1-1-2009

An evaluation of the thermal protective clothing used by six Australian fire brigades

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Abstract

Individuals working in hot environments experience an increase in body core temperature due to the combined influences of physical activity, which elevates metabolic heat production, and external heat sources, which impede heat loss. Since dry heat exchanges are dependent upon thermal gradients, then hotter environments restrict heat dissipation, particularly when the air temperature approaches and exceeds that of the skin. Heat loss will now become progressively more reliant upon the evaporation of sweat, which is also gradient dependent.

Keywords

clothing, used, six, australian, evaluation, fire, thermal, brigades, protective

Disciplines

Arts and Humanities | Life Sciences | Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Kerry, P., van den Heuvel, A., van Dijk, M., Peoples, G. E. & Taylor, N. A.S.. An evaluation of the thermal protective clothing used by six Australian fire brigades. Environmental ergonomics XIII: Proceedings of the 13th international conference on environmental ergonomics; Wollongong, Australia: University of Wollongong; 2009. 44-48.

AN EVALUATION OF THE THERMAL PROTECTIVE CLOTHING USED BY SIX AUSTRALIAN FIRE BRIGADES.

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INTRODUCTION

Individuals working in hot environments experience an increase in body core temperature due to the combined influences of physical activity, which elevates metabolic heat production, and external heat sources, which impede heat loss. Since dry heat exchanges are dependent upon thermal gradients, then hotter environments restrict heat dissipation, particularly when the air temperature approaches and exceeds that of the skin. Heat loss will now become progressively more reliant upon the evaporation of sweat, which is also gradient dependent.

The thermal protective clothing worn by firefighters represents a significant impost upon body temperature regulation, and this occurs via two primary avenues. First, clothing modifies the ease with which heat is transferred between the body and the environment. It does this by providing thermal insulation (trapped air), which can be advantageous in thermally dangerous environments, but disadvantageous when individuals are working hard and producing a significant amount of metabolic heat. Second, the vapour (moisture) permeability of the garment is important (Goldman, 1994). This is the ability of the fabric to allow water vapour to pass through, thereby facilitating evaporation at the skin surface. Clothing impedes evaporation, and this has a critical impact upon thermal comfort and body temperature regulation (Candas, 2002). The impact of these influences is a function of the properties of the fabrics used to manufacture the complete ensemble. Some fabrics are designed to allow water vapour, but not water droplets to pass through, while others are completely impermeable, and have been designed to protect the user from chemical, biological and radiological agents.

Recently, Australian manufacturers have started to incorporate moisture barriers within some forms of thermal protective clothing. The logic behind the use of these barriers has been two-fold. Such barriers were first thought to reduce the risk of steam burns in firefighters, and it was also assumed that vapour-permeable barriers would facilitate the evaporation of sweat from the skin surface by facilitating water vapour transfer down a water-vapour gradient. In the first instance, it was been assumed by some, perhaps incorrectly, that steam (scald) burns originated from super-heated, external moisture penetrating the ensemble. A moisture barrier will help prevent water penetration, and may have some protective function, if in fact such penetration played a causal role in steam burns. It has also been assumed that vapour-permeable, but moisture impermeable fabrics may enhance the evaporation and removal of sweat. However, at an external air temperature of 35^{o}C, and a water vapour pressure of 5.06 kPa (relative humidity 90%), there will be a 90% reduction in water vapour transfer through a vapour permeable fabric.

Since the physiological and psychological consequences of heat strain are well established, it is in the best interests of firefighters to be provided with protective clothing that not only affords optimal thermal protection, but also facilitates the greatest loss of metabolically generated heat.

The current project was designed to evaluate the physiological consequences of these problems, but within a controlled-laboratory environment, whilst focussing upon variations in physiological strain that may exist whilst wearing different protective ensembles, with and without moisture barriers, during work-simulated exercise and recovery periods.

METHODS

This project involved intermittent, steady-state and incremental exercise (total: 120 min) within a climate chamber (30.5^{o}C (±0.6), 38.1% humidity (±1.4)). Subjects performed work simulations, with seated rest, to replicate the metabolic demands of activities typically encountered during fire fighting (weighted box stepping, treadmill dummy drag, treadmill walking carrying hose, incremental treadmill walk/run to 85% maximal). Eight subjects performed nine separate work simulations (72 trials) wearing two types of garments: thermal protective ensembles (six options: Table 1, Figure 1) and station (duty) wear (three options: Figure 2; Kerry *et al*., 2009).

Table 1: General specifications of the thermal protective clothing.

Ensemble	Fabric description	Heat transfer HTI24 (sec)	Heat transfer T2 (sec)
1	**Outer shell:** PBI Gold **Thermal liner:** not applicable **Moisture barrier:** Gore Airlock **Inner liner:** Nomex comfort	19	24.9
2	**Outer shell:** Nomex Delta C **Thermal liner:** Sontara * 2 **Moisture barrier:** not applicable **Inner liner:** Nomex/FR viscose	17	22.0
3	**Outer shell:** Nomex Advanced **Thermal liner:** not applicable **Moisture barrier:** Gore Fireblocker **Inner liner:** Nomex comfort	19	23.9
4	**Outer shell:** Nomex IIID **Thermal liner:** not applicable **Moisture barrier:** Gore Airlock **Inner liner:** Nomex comfort	21	25.7
5	**Outer shell:** Kermel Roano **Thermal liner:** Sontara * 2 **Moisture barrier:** not applicable **Inner liner:** Nomex comfort	Not tested	Not tested
6	**Outer shell:** Nomex IIID **Thermal liner:** Sontara * 2 **Moisture barrier:** not applicable **Inner liner:** Nomex comfort	18	24.4

The thermal protective and duty wear ensembles were selected so that the textile assemblies were typical of those worn by members of six different Australian State fire brigades. These ensembles were then assembled by a single manufacturer to fit each subject, and to match the configuration and design specifications of the NSW Fire Brigades, but using the textile assembly and layer specifications of the other State brigades. Each ensemble was then cleaned five times before being used. Duty wear was not worn when the personal protective ensembles were tested, and the duty wear trials were completed without the personal protective ensembles.

Figure 1: Six thermal protective ensembles (left): options one, three and four have moisture barriers.

Figure 2: Duty or daily station wear clothing (below).

This design provided separate evaluations of the different ensemble components, which could then be combined to provide the best combination for field use. In every trial, the standard-issue helmet (1.18 kg), flash hood and gloves were worn. Self-contained breathing apparatus, with an empty cylinder, was also worn (total mass: 14.26 kg). The mask of the breathing apparatus was used, but was disconnected from the cylinder, thus avoiding the complication of changing and re-charging air cylinders. Trials were conducted in a fully balanced order across subjects, such that no two subjects were tested wearing ensembles in the same sequence.

RESULTS AND DISCUSSION

The protocol required subjects to exercise at an average oxygen consumption of 1.61 $L.min^{-1}$. The average maximal core temperature across all trials was 37.8°C (highest: 38.9°C), with the mean core temperature change being 1.36°C, and an average maximal heart rate of 131.0 $b.min^{-1}$. This corresponded to 67% of the age-predicted maximal heart rate for these subjects. On average, and across all trials, these subjects lost 1.06 kg of sweat (0.56 $L.h^{-1}$).

Differences among the duty wear ensembles were not significant, and are not reported here. However, a number of statistically significant, between-ensemble differences were observed among the thermal protective ensembles, both within and across the physiological and psychophysical indices investigated. These outcomes are summarised in Table 2.

Of the twenty-three occasions where statistically significant differences were identified, the ensembles that included moisture barriers (one, three, four) were inferior to those that had no moisture barrier in twenty-two instances. Thus, such ensembles were associated with a more adverse psychophysiological impact upon the wearer. We have previously demonstrated this to be the case in another experiment in which these moisture barriers formed an integral part of the protective ensemble (van den Heuvel *et al*., 2007). Furthermore, and with only one statistically significant exception, the ensembles containing moisture barriers did not differ from one another.

Table 2: Statistical summary. Significantly superior ensembles are indicated with "S"; significantly inferior ensembles are shown using "x". Subscript numbers indicate ensemble option codes (1-6) for which differences were statistically significant. Since several analyses were completed for each variable (peak, whole trial, during work, during recovery, terminal), rows can contain more than one entry.

Variable	**Personal protective ensembles**					
	Option 1	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**
Core temperature	x_5 x_5 x_2	$S_{1,3,5}$	x_5 $x_{5,6}$ x_2		$S_{1,3}$ S_3 S_1 x_2 x_6	S_3 S_5
Skin temperature			x_5 x_5 x_6	x_5	S_3 S_3 S_4	S_3
Heart rate	x_5 x_6	x_5 x_6	x_5 x_6 x_5 x_6 x_5		S_3 S_1 S_2 S_3 S_3	S_3 S_1 S_2 S_3
Sweat loss		S_3	x_2			
Sweat evaporation		S_3	x_2 x_4	S_3		
Thermal sensation		S_3	x_2			
Thermal Discomfort				x_4	S_4	

Conversely, the ensembles without moisture barriers (options two, five, six) were significantly superior on twenty-two occasions. The vast majority of these differences occurred between the ensembles with and without moisture barriers, and the following points relate to these observations. Ensemble five was found to be statistically superior on twelve occasions, with this occurring seven times with respect to option six, and four times relative to option two. Option six had one occasion where it performed statistically better than options two and five. Option two was statistically superior to option five only once.

On the basis of core temperatures measured during each trial, two protective ensembles stood out as being statistically superior (options five and six), whilst two other ensembles were statistically inferior (options one and three). From observations of mean skin temperature, mean body temperature and heart rate, ensemble option five was found to be statistically superior on twelve occasions, with this occurring seven times for option six and four times for option two. Thermal protective ensemble option three was associated with statistically greater sweat loss (relative to option two), and moisture accumulation within the clothing (relative to options two and four). Finally, for thermal sensation, ensemble option three performed statistically poorer than option two, while for thermal discomfort, option four performed statistically poorer than option five.

CONCLUSIONS

On the basis of these observations, it was recommended that thermal protective ensembles five, six and two (in that order) be considered least likely to adversely affect the psychophysiological status of firefighters during operational use. Conversely, it was considered that ensemble option three would place firefighters under significantly greater strain.

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ACKNOWLEDGEMENT

This project was fully supported through equal contributions from the New South Wales Fire Brigades (Sydney, NSW, Australia) and the clothing manufacturer CTE Pty. Ltd. (West Footscray, VIC, Australia).