EVALUATION OF FIVE COOLING CONDITIONS WEARING A PROTOTYPE FIREFIGHTER ENSEMBLE

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INTRODUCTION

Overexertion and thermal stress are among the most common causes of injuries and deaths amongst firefighters. In 2004, the RAND Science and Technology Policy Institute (Houser et al. 2004) reported that firefighters experience an annual average of 3200 injuries due to thermal stress, of which half were moderate or severe in nature. The thermal stress faced by a firefighter results from a myriad of sources, including the environment, work, and their protective equipment. The protective qualities of firefighter ensembles (FE) include a significant level of thermal insulation that serves to trap endogenously-generated heat from the high output of work required while on duty. In addition to wearing restrictive clothing, the firefighter must also carry the additional weight of a self-contained breathing apparatus (SCBA), communication equipment, and personal firefighting equipment. This additional equipment weighs as much as 21-22 kg, which further increases the wearer's heat stress. SCBA used by firefighters have different duration time. The common practice is to refer to cylinders as the expected duration of use 30-minute, 45-minute, and 60-minute. However, these cylinders will last less time depending on work level, and experience of user. The 30-minute cylinder has been the standard in the U.S. fire service and it will last an average firefighter actively fighting a structural fire about 15-18 minutes (Gagliano et al., 2008).

In order to enhance firefighters' safety and work performance, this study evaluates different cooling mechanisms designed to reduce heat stress, in order to identify the optimal system with regard to efficiency (more work time, better performance) and safety (lower core temperature (T_{core}), lower heart rate (HR); less cardiovascular stress). The purpose of this study was to evaluate five cooling strategies based on exploiting the conductive/convective mechanisms of body cooling. Our hypothesis was that any cooling (garments and/or ventilation) would provide a source of heat loss to the wearer thus reducing core temperature and allowing increased total exercise time.

METHODS

Six healthy subjects participated in this investigation (three of the subjects were firefighters and the rest had experience wearing protective equipment). All were nonsmokers and not taking medications. Screening measures included a physical examination, and a maximal graded exercise treadmill test. The study protocol was approved by the NIOSH Human Subjects Review Board, and both oral and written consent were obtained from all subjects.

This study used a prototype firefighter ensemble (PFE) designed to improve protection against chemical and biological hazards with the following additions (Fig. 1):

- vapor penetration-resistant front zipper closure on the jacket;
- integrated hood with face piece gasket;
- booties incorporated into the pants; magnetic gauntlet glove/sleeve interfaces;
- re-routing of exhaled gases through a rubber hose from the SCBA respirator to the anterior right side of the jacket to enhance chemical/biological protection (through positive pressure effects preventing inward leakage) and cooling (through enhanced convection).

Figure 1. PFE new design features: booties, gloves, integrated hood, and hose.

Each subject completed six exercise sessions using the same PFE garment under random conditions with five different cooling sessions and one control session without cooling (CS). The five cooling sessions were conducted wearing various cooling strategies, as follows:

1) a shortened whole body cooling garment (SCG) (Fig. 2);
2) SCG plus air ventilation (AV) from the PFE hose (SCG+AV);
3) a top cooling garment (TCG) (Fig. 3);
4) TCG plus AV (TCG+AV);
5) only AV from the PFE hose (AV).

Each session consisted of 3 stages of 15 min exercise on a treadmill at 75% VO_{2max} with 10 min rest between stages while T_{core} (Fig. 4) and HR were measured. T_{core} was measured with a rectal probe inserted 12 cm (4600 Precision Thermometer; YSI Temperature, Dayton, OH); HR was measured with a S410 Polar heart rate monitor. Each session was completed in an environmental chamber operating at 35°C and 50% RH. Subjects were randomly assigned to sessions. Comparisons were made (Table 1) for the different cooling sessions and control at the end of the exercise using repeated measures analysis of variance (ANOVA) with each of the parameters (HR, T_{core}, total exercise time).

Figure 2. SCG cooling garment body surface covered details.

Figure 3. TCG cooling garments body surface covered details.

RESULTS

Results from this study showed that total exercise time for the CS was 13.4 and 14.9 min shorter than SCG and SCG+AV ($p \leq 0.05$), respectively. T_{core} and HR were lower for SCG and SCG+AV than for CS ($p \leq 0.05$). The other three conditions (TCG, TCG+AV, and only AV) were not significantly different from CS. Figure 4 shows an individual T_{core} dynamic for the six sessions. It can be observed that time was longer for SCG and SCG+AV with a lower T_{core}. It can also be observed how the cooling provided by the SCG and SCG+AV reduces T_{core} during the rest time between exercise stages while T_{core} continues increasing during rest for CS.

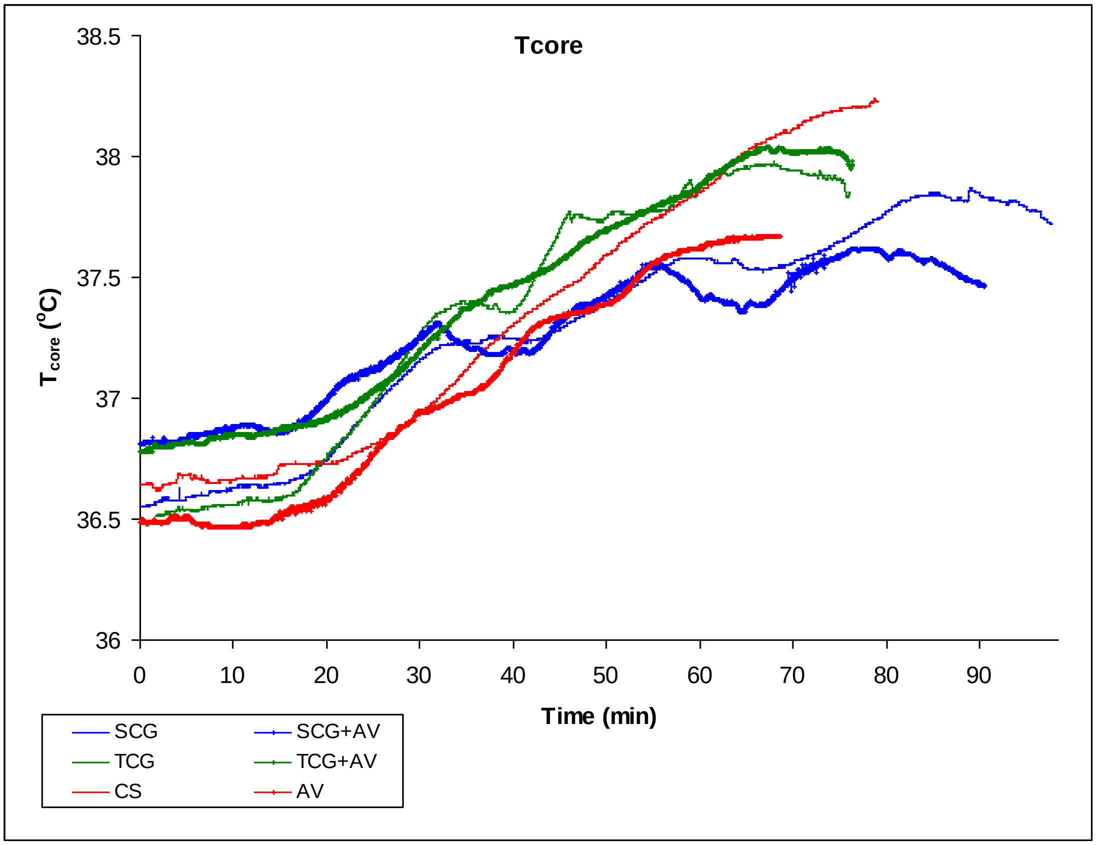

Figure 4. T_{core} dynamic during the six sessions of the study for one of the test subjects.

Table 1. Mean (SD) of HR, T_{core}, and Total Exercise Time for the Different Sessions

Parameters (mean/SD) / Cooling used	**CS**	**AV**	**TCG**	**TCG+AV**	**SCG**	**SCG+AV**
Max. Heart Rate, BPM	180.8 (7.8)	179.2 (6.5)	179 (8.9)	178.8 (8.6)	171.7 (12.6)	172.7 (12.1)
Max. Core Temperature, °C	38.29 (0.3)	38.07 (0.4)	38.25 (0.4)	38.17 (0.2)	38.01 (0.2)	37.95 (0.4)
Total Exercise Time, min	24.9 (2.8)	21.4 (2.7)	25.8 (4.3)	25.3 (3.9)	38.3 (8.3)	39.8 (4.6)

DISCUSSION

To increase the protection against external chemical and biological hazards, the PFE incorporates new design features. While these features provide additional protection to the wearer, the prototype design further encapsulates the wearer such that essentially all routes of heat exchange between the body and the external environment are blocked. Use of cooling garments allows the wearer to work longer and safer (lower T_{core}) even in such an encapsulated environment.

T_{core} indicated that the maximal internal temperature was lower ($p < 0.05$) while wearing the SCG or SCG+AV. A lower average T_{core} with either the SCG or the SCG+AV might reduce some of the health and safety problems that firefighters encounter.

HR was also lower during extended time for SCG and SCG+AV suggesting that the cardiovascular system was less affected by the heat and the strenuous exercise.

CONCLUSIONS

The results of this research suggest that a shortened whole body cooling garment (SCG) with or without the additional ventilation system (AV) can be helpful in reducing thermal stress and the risk of heat-related injuries. This study also suggests that the SCG with or without the AV can prolong the time that firefighters are able to exercise at specific workloads, thus increasing their work performance. In addition, air ventilation (convective heat loss) through the hose seems to augment the effect of the cooling garments to reduce core temperatures and decrease heat stress. However, the hose system used for convective heat loss does not show any improvement by itself and even decreases the total exercise time.

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Acknowledgement:
This research was performed while Dr. Coca held a National Research Council Resident Research Associateship at the National Personal Protective Technology Laboratory (NPPTL).