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Evaluation of body heating protocols with graphene heated clothing in a cold environment

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Abstract

Purpose – The purpose of this paper is to evaluate the effects of intermittent and continuous heating protocols using graphene-heated clothing and identify more effective body region for heating in a cold environment.

Design/methodology/approach – Eight males participated in five experimental conditions at an air temperature of 0.6°C with 40 percent relative humidity: no heating, continuous heating the chest, continuous heating the back, intermittent heating the chest, and intermittent heating the back.

Findings – The results showed that the electric power consumption of the intermittent heating protocol (2.49 W) was conserved by 71 percent compared to the continuous protocol (8.58 W). Rectal temperature, cardiovascular and respiratory responses showed no significant differences among the four heating conditions, while heating the back showed more beneficial effects on skin temperatures than heating the chest.

Originality/value – First of all, this study was the first report to evaluate cold protective clothing with graphene heaters. Second, the authors provided effective intermittent heating protocols in terms of reducing power consumption, which was able to be evaluated with the characteristics of fast-responsive graphene heaters. Third, an intermittent heating protocol on the back was recommended to keep a balance between saving electric power and minimizing thermal discomfort in cold environments.

Keywords Thermal comfort, Body heating, Cold protective clothing, Graphene heater, Rectal temperature, Skin temperature, Thermal sensation, Core body temperature

Paper type Research paper

1. Introduction

Physiological responses to cold include body temperature falling, the strain on the heart and respiratory system, or shivering, while 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,

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hypothermia, or 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 would be two major methods used to reduce heat loss through clothing: a passive and an active method. A passive method is used to increase thermal insulation which is done by increasing the air layer of clothing using down filler, or multi-layered clothes. However, the passive method increases the weight and volume of clothing, which could raise the energy metabolic consumption of wearers by 3 percent 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). An active method can be defined by providing extra heat using heating textiles or units, such as moisture-absorbing heat release, far-infrared, solar, chemically heated textiles or electrically aided heating units (Choi *et al.*, 2004; Park *et al.*, 2006, 2016; Sarier and Onder, 2007; Shim and McCullough, 2000; Song *et al.*, 2015). The heating textiles slightly increase the thermal insulation value (Jin *et al.*, 2012; Lee *et al.*, 2015; Shim *et al.*, 2009), but electric heating materials increase over 10°C from the base temperature (Kang and Lee, 2015). However, improvements of the electrically aided heating units are still needed for practical application in terms of power consumption, ergonomic design of the system, total weight, etc.

To overcome the disadvantages of the existing electrically aided heating units and to improve the performance, 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) with high conductivity (Prasher, 2010). The 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 light weight qualities will provide comfort and mobility to wearers. A thin form of graphene could contribute to design 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, 2015). To the best of our knowledge, however, no research has been reported that evaluated the practical implications of graphene heaters for protective clothing 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 but it causes the degradation of battery capacity. In this regard, an intermittent heating protocol using the graphene heater can save power consumption and 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.

Considering the total mass of cold protective clothing with electrically aided heating units, it is crucial to decide the optimal body region for selective heating to minimize the total mass of the unit. In this study, the chest and upper back heating were compared for cold protective upper jackets. The reason for not considering the arms and stomach for heating was because the thermal inefficiency of arms in cold (Jeong and Tokura, 1993) and relatively thickly distributed subcutaneous fat on the stomach. The purpose of this study was to explore the practical applicability of graphene heaters for humans in cold environments. We hypothesized the following:

H1. An intermittent heating protocol would bring warmer sensations when compared to a continuous heating protocol applied.

H2. The upper back would be more effective for maintaining body temperature than the chest on the trunk of the human body.

2. Materials and methods

2.1 Subjects and clothing

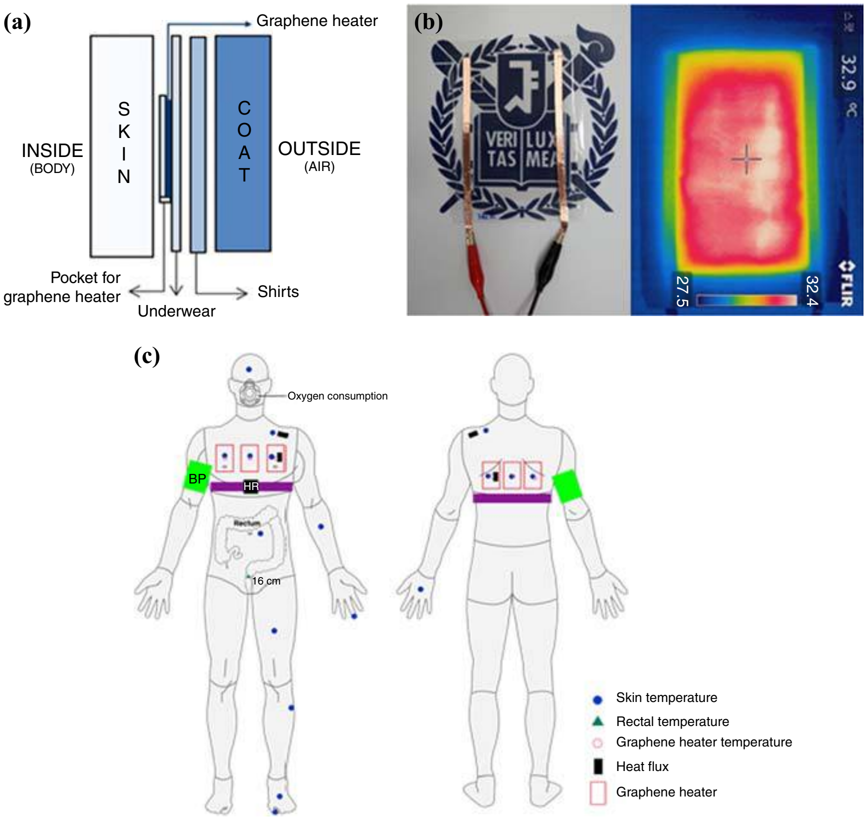
Subjects abstained from alcohol, smoking and strenuous exercise for the previous 24 h and were prohibited from taking any food for 2 h prior to their scheduled tests. Informed consent was obtained from the subjects. The experimental protocol was approved by the Institutional Review Boards of Seoul National University (IRB No. 1508/001-017). Experimental clothing (about 1.37 clo) consisted of under shorts, thermal underwear top and bottom, shirts, pants, coat, leather gloves, socks, and running shoes. The thermal underwear top was mended with a pocket on the chest and the other pocket on the upper back so that the graphene heaters were located in. The pockets were added inside the thermal underwear top, up to three graphene heaters were able to be placed in a row in one pocket (Figure 1(a)). Due to the elasticity of the fabric used for the pocket, the graphene heater was tightly fitted into the body. The tightness design improved the heat conductivity between the body skin and heaters. Thermal conductivity and thickness of the pocket fabric were 2.2669×10^{-5} W•cm^{-1}•°C^{-1} and 0.352 mm, respectively.

2.2 Production of graphene heaters

2.2.1 Synthesis of graphene. We followed the identical method for the synthesis of graphene as the chemical vapor deposition (CVD) method which used hydrogen (15 sccm) and methane (150 sccm) gases with a Cu foil in vertical CVD to grow 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 from reactive ion etching 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.

2.2.2 Manufacturing 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 percent, Samchun), the graphene on PET carried out the multiple stacking process 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.

2.2.3 Characterization. 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 was 0.05 mm. Voltage was supplied by a DC power supply (M8812, Maynuo Electronics, China) at the T_a of 27.9±0.5°C and H_a of 54±3 percent relative humidity (RH). The surface temperature of the graphene heater was recorded every 5 s on



Notes: (a) Schematic illustration of clothing layers and location of graphene heater; (b) a graphene heater and thermographic image of the heater; (c) a diagram of measurement sites which includes skin temperatures, rectal temperature, graphene heater temperature, heat flux, oxygen consumption, heart rate (HR), blood pressure (BP) and locations of graphene heater

Figure 1. Schematic, thermographic image of graphene heater and measurement sites

the center of the film (LT-8A, Gram Corporation, Japan, resolution 0.01°C). The surface temperature distribution was characterized by an infrared thermographic camera (T650sc, FLIR, Sweden) (Figure 1(b)). The heating rate of the graphene heaters was examined with the voltages 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 I).

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

Voltage	Heating rate of graphene heater ($^{\circ}C \cdot m^{-1}$) 83 Ω	123 Ω	141 Ω	Maximum temperature of graphene heater (°C) 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

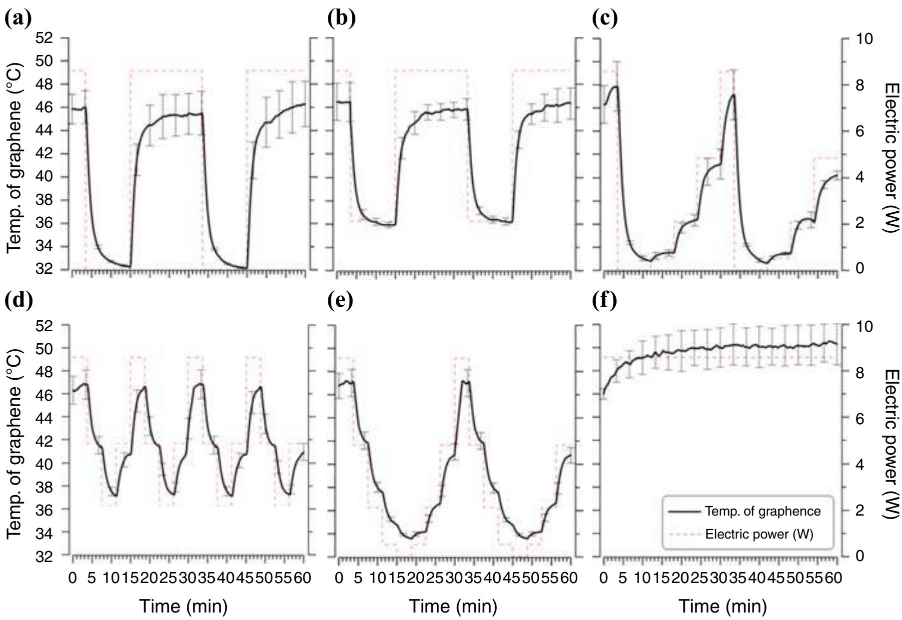
2.3 Maximum temperature of graphene heater for human application

Two young males (mean±SD: 24.0±4.2 year in age, 176.5±3.5 cm in height, and 70.2±9.3 kg in body mass) participated in this test. The experiment consisted of two conditions: chest heating and upper back heating. Subjects participated in two conditions on different days. We assigned different conditions to different subjects to start with to avoid the order effect. After equipping skin temperature sensors on the chest and upper back, subjects changed into experimental clothing. An experimental chamber was maintained at a T_a of 0.4±0.5°C with 41±1 percent RH and an air velocity of 1.3±0.4 $m \cdot s^{-1}$ (Wind Chill Index, WCI: −1.0°C). Subjects kept a standing posture until the end of the experiment. The experiment was terminated if the following cases were reported: skin temperature under the graphene heater increased up to 44~51°C, or subjects felt too hot and/or thermal pain due to the graphene heater. Two pieces of graphene heaters were put in the pockets of the thermal underwear top on the left and middle side of the chest (or upper back). 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. 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). 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.

2.4 Evaluation of graphene heating protocols in human wear trials

2.4.1 Developing intermittent heating protocols. 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 a graphene heater, respectively. These values were derived from a voltage supply experiment at a graphene heater resistance of 140 Ω. If a graphene heater had a resistance value lower than 140 Ω, resistors were added to have the same temperature in accordance with the voltage. Tests were conducted at T_a 30°C and H_a 10 percent RH. A value of 20 V was selected as a maximum voltage for human trials. Intermittent heating protocols can be developed in various ways through adjustment of on-off time or temperature setting, but only five protocols were selected in this study according to electric power consumption (Figure 2). The total duration of protocols was 60 min. 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). 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 percent RH. To compare the effect of the smallest electric power intermittent heating protocol with continuous heating protocol, IP-3 was selected for the following human wear trials.

2.4.2 Evaluating heating protocols during human wear trials. Eight young males (mean ±SD: 24.3±2.1 year 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. All subjects participated in the following five experimental conditions: no heating (NH), continuous-chest heating (CC), continuous-back heating (CB), intermittent-chest heating (IC), and intermittent-back heating (IB). Experimental conditions were randomly distributed according to Latin



Notes: (a) IP-1; (b) IP-2; (c) IP-3; (d) IP-4; (e) IP-5; (f) CP

Figure 2.
Averaged surface temperature and sum of electric power of three pieces of graphene heaters according to continuous and intermittent heating protocols for 60 min (mean ± SD)

square design 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 total sweat rate. After equipping all measurement sensors on the body, subjects changed into experimental garments. Subjects rested 10 min in a sitting position on a stool at T_a of 25±4°C and H_a of 28±15 percentRH with an air velocity 0.01±0.02 m·s^{-1}. After inserting three pieces of graphene heaters into the pocket 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 percentRH with an air velocity of 1.4 ± 0.4 m·s^{-1} (Wind Chill Index, WCI: −0.9°C). The air flow was created by placing six fans in a circle around the subject. At the chamber, subjects kept a standing posture and graphene heaters were activated for 60 min. 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.

Thermal, cardiovascular, respiratory responses and subjective perceptions were measured during the experiments. 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) (Figure 1(c)). 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), abdomen, upper back (the left, middle and right side under the three pieces of graphene heaters), anterior shoulder, posterior shoulder, forearm, hand, finger, thigh, calf, foot and toe.

Mean skin temperature ($\overline{T}_{sk}$) was estimated from a modified Hardy and DuBois' equation (Hardy and DuBois, 1938):

$$\overline{T}_{sk} = 0.07T_{forehead} + 0.35(T_{chest1} + T_{chest2} + T_{chest3} + T_{anterior\ shoulder} + T_{abdomen} + T_{upper\ back1} + T_{upper\ back2} + T_{upper\ back3} + T_{posterior\ shoulder})/9 + 0.14T_{forearm} + 0.05T_{hand} + 0.19T_{thigh} + 0.13T_{calf} + 0.07T_{foot}. \quad (1)$$

Heat flux was recorded every 5 s on the following four body parts: the left side of chest and upper back both under the graphene heater and over the graphene heater (MCV-4V, T&D Corp., Japan). Heart rate (HR) was measured every 5 s using an HR monitor (RS400, Polar Electro, Finland) (Figure 1(c)). 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 was 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). 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), and thermal comfort (−3: very uncomfortable, −2: uncomfortable, −1: a little uncomfortable, 0: not both, 1: a little comfortable, 2: comfortable, and 3: very comfortable). Subjects expressed shivering onset whenever shivering occurred, and the occurring time and body regions of the shivering were recorded. All data were expressed as 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. 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 $p < 0.05$.

3. Results

3.1 Permissible temperature of graphene heater for human application

The permissible temperature of the graphene heater for human application was decided to be around 45°C considering pain sensation, subjective perceptions (Table II) and the prevention of skin burn injury (Moritz, 1947). 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 was 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 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

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

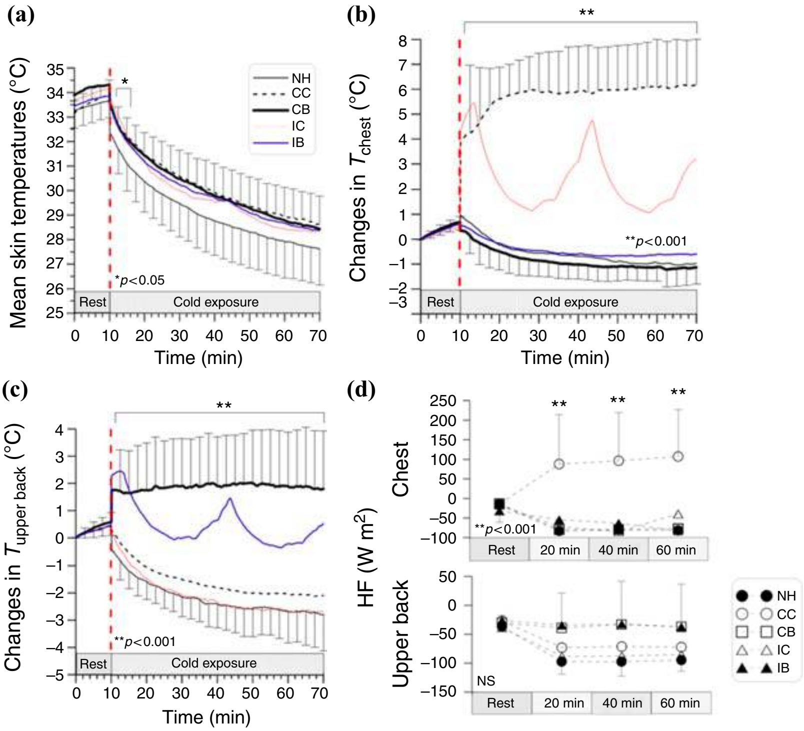
Body region	Subject	Permissible temperature of graphene (left) (°C)	Permissible temperature of graphene (middle) (°C)	Skin temp. under the permissible temperature of graphene (°C)	Voltage stopped (V)
Chest	A	45.2	41.5	38.1	20
	B	49.7	59.8	38.5	24
Back	A	45.6	42.9	41.5	20
	B	43.7	39.5	36.3	20

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.

3.2 Evaluation of heating protocols in human wear trials

3.2.1 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 CC, CB, IC, and 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.

3.2.2 Thermoregulatory, cardiovascular and respiratory responses. No differences were found in rectal temperature (T_{re}) among the five conditions, while mean skin temperature ($\overline{T}_{sk}$) showed the lowest temperatures for the NH 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 3(a)). 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



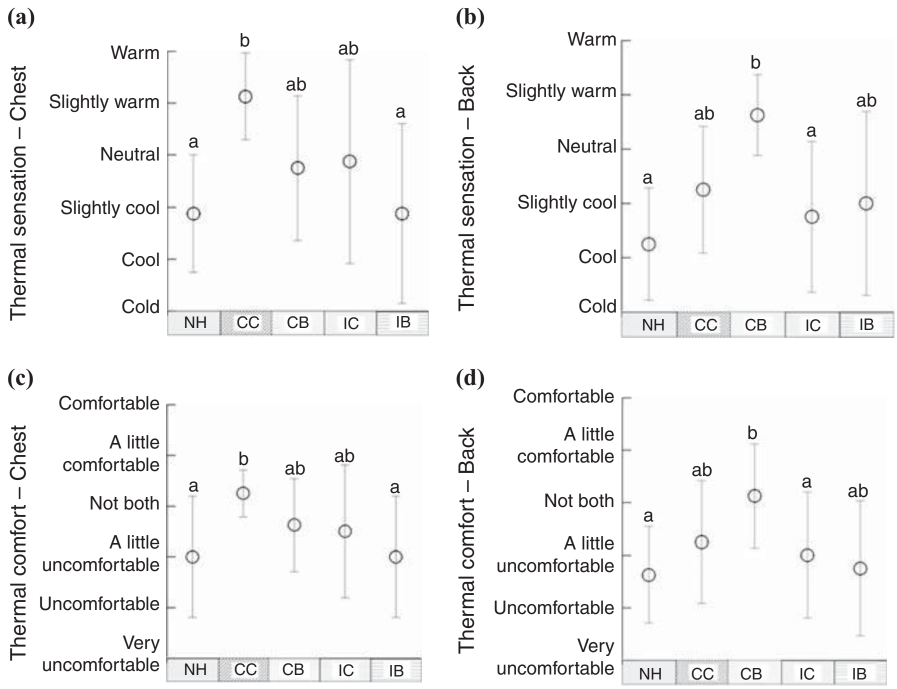
Notes: (a) Mean skin temperature; (b) changes in chest temperature; (c) changes in upper back temperature; (d) heat flux on the chest and upper back. NH, no heating; CC, continuous heating the chest; CB, continuous heating the back; IC, intermittent heating the chest; IB, intermittent heating the back

Figure 3. Changes in skin temperatures and heat flux

IB ($p < 0.001$) (Figure 3(b)). 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 3(c)). 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 3(d)). No significant differences were found in heat flux on the upper back among the five conditions.

HR was 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). BP increased over time during cold exposure without any differences among the five conditions. Insensible body mass loss showed no group differences and the values were in the normal range of 140~170 g for 2 h. On average, shivering onset time was 20.9±12.8 min and shivering was subjectively perceived as 4.4±2.3 times during the 60-min cold exposure. 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.

3.2.3 Psychological responses. For thermal sensation on the chest, subjects felt the most warmth in CC and the least warmth in NH (Figure 4(a)). Intermittent heating the chest had an insignificant effect on the improvement of chest thermal sensation because of great individual variations. 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 (Figure 4(b)), but intermittent heating the back had an insignificant effect on the improvement of back thermal sensation. For thermal comfort on the chest (Figure 4(c)) and/or back (Figure 4(d)),



Notes: Small letters (a, b and ab) represent statistical differences among the five groups by Turkey *post-hoc* test (a<b)

Figure 4.
Thermal sensation on (a) the chest, (b) the back and thermal comfort on (c) the chest, (d) the back in the five conditions at the 60th min during the cold exposure

similar results as thermal sensation were obtained from both chest and back. Overall, no significant differences were found in thermal sensation and thermal comfort among the five conditions.

4. Discussion

4.1 Advantages in intermittent heating protocol

4.1.1 Electric power saving. In this study, electric power consumption was able to be conserved up to 71 percent by using the intermittent heating protocol. In previous studies related to electrically heated clothing, electric power was conserved up to 50 percent 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 because 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 percent 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 help of above studies. 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 area of heating 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 a balance 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.

4.1.2 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 during human wear trials. 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 $T_{\text{upper back}}$ under the graphene heaters were 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 regard to preventing skin burn injuries.

4.2 Advantages of heating the back than the chest: 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 that 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 back temperature was 32.4°C at T_a 15.6°C for 2 h, Webb (1992) showed left chest anterior (30.1±2.0°C) was higher 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 bellow effect 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). 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 wind in cold environments is an important factor to decide temperature distribution between the chest and back in terms of bellow effects. 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.

4.3 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 gets adapted to continuous thermal stimuli. However, intermittent heating did not induce significantly positive influences on thermal sensation or thermal comfort, which might be relative to great individual variations. Among the four heating conditions, 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 were calculated by a modified Burton's equation (Burton, 1935), 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 a self-controlling system enabling wearers to choose their own preferred method between continuous heating and intermittent heating for the active heating clothing system with graphene heater in the future.

4.4 Limitations

In this study, we selected an intermittent 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 or 2 min intervals, including the other four types of the protocol developed in this study. In order to find the optimum and personalized protocol for each individual, various protocols should be developed and evaluated in further studies. Through the further studies, we will be able to propose specifications for the heating temperature and temperature range depending on environmental temperature, clothing microclimate, voltage pulse generation or individual characteristics so that wearers can easily develop customized heating protocols. Personalized heating protocols will result in positive physiological and psychological results as well as reduced power consumption. Furthermore, studies on the thermal conductivity of the heater pocket fabric and the minimization of the heat dissipation of the heater using the radiant barrier are required to increase the thermal efficiency of the graphene heater.

5. 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: conserving electric power as much as 71 percent compared to continuous heating as thermoregulatory, respiratory and psychological responses maintained at a similar level, and preventing low temperature burns due to overheating. For continuous heating protocols, 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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