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Effects of Liquid Cooling Garments on Recovery and Performance Time in Individuals Performing Strenuous Work Wearing a Firefighter Ensemble

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This study investigated the effects of body cooling using liquid cooling garments (LCG) on performance time (PT) and recovery in individuals wearing a fully equipped prototype firefighter ensemble (PFE) incorporating a self-contained breathing apparatus (SCBA). Six healthy male participants (three firefighters and three non-firefighters) completed six experimental sessions in an environmental chamber (35°C, 50% relative humidity), consisting of three stages of 15 min exercise at 75% VO_{2max}*, and 10 min rest following each exercise stage. During each session, one of the following six conditions was administered in a randomized order: control (no cooling, CON); air ventilation of exhaust SCBA gases rerouted into the PFE (AV); top cooling garment (TCG); TCG combined with AV (TCG+AV); a shortened whole body cooling garment (SCG), and SCG combined with AV (SCG+AV). Results showed that total PT completed was longer under SCG and SCG+AV compared with CON, AV, TCG, and TCG+AV (*$p < 0.01$*). Magnitude of core temperature (*T_c*) elevation was significantly decreased when SCG was utilized (*$p < 0.01$*), and heart rate recovery rate (10 min) was enhanced under SCG, SCG+AV, TCG, and TCG+AV compared with CON (*$p < 0.05$*). Estimated* E_{sw} *rate (*$kg{\cdot}h^{-1}$*) was the greatest in CON, 1.62 (0.37), and the least in SCG+AV 0.98 (0.44): (descending order: CON > AV > TCG = TCG+AV > SCG > SCG+AV) without a statistical difference between the conditions (*$p < 0.05$*). Results of the present study suggest that the application of LCG underneath the PFE significantly improves the recovery during a short period of rest and prolongs performance time in subsequent bouts of exercise. LCG also appears to be an effective method for body cooling that promotes heat dissipation during uncompensable heat stress.*

Keywords core temperature, firefighter ensembles, heat stress, liquid cooling garments

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INTRODUCTION

Fire fighting is one of the most physically demanding occupations that entail not only high thermal exposure but potentially exposure to hazardous chemical/biological materials. While firefighter ensembles incorporating a self-contained breathing apparatus (SCBA) may effectively protect the firefighter from such hazards, wearing the protective ensemble decreases maximal physical performance, increases metabolic heat production, and reduces body heat dissipation due mainly to increased encapsulation by the clothing layers, which, in turn, hinder vapor permeability.(1–3) The physiological and thermoregulatory challenges of fire fighting are often exacerbated when working in hot and humid environments, creating the potential for uncompensable heat stress where required evaporative heat loss to maintain a thermal balance exceeds evaporative potential of environment.

The National Fire Protection Association(4) recommends that firefighters be withdrawn from an operation after 30–60 min of activity, depending on the duration of the SCBA, work rate, and environmental conditions. After withdrawal from active fire fighting, firefighters then engage in a recovery period for 10 to 20 min before returning to fire fighting activities. However, it has been well documented that passive body cooling during a short period of time, relying on the natural process of sweat evaporation together with doffing protective ensemble and/or equipment, is not an effective method of alleviating thermal strain, nor does it result in a significant reduction in core body temperature.(1) A number of previous studies have investigated active cooling methods applicable for firefighters during the activity and/or recovery period, including cooling vests with ice packs(5) or phase changing materials,(6,7) cooling fans,(8) and cold water immersion.(9,10)

Liquid cooling garments (LCG), first introduced in aviation and space missions, have proved to be a safe, efficient, and powerful cooling method to suppress heat stress and support thermal comfort during muscular activity and external heat exposure.[11,12] In addition, several studies have examined the efficacy and application of LCG underneath protective clothing, such as nuclear, biological, and chemical (NBC) clothing,[13,14] and military protective clothing,[15] and also reported that the level of thermal strain and heat storage is significantly reduced and work performance and tolerance to heat stress are enhanced during a prolonged performance trial.

However, these aforementioned studies examined the cooling effect of LCG on individuals who perform at moderate intensity for a maximal sustainable duration in a continuous manner, whereas certain vocational activity such as fire fighting often involves strenuous work intensity with occasional bouts of work and rest during a relatively short period of time (<1 hr). The purpose of this study was therefore to investigate the effects of body cooling by means of an LCG on recovery and exercise performance time in individuals performing a simulated fire fighting activity that involves repeated work and rest bouts. We hypothesized that using body cooling via LCG underneath the PFE would reduce thermal strain and increase recovery rate that, in turn, would improve performance time on a subsequent bout of exercise.

METHOD

Participants

Six healthy males (three firefighters and three non-firefighters with previous experience wearing protective clothing and equipment), (mean ± SD) age: 30.5 ± 6.8 years old; height: 182 ± 8 cm; weight: 90.6 ± 12.2 kg; BMI: 27.7 ± 5.32 kg/m^2; body surface area: 2.11 ± 0.13 m^2; VO_{2max}: 46.3 ± 6.6 ml/kg/min, were recruited. All participants completed a maximal graded exercise test (GXT) without any evidence of cardiovascular dysfunction. Maximal oxygen consumption (VO_{2max}) was measured during the GXT, and this value was used to calculate relative exercise levels to be used during subsequent testing. Prior to experimental participation, each participant was also familiarized with the experimental procedures: donning/doffing the firefighter ensemble and gear and walking on a treadmill at 50% of their VO_{2max} for 30 min while wearing the complete firefighter ensemble. Both written and oral consent were obtained from all participants prior to their participation, and the study was approved by the National Institute of Occupational Safety and Health (NIOSH) Human Subjects Review Board (HSRB).

Firefighter Ensemble

The prototype firefighter ensemble (PFE) (Morning Pride/Total Fire Group, Dayton, Ohio), along with a standard SCBA with 45-min rated carbon cylinder (NxG2 Air-Pak; Scott Health & Safety, Monroe, N.C.), were used as the ensemble in this study. Detailed design and functional features of the PFE has been reported previously.[16] Briefly, the PFE consists of the same compartments as a conventional firefighter ensemble but with several additional features that increase the protection from chemical and biological hazards. These features include a sleeve-glove and boot-pants interface, an anti-vapor penetration zipper closure, integrated rubber hood-facepiece flange interface, and SCBA air exhaust system with an exhaust air collection hose attached to the jacket. While providing additional protection, the extra protective features impose a greater level of encapsulation as well as additional weight to a wearer, which potentially exacerbates heat stress. However, it was proposed by the manufacturer that the SCBA air exhaust system provide convective cooling by rerouting exhaust gases into the ensemble. Design features of the air exhaust system and the PFE have been described elsewhere.[16] The total weight of PFE and SCBA subjects carried in this study was 21.21 ± 0.37 kg. Weight of the SCBA (filled) did not change (decrease) during the exercise periods because an in-line compressed air line supplied breathing air rather than the air being supplied directly from the SCBA tank (so as not to have to halt testing prematurely in the event that the subject used all the available SCBA air).

Liquid Cooling Garments

Two types of LCGs were used: a top cooling garment (TCG) and a shortened cooling garment (SCG). Both are physiologically designed garments that selectively cool body parts with higher heat exchange capabilities introduced by Koscheyev et al.[17,18] The garments have tubing sewn into the fabric on the inner surface and are thus in contact with the skin for heat exchange. The tubing is infused with cooled water (18°C) supplied by an external water circulator. Body surface areas covered by TCG and SCG tubing are head/forearm and head/torso/forearm/thigh area, respectively. Cooling garment specifications are detailed in Table I.

Procedures

All the participants completed six experimental exercise sessions under randomly assigned cooling conditions while

TABLE I. Specifications of Liquid Cooling Garments

	Garment		Tubing			
	Weight (kg)[A]	Material	Length (m)	ID/OD (mm)	Material	Flow Rate (kg/min)[B]
TCG	0.40	Spandex PE	15.3	2.4/4.0	PVC (Tygon tubing)	0.20
SCG	0.95		55.0			0.65

[A]Garment weight when tubing is filled in water.
[B]Flow rate when garment is not worn under the pumping flow rate of 15 kg/min.

wearing the PFE and SCBA. The experimental conditions were as follows: control (no cooling garment, air ventilation disconnected, CON); air ventilation using the SCBA air exhaust system (AV); top cooling garment (TCG); TCG combined with AV (TCG+AV); a shortened whole body cooling garment (SCG); and SCG combined with AV (SCG+AV). Prior to the treadmill exercise, participants were seated on a chair at rest to allow their vital signs to stabilize, and they consumed a controlled amount of water (5 mL/kg body mass). During this rest period, all baseline vital sign and temperature measurements were obtained. After the 5- to 10-min stabilization period, the participants mounted the treadmill and slowly walked for a 2-min warm-up period. Each cooling protocol was initiated as participants proceeded to the first exercise stage. Inlet temperature of water circulating TCG and SCG was set at a constant 18°C by an external refrigerated water bath (NESLAB RTE-10; Thermo Fischer Scientific, Newington, N.H.).

The exercise protocol consisted of three stages of 15 min exercise on a treadmill at 75% VO_{2max}, with 10 min rest sitting on a chair in the environmental chamber (35°C and 50% relative humidity). Subjects removed their facemask and opened their turnout jackets halfway through (at the last rest stage, turnout jacket was completely removed), following each exercise stage. However, exercise was terminated and progressed to a rest stage when the participants reached their 90% maximum heart rate (HR_{max}, the highest HR observed at the end of the GXT) or requested that the test be terminated. Since the participants did not perform heat acclimation training, each cooling condition was randomly assigned, and experimental participation was separated by at least 5 days to minimize progressive heat acclimation effects.

Measurements

Body core temperature (T_c) was measured by a rectal (T_{re}) probe (4600 precision rectal thermometer; YSI Temperature, Dayton, Ohio) inserted 13 cm beyond the anal sphincter (accuracy ± 0.05°C, between 25–50°C). Skin temperature was measured by skin thermisters (SQ2020–1F8 skin temperature logger; Grant Instruments Ltd., Cambridgeshire, England) attached to four skin sites (chest, arm, thigh, and calf). Accuracy was 0.01% between –50°to 150°C. Temperature measurements from these skin sites were used to calculate mean skin temperature (T_{sk}) using the weighting coefficient of Ramanathan.[19] T_{re} and T_{sk} data were continuously acquired and saved by a data acquisition system every second throughout each session and then represented as 1-min average values. Microclimate temperature was also continuously monitored using an additional thermister. The microclimate sensor was partially encapsulated by surgical tape and placed in a bulk space inside the turnout jacket to avoid contacting the surface of cooling garment and/or jacket.

Heart rate was continuously measured (heart rate monitor series 610; Polar, Lake Success, N.Y.) during each experimental session. Changes in HR (ΔHR) were calculated after 10 minutes of each rest stage as $\Delta HR = HR_{10rest} - HR_{0rest}$; where HR_0 was the HR at the end of each exercise stage to establish HR recovery rate for each participant participating in each experimental phase.

Evaporative weight loss (E_{sw}) was estimated by calculating differences between pre- and post-nude body weight by a precision weighting scale to the nearest 2 g (electronic scale series 4450; GSE, Farmington Hills, Mich.). The scale was adjusted with corrections for fluid consumption during testing and changes in the weight of the ensemble, underwear, and cooling garments from the absorption of sweat. Since mass loss through respiration was not independently determined, total E_{sw} is the sum of sweat and respiratory evaporation.

Subjective heat perception and fatigue were measured at the beginning of each rest stage using separate visual analogue scales (VAS)[20] anchored "None" at the left end and "Maximal" at the right end. These subjective data were then converted against a scale from 0 to100 for data analysis.

Statistical Analysis

All variables measured were first calculated as mean and standard deviation for each individual subject across all experimental conditions. Data were then summarized for baseline, end point of each exercise, and each rest stage for statistical analysis. The dependent variables were T_c, T_{sk}, HR, weight loss (i.e., sweat rate and total sweat loss), performance time, and subjective measures. A repeated measures analysis of variance (ANOVA) was used to determine main effects and interactions of each variable across the cooling conditions. The Greenhouse-Geisser correction for sphericity was used to designate significance level, and the least significant difference (LSD) adjustment was chosen for post-hoc pairwise comparison. Statistical significance was accepted when $p < 0.05$.

RESULTS

All participants completed the experimental protocol under one control and five different cooling conditions for a total of 36 sessions. There were significant differences in T_c changes during rest (mean of three rest stages) under SCG and SCG+AV compared with all the other conditions ($p < 0.05$) (Figure 1A). Decrease in T_c was observed in some of the subjects during rest under SCG and SCG+AV cooling conditions, but individual differences were greater as represented in SD values for SCG+AV condition. No statistical difference was found in T_c change between CON and TCG or AV effect in terms of T_c cooling ($p > 0.05$).

Mean HR recovery rate during rest stages appeared to be greater in TCG, TCG+AV, SCG, and SCG+AV than in CON ($p < 0.05$); however, only SCG showed significantly greater HR recovery rate compared to AV (Figure 1B). No effects of AV on HR recovery were found when combined with TCG or SCG.

No statistical difference was found in mean T_{sk} recovery rate during rest in any subject regardless of conditions ($p > 0.05$). Interestingly, T_{sk} recovery rate tended to be decreased

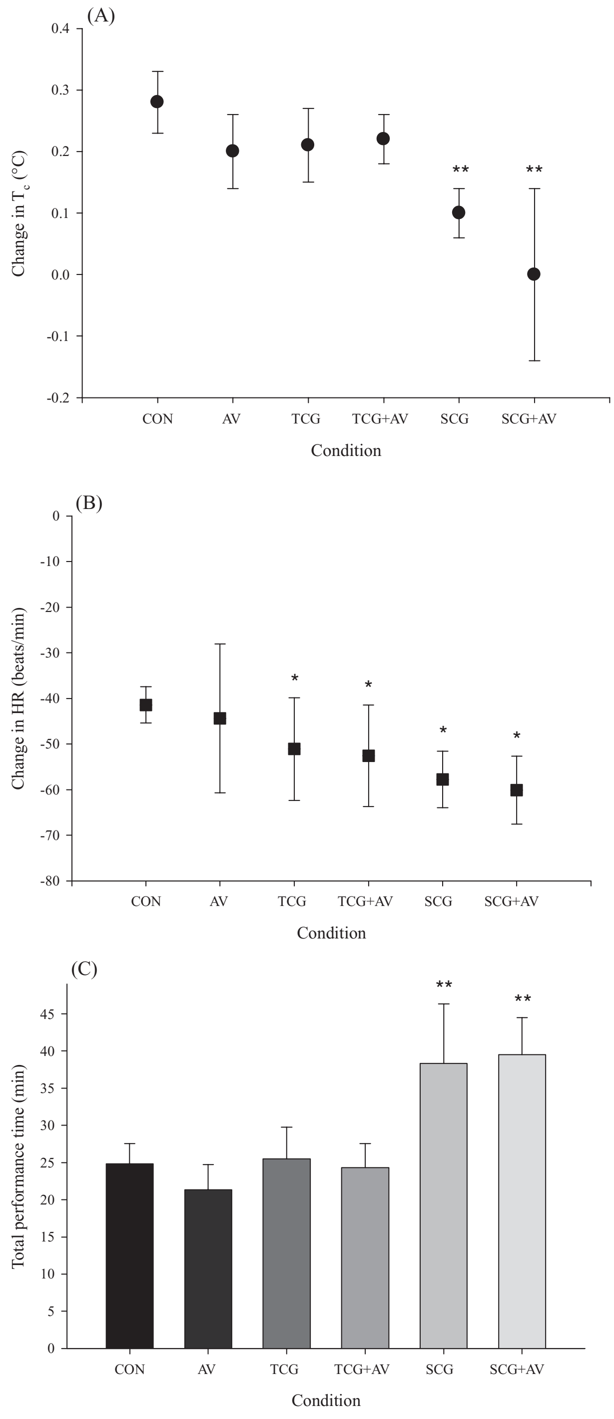

FIGURE 1. Comparison of mean change in T_c (A) and HR (B) during rest stages (mean of three rest stages; 10 min each) and total PT (C) under control and cooling conditions (the sum of exercise time completed from three exercise stages; maximum duration of 45 min). * Significantly different compared to CON ($p < 0.05$). ** Significantly different compared to CON, AV, TCG, and TCG+AV ($p < 0.05$)

in conditions with AV. This tendency became obvious when each rest stage was independently analyzed and compared with mean values of all rest stages. However, the results did not statistically support the notion that AV and/or AV combined cooling conditions would negatively affect T_{sk} recovery. In the latter analysis, SCG, –0.25 (0.07) and SCG+AV, –0.43 (0.24) were statistically different from AV, 0.27 (0.11) in rest stages 1 and 2 ($p < 0.05$).

Total performance time (min) completed from three exercise stages for each condition is shown in Figure 1C. The subjects performed significantly longer under SCG and SCG+AV than the other conditions ($p < 0.01$). However, no statistically significant differences were found for positive effects of AV in terms of enhancing performance time when combined with either SCG or TCG or with comparisons between CON and AV ($p > 0.05$).

There were no statistical differences in net E_{sw} between experimental conditions ($p > 0.05$). Estimated E_{sw} rate (kg·h^{-1}), adjusted for total test duration, showed the greatest E_{sw} in CON, 1.62 (0.37) and the least in SCG+AV, 0.98 (0.44): (descending order: CON > AV > TCG = TCG+AV > SCG > SCG+AV). However, no statistical differences were found between any comparisons.

Progressive increases in microclimate temperature were observed in all conditions during each exercise bout. However, the magnitude of the increase was significantly smaller in SCG and SCG+AV than the other conditions, while there was no significant difference in baseline measurements. Mean increase in microclimate temperature (°C) between pre- and post-session appeared to be much greater in CON, 7.7 (1.5); AV, 6.5 (1.9), TCG, 7.1 (2.0); TCG+AV, 5.3 (1.7) than in SCG, 0.1 (2.2); SCG+AV, 2.0 (2.9) (Figure 2).

Analyzed VAS data for subjective heat perception during rest indicated that the subjects felt significantly hotter in CON and AV than in other conditions. Overall (mean of three rest stages) subjective heat perception in CON, 81.8 (4.4) and AV, 83.4 (7.0) was significantly higher ($p < 0.05$) than in TCG, 62.2 (14.2); TCG+AV, 58.0 (16.2); SCG, 50.7 (24.5); and SCG+AV, 52.4 (12.0) (Figure 3A). While no statistical differences were found in subjective fatigue ($p > 0.05$), overall fatigue level was the greatest in AV, 53.2 (28.2), and the least in SCG, 45.1 (21.3) (Figure 3B).

As an example, from one participant, Figure 4 indicates the trend of HR and T_c responses throughout each experimental trial. It is clearly shown that the subject's HR recovered more rapidly during rest and remained lower ($\leq 90\%$ HR_{max}) during exercise bouts in conditions where SCG was worn. Also, the extent to which T_c increased was moderate in SCG and SCG+AV compared with other conditions that resulted in a significantly higher level of T_c change between baseline and the trial end point.

DISCUSSION

The primary finding of the present study was that body cooling using LCG (SCG and SCG+AV conditions) underneath the firefighter ensemble is an effective method for reducing thermal strain under conditions of uncompensable heat stress. During exercise in CON, mean elevation in T_{sk}

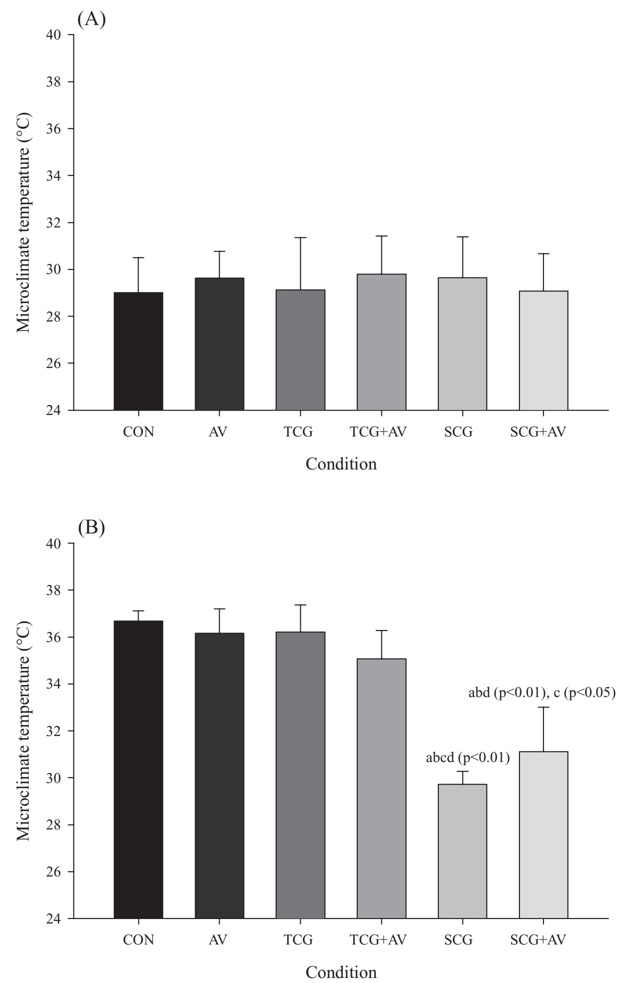

FIGURE 2. (A) Pre- microclimate temperature under control and cooling conditions; baseline measurement. (B) Post- microclimate temperature under control and cooling conditions; measurement at the end of exercise bout 3. Superscripts show significant differences: a: CON, b: AV, c: TCG, d: TCG+AV, e: SCG, f: SCG+AV.

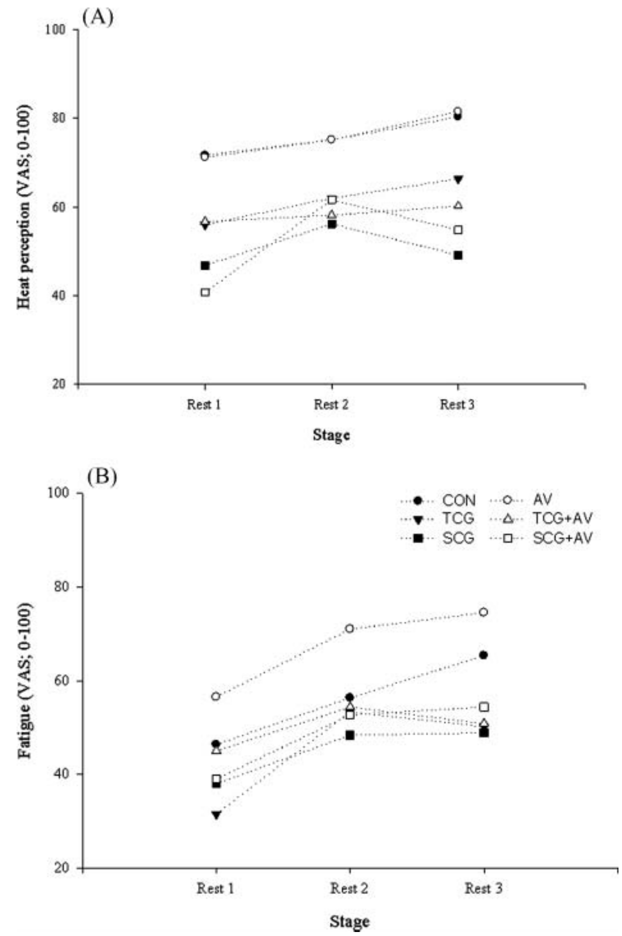

FIGURE 3. Mean subjective heat perception (A) and fatigue level (B) during rest under control and cooling conditions. Heat perception: *significantly different compared to TCG, TCG+AV, SCG, and SCG+AV ($p < 0.05$). Fatigue: no significant difference among conditions ($p > 0.05$)

and T_c was 2.63°C and 1.50°C, corresponding to the rate of 0.046 and 0.026°C/min, respectively. These results are similar to those of previous investigations that examined the physical demands of fire fighting as reviewed by Barr et al.[1] However, in the present study, no decline in T_c during rest was observed in either CON or AV, but progressive elevation of T_c was observed in all subjects. In a previous study[7] progressive decline in T_c was reported during 20 min of passive recovery in an ambient temperature of 15°C. In other studies,[9,10] T_c was observed to increase during passive recovery at a rate of 0.01 ± 0.01°C/min in an ambient temperature of 21°C and ∼ 0.62 ± 0.1°C/hr in an ambient temperature of 35°C. Combined with the results of the current study, it is suggested that a passive cooling strategy relying on body cooling through natural evaporation following bouts of strenuous fire fighting activity is unlikely to either reduce thermal strain or elicit core cooling effects. Rather, T_c may continuously increase during recovery if ambient temperatures are high. Even in a thermoneutral environment, removing a part of protective clothing, such as opening up the turnout jacket, does not seem to greatly promote heat dissipation.

Mean HR observed during exercise was ∼80 to 92% of the subjects' HR_{peak}. Overall, the time to reach the exercise termination criteria of HR (>90% HR_{peak}) was less in CON and AV than in SCG trials. Mean HR recovery rate during 10 min of rest in both CON and AV was <40 beats/min. Thus, the subjects' HR still remained at ∼65–70% of their HR_{peak} by the end of the 10-min rest period. This elevated HR during the 10 min of rest contributed to the rapid increase in HR in CON and AV during the next exercise bout, allowing the attainment of ∼90% HR_{peak} more rapidly than during previous exercise bouts. Higher HR during rest may be the result of increased blood volume to peripheral tissues for dry heat exchange, resulting in a decrease in effective blood volume. This trend is more evident during uncompensable heat stress combined with a protective ensemble.[21] During this time, HR

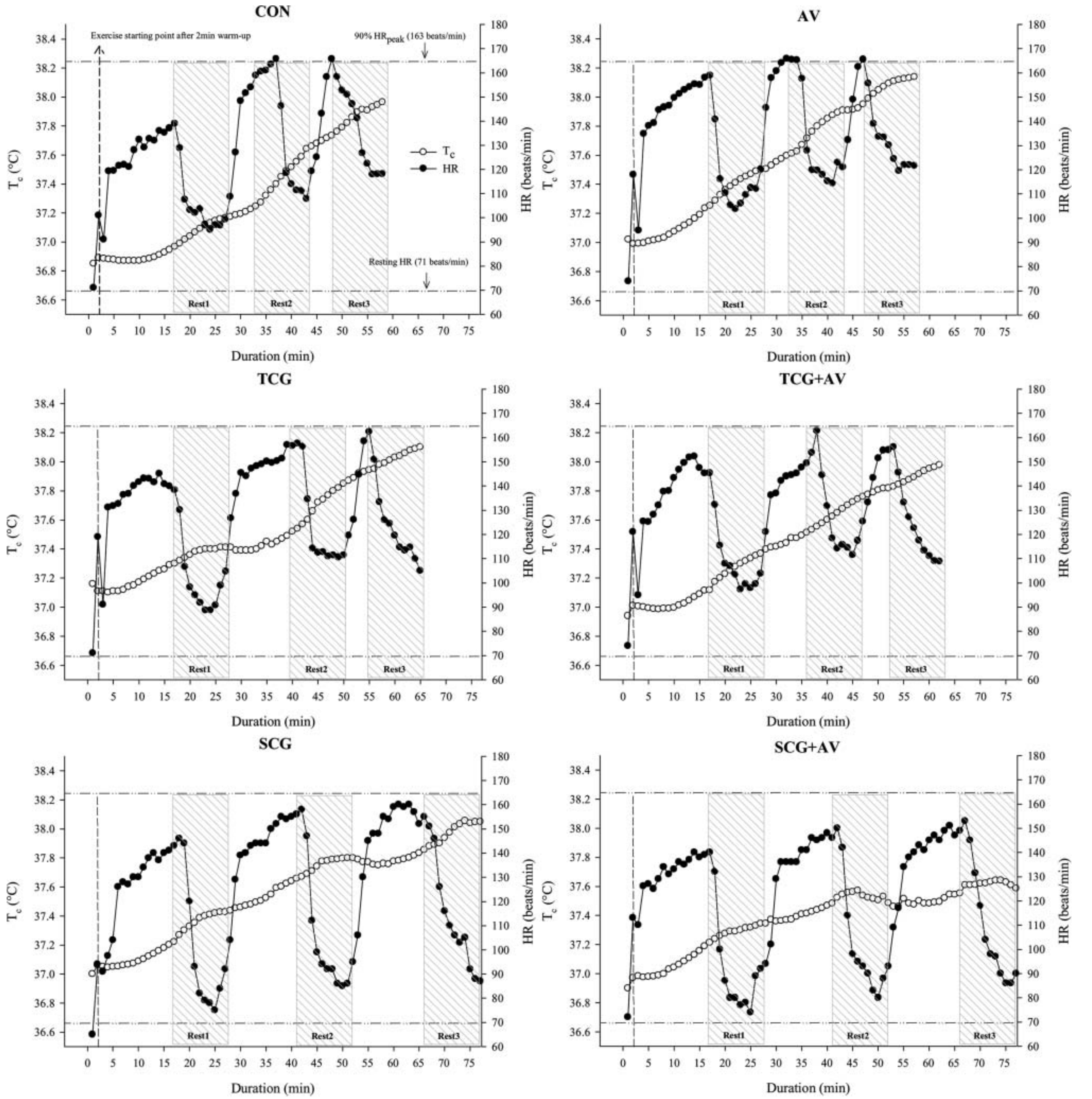

FIGURE 4. T_c and HR responses of one subject under control and each of the cooling conditions. Subject (a professional firefighter) characteristics: age, 40 yrs; height, 173 cm; weight, 87.4 kg. Total PT (min) completed under each condition, excluding 2-min warm-up, was 26 (CON), 25 (AV), 33 (TCG), 30 (TCG+AV), 45 (SCG), and 45 min (SCG+AV).

was maintained at a lower average rate at any given time during exercise and then recovered more rapidly (~6 beats/min) in subjects participating in SCG and SCG+AV trials.

The study also showed that exercise performance time was significantly greater while wearing the SCG compared with CON and AV conditions. Total performance time in SCG and SCG+AV increased approximately 57% (14.1 min) and 82% (17.6 min) compared with CON and AV. Performance time completed in CON and AV decreased as the subjects continued through the next bout of exercise. Mean PT completed for first, second, and third bouts was 15.0, 6.8, and 3.0 min, respectively. A number of previous investigations[22,23–25] demonstrated that a critical level of T_c limits exercise performance and causes fatigue, while multiple other factors such as hydration, fitness, acclimation status, and so on, also contribute to the development of fatigue. A proposed level of T_c at which exhaustion occurs in uncompensable heat stress is 40.1–40.3°C during a no-weight-bearing exercise condition[23] and 38.6–40°C in a protective ensemble.[22 24 25] However, no subject in the present study met the T_c criteria. Mean T_c at the end of the third bout in CON was 38.02 ± 0.28°C, and no significant interaction was found between T_c and performance time. The reason for a relatively lower T_c even in CON might be due to the study design: repetition of intense exercise for 15 min followed by a rest period, rather than continuous/prolonged exercise for the maximum tolerance time.

The AV system of the PFE, designed to provide cooling by rerouting exhaust gases into a turnout jacket, appeared to have no cooling effect on T_c compared with CON, nor showed any significant improvement to TCG or SCG in the present study. Rather, the AV features could adversely affect microclimate temperature of the PFE by reducing the evaporative cooling capacity of the body. This result could be expected because the temperature of the expired air in exercising subjects in a hot environment could range between 34 and 37°C with humidity ranging from 80 to 100%.[26] On the other hand, application of SCG appeared to provide the wearer of the PFE an amount of cooling sufficient to suppress heat strain and enhance recovery during short rest periods. Heat removal capacity of the SCG, estimated from mass flow rate (L/min) × the specific heat of water (4.18kJ/kg/°C) × the difference between inlet and outlet coolant temperature (°C), was ∼11.8 kJ/min during exercise and ∼6.2 kJ/min during rest. This corresponds to ∼200 and 100 $W \cdot h^{-1}$, respectively, assuming that the coolant temperature (18°C) supplied and the heat removal rate are constant over the time. While not being sufficient to compensate for the net metabolic heat production during typical fire fighting activity (especially when combined with exposure to high thermal energy in the field), the heat removal capacity of the SCG or LCGs in up-to-date operational capacity,[11] but not the TCG, could alleviate heat strain during a short recovery phase and enhance a subsequent task performance.

STUDY LIMITATIONS

This study was conducted within the controlled conditions of an environmental chamber. The hot and humid environmental conditions were chosen to simulate some of the heat faced by firefighters under actual fire ground conditions. However, those conditions are much worse than the ones used in this study. Therefore, our results must be tempered with this consideration. This study also simulated a fire fighting routine of 15 min work and 10 min rest that may not be representative of actual fire fighting activities. Nevertheless, these limitations are mitigated by the fact the cooling garments showed greater performance improvement; so, given worse conditions, the differences may probably have been greater. Another factor that could plausibly have significantly affected the study is the relatively small sample size ($n = 6$), which may have been too undersized to detect a true difference (β-error) among the six conditions, although other studies have utilized similar numbers and also achieved statistical significance.

CONCLUSION

The findings of the present study indicate that the level of simulated fire fighting activity, combined with the additional burden from protective clothing and high thermal environment, is physically demanding exercise that can result in significant physiological and thermal strain. Passive recovery, relying on body cooling via natural evaporation during a short period of time followed by a bout of strenuous level of physical activity, was not an effective cooling strategy to reduce thermal strain or restore the baseline physiological state. This was especially true in hot and humid environmental conditions. Body cooling via a wearable liquid cooling garment (SCG) underneath the fire fighting ensemble appeared to significantly reduce thermal strain, enhance recovery, and extend exercise performance time in subsequent bouts of exercise.

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