Evaluation of a Carbon Dioxide Personal Cooling Device for Workers in Hot Environments

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Evaluation of a Carbon Dioxide Personal Cooling Device for Workers in Hot Environments

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This study tested the effectiveness of a carbon dioxide cooling device in reducing heat strain for workers in a hot and humid environment. Ten participants completed two trials in an environment of 30°C WBGT (75% relative humidity) with a novel liquid carbon dioxide cooling shirt (CC) or no cooling (NC) in a randomized order. Mean time-weighted workload for each individual equaled 465 W (400 Kcals·h⁻¹). In the CC condition, the work time was significantly increased by 32% (97 ± 36 min) compared with NC (74 ± 26 min) (p < 0.05). There was no significant difference in mean skin temperature over the trials. Rectal temperature (Tre) was significantly different after 50 min (p < 0.05). Mean heart rate, the delta Tre increase rate, and heat storage at 55 min (last point with n = 8) were significantly lower in CC (p < 0.05). Overall heat storage was 54 ± 41 W and 72 ± 40 W for CC and NC, respectively (p < 0.05). Participants also indicated favorable subjective responses for CC vs. NC (p < 0.05). These findings suggest that this novel cooling device would effectively attenuate heat strain and increase work productivity for personnel working in a hot and humid environment. Practical aspects of use, such as cost, convenience, weight, cooling duration, and rise in ambient CO₂ concentration in confined spaces must also be considered.

Keywords heat stress, heat tolerance, personal cooling, thermoregulation

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INTRODUCTION

Significant numbers of workers on occasion endure long periods of work in conditions of elevated heat stress. When moderate to high workloads are required, as can often be the case in emergency response, industrial, and military tasks, metabolic heat production increases accordingly, and if such work must be accomplished in hot environments, the elevated metabolic heat production, along with the external environmental heat gain, can be a considerable danger. It has been well documented that heat stress can greatly diminish work capabilities(1−5) and put workers at increased risk for heat injuries.(6)

Because heat stress can threaten the life, health, and productivity of workers, mitigating heat stress with microclimate personal cooling is important. Many efforts have focused on different types of personal cooling systems, including (1) ice vests,(7,8) (2) cooled air vests,(9–11) and (3) liquid circulated garments.(12,13) Each of these methods is effective in reducing heat stress, attenuating physiological strain, and increasing work time. However, lack of mobility, limited cooling capacity, logistics, cost, and other factors limit their practical application.

Recently, an alternative approach to cooling has been developed. A nonpowered cooling garment based on the endothermic vaporization of liquefied carbon dioxide (CO₂) (Porticool Personal Cooling System, Porticool, Inc., Morrisville, N.C.) is now available. The cooling consists of two phases. In Phase 1, liquid CO₂ dispensed through a control valve travels through flexible tubing, undergoing a continuous pressure drop toward atmospheric pressure. As this happens, the liquid flashes to vapor absorbing energy equal to the heat-of-vaporization for CO₂.

In Phase 2, the newly vaporized cool and dry CO₂ is vented over a thin textile layer (100% cotton blended fabric) in direct contact with the skin, providing further cooling to the extent that it enhances ambient sweat evaporation. Heat and moisture are then expelled from the system with the flow of the gaseous CO₂. Through these processes, this personal cooling system provides heat removal during work in temperate and hot environments. In operation, the system has no moving parts, and is portable, relatively lightweight, and relatively inexpensive to operate due to the low cost of CO₂.
The purpose of this study was to evaluate this novel personal cooling device for workers in a hot and humid environment. Effective control of heat stress in industrial workers, first responders, and military personnel working in the heat can improve worker safety and increase productivity. In the case of emergency response personnel, these improvements may reduce mortality and morbidity of the workers and those being rescued.

METHODS

Participants

Ten physically active males volunteered for this study. Females were not included because this was a preliminary study specifically targeted at industrial labor populations. The normally large variability in male thermoregulatory responses would be further expanded by the addition of the gender difference in thermoregulation. The physical characteristics of age, height, weight, estimated body fat percentage, and VO₂ max were (mean ± standard deviation): 26 ± 3 yr, 177.0 ± 7.8 cm, 75.9 ± 17.1 kg, 13 ± 6% body fat and 55 ± 9 ml·kg⁻¹·min⁻¹, respectively. In general, this was a diverse group of young males varying in fitness level. None of the participants were acclimated to the heat, though two had a high level of aerobic fitness (VO₂ max > 60 ml·kg⁻¹·min⁻¹). All participants were informed of the nature of the study, cleared by a physician for participation, and signed a written informed consent before participation. This study was approved by the University of Alabama’s Institutional Review Board for Protection of Human Subjects.

Determination of Exercise Regimen

The metabolic rate for the experimental trial for each participant was determined prior to heat exposure by collecting and analyzing ventilatory expirations (Vacumed Vista MX; Vacumetrics Inc., Ventura, Calif.) to establish the desired metabolic rate. The metabolic system was calibrated before each trial with a gas of known composition. A 7-L syringe (Hans Rudolph, Kansas City, Mo.) was used to calibrate the measurement of ventilation. The cooling shirt including the control system was worn during this initial measurement of metabolic rate. Once determined, that individualized exercise regimen was fixed for all successive trials. According to the classification by the ACGIH®, a moderate work rate of 465 W was chosen. The exercise regimen at a rate of 465 W (400 Kcal·h⁻¹) (oxygen uptake 1.35 L·min⁻¹) consisted of 12 min (80% of total work cycle time) of walking on a motor-driven treadmill (Q55xt, Series 90; Quinton Instrument Co., Seattle, Wash.) at 1.33 m·s⁻¹ and at a grade to elicit a metabolic rate of 523 W (450 Kcal·h⁻¹) (oxygen uptake of 1.5 L·min⁻¹) followed by 3 min (20% of total work cycle time) of arm curls at a curl rate that elicited a metabolic rate of 209 W (180 Kcal·h⁻¹) (oxygen uptake of 0.6 L·min⁻¹). Arm curls were done with a bar weighing 13.9 kg. This work rate is similar to work rates used many times by our laboratory.

Experimental Design

This study was designed to evaluate the physiological responses to a novel cooling shirt worn in a hot and humid environment. The participants were asked to refrain from heavy exercise and to drink adequate water to ensure normal hydration the day before the experimental trials. The CO₂ cooling shirt (CC) trial and the control trial with no cooling (NC) were assigned in a random order with a minimum of 72 hr between trials.

On arriving at the lab, the participant’s nude weight (with shorts only) was measured before each trial on a calibrated scale (Detecto Scales Inc., Brooklyn, N.Y.). Then participants self-inserted a rectal thermocouple (Physitemp, Clifton, N.J.) 8 cm beyond their anal sphincter. Skin thermocouples (Physitemp) were placed on the right forearm, upper-right chest (approximately 2–3 cm above the last cooling tube of the cooling shirt), and the right calf. Participant’s thermocouples were monitored with a portable system (Thermalert Thermometer TH-8; Physitemp). Environmental thermocouples were monitored with a computerized system (Iso-Thermed Model 256, Columbus Instruments, Columbus, Ohio).

All thermocouples were calibrated prior to use and a reference thermocouple in a calibrated water bath was monitored during trials. A heart rate monitor (Polar Electro Inc., Lake Success, N.Y.) was worn throughout the test. During the trials, participants wore their own cotton t-shirt, shorts, jeans, socks, and athletic shoes. For the CC trial, the cooling shirt was worn over the t-shirt. A full-clothed weight was recorded.

On dressing, participants entered the test chamber and exercised at a temperature of 30°C wet bulb globe temperature (WBGT: 33°C dry bulb, 29°C wet bulb, 33°C globe; relative humidity of 75%). This environmental setting represents typical temperature in the southeastern United States during the summer time. Also, the cooling system would be less likely to be used in milder environments. Participants did the leg and arm work at their predetermined treadmill inclination and arm curl pace. Water was freely available during the whole trial period, and the total volume consumed was recorded.

Any of the following criteria were used to terminate the trial: (1) rectal temperature ≥ 38.7°C; (2) heart rate ≥ 95% of age-predicted maximum over a 3-min period; (3) participant’s volition; (4) symptoms of onset of heat injury (e.g., lightheadedness, dizziness, exhaustion, heat cramps); or (5) work cycle time equaled a maximum of 4 hr. After finishing the trial, participants’ clothed body weight and nude body weight were immediately recorded again.

Instrumental and Sensory Measurements

Rectal temperature (T re), body skin temperature (chest, forearm, and calf), heart rate (HR), and thermal rating were recorded every 5 min during the test. Weighted skin temperature at the chest, forearm, and calf was computed as mean skin temperature (T sk) (14). Heat storage (ΔS) was calculated as: ΔS = human body specific heat (3,474 kJ·kg⁻¹·°C⁻¹) × (0.8 × ΔT re + 0.2 × ΔT sk)·TT in Watts, where TT stands for tolerance time. (15) Change in rectal temperature
over the whole experimental period (ΔTre rate) was also calculated as the difference of post-exercise and pre-exercise rectal temperature divided by the heat tolerance time.

Pre-exercise, post-exercise nude, and clothed body weights and fluid intake were recorded. Sweat production rate was calculated from the difference of pre-exercise and post-exercise nude body weight adjusted by total fluid intake, divided by trial duration. Sweat evaporation rate was calculated from the difference of pre-exercise and post-exercise clothed body weight adjusted by total fluid intake, divided by the trial duration. Evaporative efficiency was defined as the percentage of sweat evaporation relative to sweat production. Because it was not logistically possible to determine the sweat volume dripped, this represents an error in calculating the sweat evaporation rate and evaporative efficiency. Water intake rate was calculated from the total water consumed divided by trial duration. Hypohydration was calculated as change in nude body weight adjusted for fluid intake divided by initial nude body weight times 100.

During the experimental trials, participants reported their thermal rating every 5 min. The thermal rating scale[16] ranged from 0.0 to 7.0 in increments of 0.5 with 0.0 representing “unbearably cold” and 7.0 was labeled “unbearably hot.” At baseline and immediately on test termination, participants rated their perceptions of overall comfort. Using a pencil, they marked their ratings on a 100-mm visual analog scale (from “0” representing “Very Uncomfortable” to “100” representing “Very Comfortable”), skin wetness (from “0” representing “Not Sticky” to “100” representing “Very Sticky”), clothing stickiness (from “0” representing “Very Dry” to “100” representing “Very Wet”), and perceived temperature (from “0” representing “Very Cool” to “100” representing “Very Hot”).

**Data Analysis**

Data were reported as mean values and standard deviations. A two-factor (time and condition) repeated measures analysis of variance (ANOVA) was used to determine differences among treatments for Tre, Tsk, HR, heat storage, and thermal rating over the trial period. A post hoc Tukey’s test was applied, when appropriate, with attention on the main effect for the CC vs. NC, particularly at 40 min (last point with n = 10), heat storage at 55 min (last time point with n = 8). Student’s t-test was used to compare the overall heat storage, sweat production rate, sweat evaporation rate, evaporative efficiency, water intake rate, and hypohydration between the two trials. Type I error level was set at p < 0.05.

**RESULTS**

Of the total 20 trials, 17 were stopped due to reaching predetermined rectal temperature limit of 38.7°C. One trial (CC) was stopped for equipment failure, whereas one participant each was removed for voluntary fatigue (CC) or muscle cramping (CC).

**Rectal Temperature and Mean Skin Temperature**

Figure 1a illustrates the changes in rectal temperature (Tre) across time. Tre rose steadily across time under both

**FIGURE 1.** (a) Mean (± SD) rectal temperature, (b) mean skin temperature, (c) mean heart rate, and (d) thermal rating, across time for each of two conditions: with cooling (CC) and without cooling (NC) under a WBGT of 30°C and at a work rate of 465 W (sample size is indicated at each time point, with statistical power of 0.8 for n = 8). *Indicates p < 0.05 CC vs. NC. Key time points are marked.
conditions, with and without cooling device, from the start of exercise. Significantly lower Tₑ was found at 55 min for CC compared with NC (CC = 38.2 ± 0.3°C, NC = 38.4 ± 0.3°C; n = 8, p < 0.05). A similar trend was found in the mean skin temperature (Tₛₖ) across time (Figure 1b). The rectal temperature and mean skin temperature response across time was consistent with a reduced body heat storage at 55 min under CC (Table I).

### Cardiovascular Strain

Changes in heart rate in the two conditions are shown in Figure 1c. No differences in average HR were found between the CC and NC during the first 20 min. After this time point, the differences in HR became evident. Significant differences (p < 0.05) were observed at 25 min (CC: 128 ± 16 vs. NC: 136 ± 15 beats-min⁻¹), 40 min (CC: 141 ± 20 vs. NC: 146 ± 17 beats-min⁻¹), 45 min (CC: 115 ± 16 vs. NC: 124 ± 13 beats-min⁻¹), 55 min (CC: 142 ± 17 vs. NC: 147 ± 17 beats-min⁻¹), 65 min (CC: 140 ± 19 vs. NC: 147 ± 17 beats-min⁻¹), and 70 min (CC: 143 ± 18 vs. NC: 152 ± 16 beats-min⁻¹).

### Heat Storage and Tolerance Time

Cooling condition significantly increased (p < 0.05) work time by 32% over NC condition (Table I). Mean heat tolerance times were 97 ± 36 min for CC and 74 ± 26 min for NC, while participants' improvement varied from 9% to 64% (Table II). Heat storage values under the two conditions are presented in Table I. There was no difference in heat storage between cooling conditions at 40 min (n = 10); however, at 55 min (n = 8), heat storage was significantly greater (p < 0.05) for NC. In addition, ΔTₑ rate and overall heat storage were also significantly greater for the NC vs. CC (p < 0.05). Based on the change in weight of the cooling bottle, and the latent heat of vaporization of CO₂, we calculated the mean cooling capacity of the CC to be ~136 W.

### Sweat Rate and Dehydration

Sweat production rate, sweat evaporation rate, and the evaporative efficiency are presented in Table III for both trials. Although sweat production rate (CC = 987 ± 262 g·h⁻¹, NC = 1051 ± 292 g·h⁻¹) and sweat evaporation rate (CC = 576 ± 115 g·h⁻¹, NC = 540 ± 182 g·h⁻¹) were similar (p > 0.05), the evaporative efficiency was significantly higher in CC compared with NC (59.8 ± 10.2% vs. 51.4 ± 10.2%, for CC and NC, respectively; p = 0.05). There was no significant difference in the water intake rate; however, the hypohydration was significantly higher (p < 0.05) in the CC (2.1%) condition compared with NC (1.8%) (Table III), as the duration was longer in the CC.

### Sensory Measurements

Thermal rating across time for the two conditions is graphically presented in Figure 1d. After 5 min of exercise heat stress and till the end (except at 25 min when loss of cooling due to the CO₂ bottle emptying), the thermal rating

### Table I. Mean Tolerance Time, Change in Rectal Temperature (ΔTₑ) Rate, Heat Storage Rate at 40 min (HS₄₀) (n = 10), Heat Storage Rate at 55 min (HS₅₅) (n = 8), and Overall Heat Storage Rate for Each of Two Conditions: With Cooling (CC) and without Cooling (NC) under a WBGT of 30°C and at a Work Rate of 465 W

<table>
<thead>
<tr>
<th>Variables</th>
<th>CC</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerance time (min)</td>
<td>97 ± 36</td>
<td>74 ± 26</td>
</tr>
<tr>
<td>ΔTₑ rate (°C·h⁻¹)</td>
<td>0.7 ± 0.4</td>
<td>1.0 ± 0.4</td>
</tr>
<tr>
<td>HS₄₀ (watts)</td>
<td>84 ± 52</td>
<td>85 ± 42</td>
</tr>
<tr>
<td>HS₅₅ (watts)</td>
<td>54 ± 14</td>
<td>74 ± 27</td>
</tr>
<tr>
<td>Overall HS rate (watts)</td>
<td>54 ± 41</td>
<td>72 ± 40</td>
</tr>
</tbody>
</table>

*Significantly different from NC (p < 0.05).

### Table II. Individual Overall Heat Tolerance Time for Each of Two Conditions: With Cooling (CC) and without Cooling (NC) under a WBGT of 30°C and at a Work Rate of 465 W

<table>
<thead>
<tr>
<th>Subject</th>
<th>CC (min)</th>
<th>NC (min)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>55</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>37</td>
<td>49</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>70</td>
<td>43</td>
</tr>
<tr>
<td>6</td>
<td>85</td>
<td>70</td>
<td>21</td>
</tr>
<tr>
<td>7</td>
<td>115</td>
<td>70</td>
<td>64</td>
</tr>
<tr>
<td>8</td>
<td>115</td>
<td>105</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>55</td>
<td>40</td>
<td>38</td>
</tr>
<tr>
<td>10</td>
<td>170</td>
<td>115</td>
<td>48</td>
</tr>
</tbody>
</table>

Mean ± SD 97 ± 36 74 ± 26 32 ± 19

*Significantly different from NC (p < 0.05).

### Table III. Mean Water Intake Rate, Hypohydration, Sweat Production Rate, Sweat Evaporation Rate, Evaporative Efficiency for Each of Two Conditions: With Cooling (CC) and without Cooling (NC) under a WBGT of 30°C and at a Work Rate of 465 W (n = 10)

<table>
<thead>
<tr>
<th>Variables</th>
<th>CC (ml·h⁻¹)</th>
<th>NC (ml·h⁻¹)</th>
<th>Hypohydration (%)</th>
<th>CC (%)</th>
<th>NC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water intake rate</td>
<td>730 ± 320</td>
<td>779 ± 392</td>
<td>2.1 ± 0.99</td>
<td>1.8 ± 0.9</td>
<td>51.4 ± 10.2</td>
</tr>
<tr>
<td>Hypohydration (%)</td>
<td>987 ± 262</td>
<td>1051 ± 292</td>
<td>576 ± 115</td>
<td>540 ± 182</td>
<td>59.8 ± 10.2</td>
</tr>
</tbody>
</table>

*Significantly different from NC (p < 0.05).
was consistently cooler (p < 0.05) for CC in comparison with NC condition. Figures 2a–d show the changes in the 100-mm subjective scales under both conditions. There were no significant differences between pre-trial scores, but post-trial scores were significantly different for clothing stickiness and skin wetness (p < 0.05). These findings suggested an overall greater subjective comfort under the CC condition.

**DISCUSSION**

This study evaluated a novel, personal cooling system under conditions often encountered during the summer months in the United States. The work rate and clothing were selected to maximize both ecological and external validity. The combination of environmental and exercise stress in the current study created considerable heat stress as evidenced during the NC condition. Because mean heat tolerance time in CC significantly increased by 23 min (32% advantage) over NC, work productivity significantly increased. Our findings suggest that this portable, lightweight cooling system is effective in attenuating heat strain of personnel working in a hot and humid environment. Our previous experience suggests that cooling systems are most effective under hot conditions and high metabolic rates. Thus, the conditions of this study may be close to optimal for effectiveness of this system while preserving ecological validity.

When the cooling shirt was used, heat stress was significantly reduced. Though the increases of mean T_re and T_sk over time were not statistically different between the two conditions, the time per unit of T_re increase (\(\Delta T_{re}\) rate) was slower (p < 0.05) with CC. The rates of overall body heat storage and total heat storage at 55 min (last time point with eight participants) of the sessions were both lower with CC. This could have occurred because of improved heat transfer between the skin and the surrounding gas phase, provided by the presence of cool, dry gas. The CC also reduced cardiovascular strain as demonstrated by lower HR after 20 min of the exercise-heat exposure for the CC compared with NC responses. This finding is similar to our previous studies employing cooling during exercise. This lower HR in CC likely resulted from a downward adjustment of cutaneous circulation, which acts as a thermoregulation response.

During exercise-heat stress, redistribution of blood flow away from muscle or inactive tissue to the skin can dissipate body heat to the environment to slow heat storage. Cardiac output requirements must be preserved for a given workload, and consequently, an increased HR is observed. While increased peripheral skin blood flow may delay the time to reach a critically high body temperature, an increased HR also places a limit on the capacity for maximal external work performance. Therefore, a lower HR supports the notion of better thermoregulation and greater reserve of work capacity associated with the cooling method in this study. In line with T_re, T_sk, and HR responses in CC, the thermal rating was also significantly lower, indicating some psychological relief with the cooling device while working in a thermally stressful environment. These attenuated physiological and sensory responses in CC ultimately led to a longer work time.
under exercise-heat stress. From a practical standpoint, the primary standard for determining the effectiveness of these cooling devices in a work setting is the total time that can be endured before a predetermined physiological cut-off point is achieved, such as a body core temperature less than 38.7°C in this study. The cooling shirt worked as expected.

Along with elevated heat storage resulting from working in a thermally stressful environment, sweating and dehydration also play an important role with regard to the onset of fatigue and hyperthermia. In this study, we found a significant difference in the evaporative efficiency (60 ± 10% vs. 51 ± 10%, for CC and NC, respectively). Apparently, vaporized cool and dry CO₂ vented over the skin, absorbed moisture from the skin, and permitted sweat evaporation, thus taking advantage of the natural heat transfer mechanism by drawing heat from the body equal to the heat-of-evaporation of sweat. This is again evidenced by the subjective scores for clothing stickiness and skin wetness, which were lower in CC relative to NC (Figure 2). Although the higher sweat evaporative efficiency in CC enhanced evaporative cooling power, the sweat production rate was about 1.0 L·h⁻¹ under both conditions (CC = 987 ± 262 g·h⁻¹, NC = 1051 ± 292 g·h⁻¹). This is commonly seen in many other commercially available microclimate cooling systems. When comparing current CO₂-based cooling shirt provided a 150% advantage relative to a 2.2 kg ice-based cooling vest.

The impact of cooling on sweat production is important because higher sweating rate increases the risk of dehydration that may lead to decreased work performance and heat injury. In contrast, we also saw a slightly greater hypohydration (with statistical significance) during CC use (hypohydration level for CC was 2.1 ± 0.9% total body weight loss, and for NC was 1.8 ± 0.9%). This may represent a slight blunting in the thirst drive due to external cooling and can be attributed in part to the longer duration in the CC. Body weight loss over 2% can result in decrements of exercise performance, with greater impact under heat exposure conditions. These findings suggest that the current cooling shirt cannot provide enough cooling power to substantially lower the sweat production rate as a mean for body cooling. Furthermore, any benefit of evaporative cooling under normal clothing conditions would be reduced under protective clothing or other impermeable clothing ensembles.

Muza et al. studied the effect of a portable ambient air microclimate cooling system in selected environmental conditions. The cooling vest with battery packs weighed 5.45 kg, and the maximum theoretical cooling power varied from 173–528 W based on different airflow rates. Muza and colleagues found that tolerance time was extended (by 19% and 42%, respectively, for different flow rates) compared with a computer-predicted tolerance time of no cooling, and concluded the air vest was effective in reducing heat stress. However, they did not state the battery life, which is a main concern for portable cooling systems.

A 5-kg ice-based personal ice cooling unit has also been investigated. When considering a cooling power of 150 W over a 30 min period, heat storage with the personal ice cooling unit was 45 ± 14 W·m⁻². When compared with a previous study in our lab, using similar workloads (450 W) and similar environmental condition (28°C WBGT), we found that the current CO₂-based cooling shirt provided a 150% advantage relative to a 2.2 kg ice-based cooling vest.

The issues of most microclimate cooling technologies for practical application include cost-saving, ergonomics, and in most cases, cooling capacity. In Table IV, a comparison of system weight vs. cooling power is provided. Liquid cooling technologies provide moderate to high cooling capacity (200–500 W). However, these systems usually require bulky equipment or a tether to provide sustained cooling power.

Other cooling technologies such as air cooling, phase-change cooling, or portable hand cooling may provide cooling capacity similar to that found in this novel CO₂ device but at a cost of extra weight, which may restrict the freedom of movement. Therefore, an ideal approach would be a balance of...
acceptable cooling power, weight, and mobility. The cooling shirt in this study uses a liquid CO₂ bottle (454 g) as a heat sink. The refillable bottle along with the control device (adjusts flow rate) fit into a nylon pouch that was strapped to a belt and allowed users to freely move around. The total weight of the whole system is about 1.3 kg, and it provided 136 W cooling power at the moderate setting (high and low settings are available but were not tested) over about a 25-min period under a hot and humid condition before the bottle had to be replenished.

In general, the cooling systems with a high cooling capacity also had a high weight. The present system is one of the lighter systems and yet evidenced effective total cooling capacity. The difference between heat storage at 55 min for CC and NC was 18 W (Table I). The cooling power was calculated as 136 W (excluding evaporation of sweat). This meant that the efficiency of delivery of the total cooling power was less than 13% (not including evaporative cooling). Whereas this sounds low, there are inevitable losses to the atmosphere. Further, maximizing heat loss in a worker involves physiological heat transfer as well as mechanical heat transfer. Optimal efficiency occurs only when the removal rate and the delivery rate are exactly matched.

As might be expected, the thermal comfort rating was consistently lower (p < 0.05) for the cooled condition for most of the duration of the trials. Although this is a subjective rating, it should not be discounted. Keeping workers more comfortable should result in greater job satisfaction and could lead to better morale, attention to task, and possibly better productivity.

While we found refilling cooling bottles to be easy, under some work conditions it may be much more trouble for a worker to operate the system. Exhausting CO₂ to a closed lab area setting (volume of ~ 29.5 m³), the highest CO₂ concentrations to rise to hazardous levels. But, in our small, closed lab area setting (volume of ~ 29.5 m³), the highest CO₂ level while a single cooling vest was in use was 0.4% monitored very near the research participants. This is influenced by numerous factors including air motion, ventilation, and other vests in the vicinity.

Optimizing the cooling power for these cooling technologies would improve their practicality for field use. Recently, Cheuvront et al. proposed that intermittent cooling is an effective way for reducing the power requirements while maintaining an equivalent thermoregulation. These authors suggested that, if skin temperature falls below 32°C, skin cooling could produce cutaneous vascular constriction that decreases convective heat transfer from the body core to the periphery, and it was observed that an intermittent cooling strategy alleviated cardiovascular and thermoregulatory strain comparable to a constant cooling method. This would be of interest since a simple 4:4 min on-off cooling ratio could double the cooling supply life.

However, in the current study, the Tₜ{s} was around 35°C, well above the suggested critical Tₜ{s} of 32°C. Furthermore, the liquid cooling technologies used had a cooling capacity higher than the current CO₂-based cooling system. It is unclear whether the intermittent cooling strategy would still work at a relatively high skin temperature and lower cooling power conditions. The CO₂ bottle in our study lasted around 25 min before being replenished. Even using a 2:1 on-off perfusion ratio would theoretically increase the cooling bottle life by 12.5 min.

Future research should examine this application. During the first 20 min (Figure 1), the cooling shirt had little impact on physiological change and added only comfort. One strategy that should be tested would be to wait ~ 25 min before donning the PCS to save one bottle refill.

CONCLUSIONS

The carbon dioxide personal cooling system appeared to be an effective method for reducing physiological stress and increasing work productivity in the heat. It is clear from these data that, under the conditions of this study, individuals performing very short work bouts (e.g., less than 50 min) would not likely benefit greatly on a physiological basis from use of this cooling system. On the other hand, the subjective responses were positive, and workers who feel better may work longer and more efficiently. This CO₂-based cooling system is light, portable, and apparently cost-effective for repeated use. Furthermore, there is minimal risk in operating the cooling system. The cooling system provides moderate cooling power, and it offers a practical approach for reducing heat strain during field operations.

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