심혈관계 반응, 호흡계 반응은

다섯 개의 가온 프로토콜간의 유의미한 차이가 발견되지 않았다. 면상 그래핀 히터 온도의 경우, 연속 가온 조건 (CC, CB)에서 좌우보다 중앙에 위치한 그래핀 히터가 과도하게 높은 온도를 보여 장시간 가온 될 경우 피부가 저온 화상을 입게 될 가능성을 보였다. 간헐적 가온 조건 (IC, IB)에서는 히터의 온도가 낮아지는 구간이 있기 때문에 이런 현상이 발견되지 않았다.

NH 조건에서 가슴 온도는 1.5 ± 0.9°C 하락하였고, 등 부위는 3.1 ± 1.1°C 하락하여 등 부위가 약 두 배의 하강도를 보였는데, 저온 환경 노출 시 특정 부위의 온도를 쾌적 범위 이상으로 상승시키는 것과 쾌적 범위 이하로의 저하를 막는 것 중 후자를 선택하는 것이 전신의 쾌적 범위를 유지하는데 유리하다는 원칙으로 볼 때 보다 등 부위의 가온이 가슴 부위의 가온보다 더 이점이 있었다.

결론적으로 연속적 가온 프로토콜보다 본 연구에서 개발한 간헐적 가온 프로토콜이 소비전력량은 71% 더 적으면서 체온조절 반응은 유사하게 유지되었다. 몸통 부위 중 가슴 부위보다는 등 부위의 가온이 저온 환경 노출 시 체온쾌적범위를 유지하는데 더 효과적이었다. 특히 간헐적 가온 방식은 윗 등 부위 전체를 가온 하는 경우 저온 화상 예방에 효과적일 수 있다.

주요어: 방한복, 면상 그래핀 히터, 국소 가온, 가온 프로토콜, 발열의류

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