Alleviation of Heat Strain by Cooling Different Body Areas during Red Pepper Harvest Work at WBGT 33°C

Jeong-Wha CHOI1, 2, Myung-Ju KIM1 and Joo-Young LEE3*

1Department of Clothing & Textiles, College of Human Ecology, Seoul National University, Gwanak-Gu, Sillim-dong, San 56–1, Seoul 151-742, Korea
2Research Institute of Human Ecology, Seoul National University, Gwanak-Gu, Sillim-dong, San 56–1, Seoul 151-742, Korea
3Department of Ergonomics, Faculty of Design, Kyushu University, 4–9–1 Shiobaru, Minami-ku, Fukuoka 815-8540, Japan

Received August 30, 2007 and accepted July 22, 2008

Abstract: The purpose of the present study was to examine the effects of different types of personal cooling equipments (PCE) on the alleviation of heat strain during red pepper harvest simulated in a climatic chamber. The experiment consisted of eight conditions: 1) Control, 2) Neck cooling scarf A with a cooling area of 68 cm², 3) Neck cooling scarf B (cooling area 154 cm²), 4) Brimmed hat with a frozen gel pack, 5) Cooling vest (cooling area 606 cm²), 6) Hat+Neck Scarf B, 7) Hat+Vest, and 8) Hat+Neck Scarf B+Vest. Twelve subjects worked a red pepper harvest simulated in a climatic chamber of WBGT 33°C. The result showed that rectal temperature (Tre) was effectively maintained under 38°C by wearing PCE. Mean skin temperature (Tsk) and heart rate (HR) became more stable through wearing PCE. When wearing the ‘Hat+Scarf B+Vest’, particularly, Tsk and HR quickly decreased to the comfort level during the mid-rest stage. We confirmed that the vest with a cooling area of only 3.3% body surface area (BSA) was effective in alleviating heat strain in a simulated harvest work. Furthermore, the heat strain of farm workers can be considerably eliminated by the combination of the cooling vest, a scarf, and a brimmed hat, with the total cooling area of 4.2% BSA.

Key words: Personal cooling equipment, Heat stress, Heat strain, Farm work, Neck cooling, Thermal comfort

Introduction

One of the heaviest farm works in Korea is known as red pepper harvest in summer. The direct sun light, lengthy work in a squatting position, the lack of break time and the increase in the participation of elderly women have been pointed out as problems in the harvesting of red pepper1). The fundamental method to alleviate worker’s heat strain is to reduce worker’s physical thermal burden through mechanization and the improvement of air-conditioning of occupational fields. However, these ergonomic interventions are not feasible in red pepper fields, because workers have to pick each red pepper by hand on fields. We have investigated the farm work environments and worker’s workload, and presented personal cooling equipment (PCE) as an alternative for farm workers1–3).

Over last 50 yr, there have been many studies that dealt with PCE for alleviating heat strain. PCE can be divided into three types by coolants: air, liquid and frozen gel (or ice or PCM). The studies have mainly focused on soldiers performing missions in deserts, pilots sitting in a small and hot cockpit4–7), workers in power plants or iron mills8, 9), and workers wearing chemical protective garments for protection from harmful chemicals10, 11). Relatively, there is few study interested in farm workers.
in light wear, under the direct sun light with an awkward work posture for long periods of time. For the farm workers harvesting in fields in summer, points to be taken into account for PCE are as follows: Which body region is effective and efficient in cooling? Which coolant among air, liquid and frozen gel is proper? Does PCE hinder worker’s mobility? How much does it weigh? Is not it too expensive? Is it easy to manage?

Regarding the body region cooled, the trunk has been mainly cooled using a vest. However, even if core temperature is maintained in an acceptable range by the cooling vest, the head and the neck can become overheated in some cases. Shvartz and his colleagues have shown that the most efficient part among the neck, the face, the arm, the hands, the trunk, the leg, and the feet, was the neck. Therefore, personal devices for the neck or head cooling as well as cooling vests can be suggested for farm worker. Besides, farm workers in summer are exposed to direct sun rays. The wearing of a brimmed hat is necessary for workers outside in summer. It is reported that when the temperature of the head was kept cool even if core temperature increased by artificial manipulation, thermal comfort did not get worse, and the sweat rate of the face decreased.

One of the disadvantages of PCE is that the garments are somewhat heavy. The weight of ice bags-vests is about 2 to 7 kg. Heavy clothing can cause an increase in energy expenditure of workers. Duggan (1988) has reported that when workers wore clothing of 3 kg and 5 kg, the energy metabolism increased as much as 5% and 9%, respectively. Therefore, PCE for farm workers working in a squatting position for a long time, should be as light as possible.

Regarding the type of cooling system, frozen gel packs are known as more appropriate coolants than an air-ventilated system (AVS) or a liquid cooling system (LCS) during outside work. That is because cooling systems using frozen gel or ice are relatively lighter than AVS and LCS; cooling capacity of ice or frozen gel is greater than that of cooled air or water; and the AVS or LCS restrict body movements because of connections with devices for supplying air or liquid. Portable AVS of LCS are too heavy because workers would have to carry the pump and battery on their backs. Cooling systems using a frozen gel pack does not restrict worker’s movements. Lastly, the price of a cooling system using frozen gel packs is much cheaper than a cooling system using circulated air or water.

In considering the above mentioned all together, a cooling vest, neck cooling scarf, head cooling or brimmed hat with a cooling function, using frozen gel packs, can be suggested as PCE for farm workers. Based on our previous studies about farm work in summer, we developed a cooling vest, a brimmed hat with a cooling function, and cooling scarves. The present study evaluated the effects of neck cooling scarves, a cooling vest, a brimmed hat, and the combination of cooling garments, on physiological and subjective responses during the red pepper harvest simulated in a climatic chamber.

**Methods**

**Subjects and personal cooling garments**

Twelve young males (Mean ± SD: Age 25.4 ± 1.6 yr, height 173.1 ± 5.0 cm, weight 69.3 ± 9.8 kg, BSA 1.86 ± 0.14 m²) participated as volunteers. None of the subjects was an athlete. Prior to participation, written and informed consent was obtained from all subjects, and a medical history questionnaire was filled out. The experimental protocol was approved by the ethics committee of College of Human Ecology in Seoul National University.

The experiment was undertaken under eight conditions: 1) Control (No cooling), 2) Neck Scarf A, 3) Neck Scarf B, 4) Hat, 5) Vest, 6) Hat + Neck Scarf B, 7) Hat + Vest, and 8) Hat + Neck Scarf B + Vest. Materials, design and cooling areas (SAcooled) of these PCE were shown in Table 1 (0.4–4.2% SAcooled). For cooling, frozen gel packs were inserted in the cooling equipment. The packs were filled with a water based crystals gel which is non toxic and absorbed water. The frozen gel pack (180 g) began to melt at the 20 min during the exposure at WBGT 33˚C, but the melting or cooling time-duration are dependent to the activity of wearer. Through our preliminary studies, the most effective brimmed hat among the three kinds of brimmed hats we developed was selected, and the most effective cooling vest was also selected through another previous study. The reason we developed cooling scarves and not a cooling hood was because of practical constraints on system design and to avoid placing a weight burden on the head. In addition, the neck is known as an advantageous site for heat removal because of the proximity of large blood vessels to the skin in this area.

As well as the effects of four kinds of PCE, the effects of combinations of the brimmed hat with other PCE were examined (Conditions 6–8). Subjects were dressed the same for each trial before being fitted with PCE. They wore shirts with long sleeves, long legged training pants, underwear, socks, work gloves and athletic shoes. These clothes were based on real farm workers’ work wear in summer.

**Procedure and measurement**

The experiments were conducted in a climatic chamber. The environmental conditions of the climatic chamber were constant at a temperature of 33 ± 0.5˚C and
65 ± 5%RH of air humidity. To simulate sunlight on the actual agricultural fields, artificial lamps on the ceiling of the chamber were used. Black globe temperature was constant at 39 ± 1˚C (WBGT 33˚C). Every experiment started at the same time (10:00 am) to minimize the difference due to individual circadian rhythms. To minimize the effects of acclimatization to the experiments, each subject was exposed to the hot environment just for two hours in a day, and the interval between successive experiments was a minimum of three days. The order of wear trials was randomized to eliminate the possible effects of training.

Subjects were instructed not to consume alcohol or drugs in the 48 h before testing. To avoid the specific dynamic effects of food, subjects did not have any food for three hours before testing but were permitted to drink water. Experiments were conducted at the end of summer (August), when the subjects were naturally acclimatized to summer heat. Before entering into the climatic chamber, subjects wore experimental garments and were equipped with PCE. After resting for one hour in another chamber kept at 25 ± 1˚C, subjects entered the heated chamber.

In most previous studies concerning the efficacy of PCE in climatic chambers, subjects rested or walked or ran on a treadmill. However, red pepper harvest is more dynamic than sitting on a chair, and less dynamic than walking or running on a treadmill. Our subjects simulated the red pepper harvest work based on a previous study. The major feature of harvesting Korean red pepper is to pick each red pepper by hand. To simulate the harvesting work in the climatic chamber, we put four potted red pepper plants in a row in the chamber and hung a total of 50 markers with the similar size as a piece of red pepper on each plant. Subjects were instructed to touch all markers according to the order of number from 1 to 200 and pretend it into their individual basket during the simulated harvest work. The work lasted a total

Table 1. Characteristics of personal cooling garments and experimental garments in the present study

<table>
<thead>
<tr>
<th>No.</th>
<th>Condition</th>
<th>Garment weight (g)</th>
<th>Cooling area (cm²)</th>
<th>Percentage of cooling area to BSA (%)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No cooling</td>
<td>Frozen gel: 0</td>
<td>0</td>
<td>0</td>
<td>Cotton shirt with long sleeves, Long legged training pants, cotton 100% underwear, cotton socks, work gloves, and athletic shoes.</td>
</tr>
<tr>
<td>2</td>
<td>Neck Scarf A</td>
<td>Frozen gel: 60</td>
<td>68</td>
<td>0.37 (0.33–0.42)</td>
<td>The dimension of a frozen gel pack was 17 × 4 cm. The pack enclosed by fabric cotton 100% was located on the back of the neck.</td>
</tr>
<tr>
<td>3</td>
<td>Neck Scarf B</td>
<td>Frozen gel: 180</td>
<td>154</td>
<td>0.83 (0.74–0.95)</td>
<td>The dimension of frozen gel pack was 14 × 11 cm. The pack enclosed by fabric cotton 100% was located on the back of the neck.</td>
</tr>
<tr>
<td>4</td>
<td>Hat</td>
<td>Frozen gel: 180</td>
<td>154</td>
<td>0.83 (0.74–0.95)</td>
<td>Made by reflective fabric (Nylon 100%, 78 g/m², 180 warp/100 inch, surface reflectance 50.7%, UV-A block 97.4%, UV-B black 99.5%, silver color), PE 100% mesh around the head girth to ventilate. The below side of the visor was finished with black T/C. A white and attachable face-shade. The shade had a pocket to insert a frozen gel pack. The frozen gel pack did not contact on the back of the neck, but there was a little space between the frozen gel pack and the skin of neck.</td>
</tr>
<tr>
<td>5</td>
<td>Vest</td>
<td>Frozen gel: 180 × 4</td>
<td>154 × 4=606</td>
<td>3.28 (2.90–3.74)</td>
<td>Reflective fabric same as the used at the brimmed hat above (N.4). The two pieces of gel pack was on the chest, and two was on the back. The body of the vest was made by PE mesh, except pockets for inserting gel packs.</td>
</tr>
<tr>
<td>6</td>
<td>Hat+Neck Scarf B</td>
<td>Frozen gel: 180</td>
<td>154</td>
<td>0.83 (0.74–0.95)</td>
<td>Combination of no.3 and no.4, except a gel pack from the shade</td>
</tr>
<tr>
<td>7</td>
<td>Hat+Vest</td>
<td>Frozen gel: 180 × 4</td>
<td>154 × 4=606</td>
<td>3.28 (2.90–3.74)</td>
<td>Combination of no.4 and no.5, except a gel pack from the shade</td>
</tr>
<tr>
<td>8</td>
<td>Hat+Vest+Neck Scarf B</td>
<td>Frozen gel: 180 × 5</td>
<td>154 × 5=770</td>
<td>4.16 (3.68–4.76)</td>
<td>Combination of no.3, no.4 and no.5, except a gel pack from the shade</td>
</tr>
</tbody>
</table>

* Cooling area × 100/the body surface area (BSA) of subjects; b) Work wear was based on Choi et al. (2007)1); c) Total weight includes the weight of frozen gel; d) The range of minimum and maximum values by subject; *In condition 2 to 8, subjects wore same work wear as Condition 1.
of 120 min (two bouts of 50-min harvest work with a 10-min rest). Subjects drank water as much as subjects want to drink before starting every experiment. Water intake was prohibited during experimentation.

Rectal temperature (T_re) was measured using a portable thermometer (LT 8A, Gram Corp., Japan) at the depth of about 13 cm in the rectum. Skin temperatures (T_sk) were measured for seven body parts using portable thermometers (LT 8A, Gram Corp., Japan), and then mean skin temperature (T¯ sk) was calculated according the Hardy & DuBois' seven point equation (Eq.1):

\[
T_{\text{sk}} = 0.07 \times T_{\text{forehead}} + 0.35 \times T_{\text{trunk}} + 0.14 \times T_{\text{arm}} + 0.05 \times T_{\text{hand}} + 0.19 \times T_{\text{thigh}} + 0.13 \times T_{\text{calf}} + 0.07 \times T_{\text{foot}}
\]

Clothing microclimate temperature (Tclo) and humidity (Hclo) were also measured on the most inner parts between the body skin and clothes, around the chest and the back using a portable thermo recorder (TR-72S, T&D Corp., Japan), with care to ensure the back Tclo and Hclo probe were not in contact with the frozen gel packs of the neck cooling scarves and the cooling vest. Heart rate (HR) was measured using a portable HR recorder (Polar, Polar Electro 3000 INC., USA). Measurements above (Tre, Tsk, Tclo, Hclo, and HR) were taken every minute. Total sweat rate (TSR) was calculated through the difference between the body skin and clothes, around the chest and the back using a portable thermo recorder (TR-72S, T&D Corp., Japan), with care to ensure the back Tclo and Hclo probe were not in contact with the frozen gel packs of the neck cooling scarves and the cooling vest. Heart rate (HR) was measured using a portable HR recorder (Polar, Polar Electro 3000 INC., USA). Measurements above (Tre, Tsk, Tclo, Hclo, and HR) were taken every minute. Total sweat rate (TSR) was calculated through the difference between before and after semi-nude body weight using a body scale (Sartorius, F150S, sensitivity 1 g, Germany). Body heat storage by Hardy and DuBois (24), physiological strain index (25), and the modified Craig Index (26) were calculated:

Heart storage, HS (kcal/m²)

\[
\text{HS} = \frac{0.83 \times (0.8T_{\text{re}} + 0.2T_{\text{sk}}) \times \text{Weight} \ (\text{kg})}{\text{BSA} (\text{m}^2)}} \quad \text{[Eq. 2]}
\]

Physiological Strain Index (PSI)

\[
\text{PSI} = 5 \frac{(T_{\text{ref}} - T_{\text{re}})}{(39.5 - T_{\text{re}})} + 5 \frac{(\text{HR}_t - \text{HR}_0)}{(180 - \text{HR}_0)} \quad \text{[Eq. 3]}
\]

Tre and HRt are simultaneous measurements taken at any time during the exposure and Tre0 and HR0 are the initial measurements.

Craig Index (CI)

\[
\text{CI} = \frac{\text{HR}_{\text{terminal}}}{100} + \Delta T_{\text{re}} + \Delta Wt \quad \text{[Eq. 4]}
\]

\[
\Delta T_{\text{re}} = \text{Rise in rectal temperature (°C/h)};
\]

\[
\Delta Wt = \text{Nude weight loss (kg/h)}.
\]

9-point ISO thermal sensation scale and 4-point ISO thermal comfort scale were selected to evaluate subjective perception. Subjects recorded their own thermal sensations and thermal comfort every ten minutes. The experiment stopped when Tre increased up over 39°C, or Tre increased more than 2°C compared to Tre at the starting point, or HR increased up over 185 bpm, or subjects wanted to stop.

Data analysis

Data were analyzed by using SPSS 12.0 for Windows (SPSS, Chicago, IL). Physiological and subjective values were reported as means and SD. Differences among eight treatments were tested using ANOVA. Duncan’s post hoc test was applied when significant effects were found. Statistical significance was set at p<0.05.

Results

Rectal temperature (T_re)

T_re increased under all conditions, but the increase was effectively inhibited through wearing PCE. Overall, the greater the cooling area was, the lower T_re was (Table 2, p<0.05). T_re increased the mean of 0.20°C for the condition of Hat+Vest, while showed the increase of 0.62°C for the condition without any cooling. During the condition without any cooling, T_re exceeded 38°C in eight out of twelve subjects. However, only three subjects in the Scarf B condition, two subjects with the Vest, and none wearing the combination of cooling equipments exceeded 38°C. The time period that T_re was above 38°C was 31.3% of the 120 min when the Control was done, but 0% in the conditions of Hat+Neck Scarf B, Hat+Vest, and Hat+Vest+Neck Scarf B.

Skin temperatures (T_sk)

As expected, T_sk showed the highest value in the control (35.2 ± 0.6°C) and the lowest value for the condition 8 with the greatest cooling area (34.6 ± 0.8°C, Table 2). When the Hat+Neck Scarf B+Vest was worn, T_sk was maintained without gradual increases. In particular, T_sk quickly decreased to the comfort level during the mid-rest stage. Forehead and the periphery temperatures did not show any significant difference between conditions with cooling equipment and without cooling (Table 2).

Clothing microclimate temperature and humidity (Tclo, Hclo)

Tclo on the chest was affected by wearing the Vest and Tclo on the back by Neck Scarf B (Table 2). A mean of Hclo was around 82–94%RH for all conditions.

Heart rate (HR) and total sweat rate (TSR)

Heart rate (HR) did not show any significant difference by cooling when comparing the mean HR of the entire duration. However, HR decreased quickly to the comfortable level during the two bouts of rest stages (Fig. 1). PCE caused a reduction in total sweat rate and the difference between with and without cooling (p<0.05, Table 2). Total sweat rate (TSR) in 7 cooling conditions showed from 119–135 g · m⁻² · h on average, while TSR
Table 2. Physiological responses during 120 min exposure in climatic chamber

<table>
<thead>
<tr>
<th></th>
<th>No cooling</th>
<th>Neck Scarf A</th>
<th>Neck Scarf B</th>
<th>Hat</th>
<th>Vest</th>
<th>Hat+Neck Scarf B</th>
<th>Hat+Vest</th>
<th>Hat+Vest+Neck Scarf B</th>
</tr>
</thead>
<tbody>
<tr>
<td>T&lt;sub&gt;re&lt;/sub&gt; (˚C)</td>
<td>37.9 (0.2)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>37.8 (0.2)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>37.8 (0.2)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>37.5 (0.2)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>37.6 (0.3)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>37.6 (0.2)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>37.6 (0.2)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>37.5 (0.3)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>∆T&lt;sub&gt;re&lt;/sub&gt; (˚C)&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>0.62 (0.2)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.48 (0.16)&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.45 (0.13)&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.34 (0.20)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.20 (0.33)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.40 (0.28)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.20 (0.25)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.31 (0.19)&lt;sup&gt;abc&lt;/sup&gt;</td>
</tr>
<tr>
<td>Maximum T&lt;sub&gt;re&lt;/sub&gt; (˚C)&lt;sup&gt;2)&lt;/sup&gt;</td>
<td>38.2 (0.3)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>38.0 (0.3)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>37.9 (0.2)&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>37.7 (0.2)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>37.7 (0.3)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>37.7 (0.2)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>37.7 (0.3)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>37.7 (0.3)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Persons showing T&lt;sub&gt;re&lt;/sub&gt;≥38˚C&lt;sup&gt;3)&lt;/sup&gt;</td>
<td>8</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Time showing T&lt;sub&gt;re&lt;/sub&gt; ≥38˚C (% of 120 min)&lt;sup&gt;4)&lt;/sup&gt;</td>
<td>31.3</td>
<td>17.6</td>
<td>11.3</td>
<td>2.3</td>
<td>4.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T&lt;sub&gt;sk&lt;/sub&gt; (˚C)</td>
<td>35.2 (0.6)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>34.9 (0.5)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>34.9 (0.4)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>34.8 (0.5)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>34.5 (0.6)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>34.9 (0.5)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>34.7 (0.7)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>34.6 (0.8)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>∆T&lt;sub&gt;sk&lt;/sub&gt; (˚C)&lt;sup&gt;5)&lt;/sup&gt;</td>
<td>0.87 (0.55)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.70 (0.47)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.69 (0.35)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.82 (0.60)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.76 (0.46)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.46 (0.22)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.73 (0.33)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.16 (0.14)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>T forehead (˚C)</td>
<td>35.9</td>
<td>35.7</td>
<td>35.0</td>
<td>35.0</td>
<td>35.0</td>
<td>35.0</td>
<td>35.0</td>
<td>35.0</td>
</tr>
<tr>
<td>T abdomen (˚C)&lt;sup&gt;7)&lt;/sup&gt;</td>
<td>35.6 (0.7)</td>
<td>35.5 (0.5)</td>
<td>35.2 (0.8)</td>
<td>35.3 (0.7)</td>
<td>35.1 (0.8)</td>
<td>35.2 (0.4)</td>
<td>35.1 (0.7)</td>
<td>35.2 (0.8)</td>
</tr>
<tr>
<td>T hand (˚C)&lt;sup&gt;7)&lt;/sup&gt;</td>
<td>35.6 (0.6)</td>
<td>35.5 (0.4)</td>
<td>35.2 (0.8)</td>
<td>35.3 (0.5)</td>
<td>35.2 (0.7)</td>
<td>35.5 (0.7)</td>
<td>35.6 (0.5)</td>
<td>35.3 (0.8)</td>
</tr>
<tr>
<td>T thigh (˚C)&lt;sup&gt;7)&lt;/sup&gt;</td>
<td>35.3 (0.7)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>34.8 (0.9)&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>34.5 (0.6)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>34.9 (0.5)&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>34.3 (0.8)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>34.5 (0.6)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>34.3 (0.6)&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>34.3 (0.8)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>T calf (˚C)&lt;sup&gt;7)&lt;/sup&gt;</td>
<td>34.8 (1.0)</td>
<td>34.6 (0.9)</td>
<td>35.0 (0.5)</td>
<td>34.9 (0.8)</td>
<td>34.6 (1.1)</td>
<td>35.0 (0.4)</td>
<td>34.7 (0.5)</td>
<td>35.0 (0.7)</td>
</tr>
<tr>
<td>T foot (˚C)&lt;sup&gt;7)&lt;/sup&gt;</td>
<td>36.1 (0.6)</td>
<td>36.0 (0.6)</td>
<td>36.1 (0.6)</td>
<td>35.9 (0.5)</td>
<td>35.9 (0.5)</td>
<td>35.8 (0.9)</td>
<td>35.8 (0.7)</td>
<td>35.7 (0.8)</td>
</tr>
<tr>
<td>Tclo-chest (˚C)&lt;sup&gt;8)&lt;/sup&gt;</td>
<td>33.3 (0.7)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>32.8 (0.6)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>32.7 (1.0)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>32.9 (0.6)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>28.8 (3.5)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>32.8 (1.0)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>29.3 (3.2)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>28.8 (3.3)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Tclo-back (˚C)&lt;sup&gt;8)&lt;/sup&gt;</td>
<td>35.1 (0.7)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>34.6 (0.7)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>30.3 (4.0)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>34.3 (0.6)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>33.9 (0.9)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>30.5 (2.8)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>33.8 (0.7)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>28.8 (4.3)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Hclo-chest (%RH)&lt;sup&gt;9)&lt;/sup&gt;</td>
<td>86.9 (8.6)&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>86.9 (10.8)&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>84.2 (11.0)&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>86.6 (9.8)&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>92.6 (8.6)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>81.8 (12.1)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>91.4 (9.4)&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>90.0 (10.0)&lt;sup&gt;abc&lt;/sup&gt;</td>
</tr>
<tr>
<td>Hclo-back (%RH)&lt;sup&gt;9)&lt;/sup&gt;</td>
<td>93.6 (8.8)</td>
<td>92.0 (6.8)</td>
<td>94.1 (6.6)</td>
<td>89.5 (10.5)</td>
<td>87.6 (12.0)</td>
<td>91.4 (8.1)</td>
<td>91.9 (12.0)</td>
<td>93.2 (9.0)</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>94 (10)</td>
<td>91 (11)</td>
<td>93 (10)</td>
<td>90 (11)</td>
<td>89 (12)</td>
<td>91 (13)</td>
<td>91 (11)</td>
<td>91 (10)</td>
</tr>
<tr>
<td>HR at 110 min (bpm)&lt;sup&gt;10)&lt;/sup&gt;</td>
<td>102 (11)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>98 (10)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>99 (8)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>99 (11)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>96 (10)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>91 (15)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>92 (12)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>87 (10)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>TSR (g·m⁻²·hr)&lt;sup&gt;11)&lt;/sup&gt;</td>
<td>145 (43)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>119 (116)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>132 (55)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>133 (60)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>116 (86)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>130 (42)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>123 (46)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>135 (68)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Data are expressed as mean (SD); Superscripts (a–d) show subsets grouped by ANOVA and Duncan’s Post Hoc test. i.e., T<sub>re</sub> for three conditions (No cooling<sup>b</sup>, Neck scarf A<sup>b</sup> and Neck scarf B<sup>b</sup>) was significantly higher than T<sub>re</sub> of the rest of conditions (Hat<sup>a</sup>, Hat+Neck Scarf, Hat+Vest+B); 1) The increase of T<sub>re</sub> to the highest value starting at the initial point; 2) The highest value of T<sub>re</sub> during the 120 min exposure; 3) Person numbers among total 12 subjects showed cases that rectal temperature increased more than 38˚C during the 120 min exposure; 4) The percentage of time showing that T<sub>re</sub> was greater than 38˚C during the 120 min exposure; 5) Mean skin temperature; 6) The increase of mean T<sub>sk</sub> to the highest value starting at the initial point; 7) Local skin temperature; 8) Clothing microclimate temperature; 9) Clothing microclimate humidity; 10) Heart rate at the last point during the second work stage (at 110 min); 11) Total sweat rate.

Fig. 1. Heart rate (HR) in the climatic chamber during the red pepper harvest simulated in the climatic chamber for 120 min (Graphs shows mean values for 12 subjects).

for the absence of cooling equipment had a mean of 145 ± 43 g·m⁻²·h.
Heat storage (HS), Physiological Strain Index (PSI) and Craig Index (CI)

We compared the efficacy of the different kinds of PCE with HS, PSI and CI (Fig. 2). There were significant differences between no cooling and seven cooling conditions. The heat strain order of the eight conditions were somewhat correlated to the order of SA cooled. Among the seven cooling conditions, the conditions that included the vest were the most effective in alleviating heat strain. Moreover, even in the case of wearing cooling scarf A with about 0.4% SA cooled a significant difference was found when compared to the control. Heat storage was evaluated more specifically by PSI rather than by CI (Fig. 2).

Subjective responses

Thermal sensation was significantly improved through the wearing of the Hat+Vest and Hat+Vest+Neck Scarf B, when compared to the control (Fig. 3). In the cases of combining more than two kinds of PCE, the subjective vote of “very hot” disappeared and votes expressing less hot increased. Mean subjective score for the Control (SA cooled 0%) and Hat+Vest+Neck Scarf B (SA cooled 4.2%) were 2.7 and 1.7, respectively (Fig. 3). That is to say, the adding 4.2% of cooling area caused an average decrease by one point in the 9-point scale, during a moderate work in heat. Regarding thermal comfort, the response of ‘Very uncomfortable’ was 0% when wearing personal cooling garments (Table 3).

Discussion

It may be no wonder that the greater the cooling area is, the more effectively the heat strain of workers allevi-
ates. Shvartz and Benor (1971)17 have shown that cooling the surface area of tube passing was about 15% of BSA, resulted in a complete elimination of heat strain in men working in hot environments. However, whole body cooling during agricultural work in fields is not feasible. Further, whole body cooling may not be necessary if partial body cooling is enough to effectively reduce heat strain27. According to the present results, the cooling of 4.2% BSA including the chest, upper back, and the back of neck was effective to reduce T<sub>re</sub>, T<sub>sk</sub>, TSR, and HR, as well as improving subjective responses.

While Neck Scarf A and Scarf B did not have any effect to the wearer’s average T<sub>re</sub>, the cooling vest alone was effective in inhibiting the increase of T<sub>re</sub>. There were no cases that T<sub>re</sub> exceeded 38˚C, in the combination of Neck Scarf A and Scarf B. How large a body surface area, and which body parts should be cooled for inhibiting the increase of core temperature? In previous studies, cooling areas of PCE were 3,500 cm<sup>2</sup> 20), 1,340 cm<sup>2</sup> 22), 20% of BSA 28), and 11% of BSA 29). The cooling areas of the present study (Max 4.2%, 770 cm<sup>2</sup>) were smaller when compared to the previous studies. For the neck cooling scarf B with a cooling area of only 0.8% BSA, perceived thermal sensation and comfort were ameliorated without any responses of ‘Very hot’ nor ‘Very uncomfortable’, while thermal physiological responses did not show significant improvement comparing to the vest cooling.

The reasons why the small cooling area showed such a significant effect may be because the cooling body parts were the trunk or/and the back of neck. The trunk is more sensitive to cold than extremities because the trunk has more cold spots22. The back of neck is known as an advantageous site for heat removal because of the proximity of large blood vessels to the skin in this area23. A second reason would be that we chose a frozen gel pack. Epstein et al. (1986)20 has reported that an ice bag of 60 g melted within one hour in the present study. Therefore, the quantity and cooling capability of frozen gel should be considered in developing PCE. Third, the weight of our PCE was lighter than those used in the previous studies. The lighter the weight of the garments is, the smaller the metabolic burden of workers is. Fourth, the ventilation of vests was improved because our cooling vest was made of mesh, except the pouches inserted with frozen gel packs.

Shvartz (1976)23 observed that neck cooling of a very small surface area, about 2.2% (net coverage of the tubing was about 0.7%) by circulating cool water resulted in decreases in T<sub>re</sub> at the end of 120 min-exposure. On the contrary, T<sub>re</sub> in the present study did not decrease by cooling the neck, about 0.83% of BSA. The reason is the difference of cooling systems. Shvartz (1976)23 selected the circulated cool water as a coolant. The surface temperature of the cooling system can be maintained irrespective of air temperature or wearer’s activity, because the ice water was supplied through a tube connected to the outside. Contrary to the liquid system, frozen gel packs melt in the hot environment over time. The cooling power of the frozen gel, itself, is the highest at the starting and gradually decreased over two hours by wearer’s body temperature and air temperature.

Yet, it would be hasty to suggest that neck cooling is not effective in stabilizing T<sub>re</sub>. With the view that the physiological aim of PCE is to keep worker’s body temperature below acceptable limits, Neck Scarf B was certainly effective in alleviating heat strain. In general, the 36.5–38.0˚C of T<sub>re</sub> was regarded as a ‘reasonable safety’ range, and over 38˚C of T<sub>re</sub> was evaluated as ‘potentially dangerous’ to health and safety, and over 39˚C was understood as a ‘dangerous’ level30. In the condition without any cooling in the present study, the T<sub>re</sub> of eight out of twelve subjects (67%) exceeded 38˚C, but for the Scarf B condition, there were just three subjects (25%) who showed over 38˚C. Therefore, it can be concluded that Neck Scarf B was effective in keeping T<sub>re</sub> in the acceptable limit in spite of the fact the cooling area was just 0.83% of BSA.

When wearing the Vest or Scarf B, T<sub>clo</sub> was less than 32 ± 1˚C, known as a comfortable range. No one felt cold among the twelve subjects. During the harvesting of red

### Table 3. Percentages of thermal comfort during 120 min exposure in the climatic chamber

<table>
<thead>
<tr>
<th>Scale</th>
<th>No cooling</th>
<th>Neck Scarf A</th>
<th>Neck Scarf B</th>
<th>Hat</th>
<th>Vest</th>
<th>Hat+Neck Scarf B</th>
<th>Hat+Vest</th>
<th>Hat+Vest+Neck Scarf B</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Very uncomfortable</td>
<td>3.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2 Uncomfortable</td>
<td>27.7</td>
<td>12.8</td>
<td>12.2</td>
<td>19.2</td>
<td>2.6</td>
<td>9.6</td>
<td>12.5</td>
<td>1.9</td>
</tr>
<tr>
<td>1 A little uncomfortable</td>
<td>66.2</td>
<td>71.8</td>
<td>75.6</td>
<td>68.6</td>
<td>82.7</td>
<td>76.9</td>
<td>73.1</td>
<td>81.7</td>
</tr>
<tr>
<td>0 Comfortable</td>
<td>3.1</td>
<td>15.4</td>
<td>12.2</td>
<td>12.2</td>
<td>14.7</td>
<td>13.5</td>
<td>14.4</td>
<td>16.3</td>
</tr>
<tr>
<td>Total (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Industrial Health 2008, 46, 620–628
pepper in summer, $T_{clo}$ on the back of all workers increased over 40°C3). This problem can be more or less solved through the wearing of neck cooling equipment. Figure 1 clearly depicts the alleviating effect. Furthermore, neck cooling did not affect the other body skin temperatures except the $T_{clo}$ on the back (Table 2).

In hot environments, the skin blood vessels are vasodilated, venous return and stroke volume are decreased. Consequently, heart rate increases11). In the same way, HR decreases through cooling the trunk or the head6, 7, 10, 11, 16). It has been demonstrated in Shvartz (1970)20) that HR was less when wearing a cooling hood with a cooling area of about 3% of BSA, than in the absence of cooling. In the present study, a decrease in HR through cooling was more noticeable during the two bouts of rest stage. Constable et al. (1994)16) and Bomalaski et al. (1995)10) also observed that the effect of body cooling to the stabilization of HR was more obvious during rest than when working or walking. This could create a better situation to begin work again. That is, PCE can positively affect the physiological recovery of workers exposed to heat, even though the cooling area is less than 5% of BSA.

In general, it has been known that total sweat rate (TSR) decrease through body or head cooling6, 7, 16). TSR of the present study was less in conditions with cooling by as much as 7–20% than in the absence of cooling (Table 2, p<0.01). Shvartz (1976)23) has mentioned that the sweat rate when cooling the neck using circulating cool water decreased by about 16–22%. Veghte and Webb (1961)31) has described that sudomotor activity in heat was inhibited by prior body cooling. Sweat rate is directly proportional to the area of the skin cooled32). Interestingly, subjects sweated less when wearing PCE, but did not show a decrease in humidity in the space between the trunk and the cooling vest. This result can be explained as that TSR decreased as body temperature decreased and the necessity of cooling through evaporation decreased, but $H_{clo}$ maintained highs because of the obstruction of evaporation from the trunk due to the cooling garments. Nunneley and Maldonado (1983)13) observed that the percentage of sweat evaporated was 53–54% without a cooling vest and only 40–41% with it.

When evaluating the relief of heat stress as subjective responses, all kinds of PCE in the present study was effective in alleviating heat strain. Particularly, there was no response of feeling ‘Very hot’, or ‘Very uncomfortable’ when wearing Scarf B or the cooling vest. Because subjects felt less hot and more comfortable using neck cooling equipment, although there is no significant difference in $T_{sk}$ or $T_{re}$ between neck cooling and no-cooling, it can be assumed that thermal sensation or comfort is sensitive to the neck skin temperature.

Bomalaski et al. (1995)10) observed that the physiological significance like $T_{re}$, HR, and sweat production, in some cases, was secondary to the improvement in subjective measures of thermal comfort and ratings of perceived exertion (RPE). One should not overlook the subjective evaluations by the subjects themselves, even though the relationship between thermal comfort and thermal strain is not definitively known. In our study, no one disliked neck or trunk cooling, and no one claimed it was too cold. Because agricultural fields of Korea in summer are hot and humid, cooling garments with the least cooling area but significant efficacy may be desirable. From a practical perspective, cooling the neck is easier than cooling the head. Therefore, neck cooling rather than head cooling is recommended for farm workers, when the least cooling area is required.

**Conclusion**

By wearing personal cooling equipment (PCE) with a cooling area about 3–5% of BSA, $T_{re}$ was maintained under 38°C, and $T_{sk}$ and HR decreased to the comfort level during mid-rest stage. Total sweat rate was also lower in seven cooling conditions than in the condition without any cooling. We confirmed that the upper body cooling using a hat, a scarf and a vest with the total cooling area of only 4.2% BSA was significantly effective in alleviating physiological and subjective heat strain in a simulated harvest work at WBGT 33°C. Further studies, 1) to keep the microclimate between the cooling garments and the body skin dry, and 2) to make the cooling capacity of frozen gel packs last longer, are needed.

**Acknowledgements**

This study was supported by Technology Development Program for Agriculture and Forestry, Ministry of Agriculture and Forestry, Republic of Korea and partially by The Second Stage of BK 21. We thank those who participated as subjects.

**References**


