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THERMAL STRESS ON FIREFIGHTERS IN EXTREME HEAT EXPOSURE

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ABSTRACT

Five students of a rescue training school cycled at 50 W for 20 minutes at 20 °C before walking up to 30 minutes in a climatic chamber at 55 °C and 30 % relative humidity. Four different types of clothing ensembles were used differing in terms of thickness and thermal insulation value were tested on separate days. All subjects completed 28-30 minutes in light clothing, but quitted after 20-27 minutes in three firefighter ensembles due to a rectal temperature of 39.0 °C or subjective fatigue. No difference in the evolution of mean skin or rectal temperature was seen for the three turnout ensembles. Sweat production amounted to about 1000 g in the turnout gears of which less than 20 % evaporated. It was concluded that the small differences between the turnout gears in terms of design, thickness and insulation value had no effect on the resulting physiological strain for the given experimental conditions.

1. INTRODUCTION

Firefighter's clothing is designed to protect against environmental hazards (1). It must resist heat, flames and hot substances and international standards are available for testing such properties (2).

In burning buildings air may quickly become hot and humid, posing high levels of heat stress on the firemen. Their protective clothing, in addition, reduces or even completely prevents the body's normal heat exchange with the environment. Above certain ambient temperatures and humidity levels there is no dissipation of heat by convection, radiation and evaporation from the body. The main effect of clothing is then to reduce environmental heat gain. Accordingly, heat stress develops quickly in live firefighting (3-8). The protective equipment worn by the firefighter can weigh more than 20 kg, imposing a considerable extra physical load (9-11).

The purpose of this study was to investigate the thermal stress of different turnout gears during moderate work in a hot, humid ambient condition. One hypothesis was that the thickness of clothing would affect heat exchange and the development of heat stress.

2. METHODS

The ethical committee at Lund University approved the study. A medical doctor and a study leader with first aid education were present at all tests.

Subjects

Five healthy male firefighting students volunteered to participate in the study. A written consent had been obtained before they participated in the experiments. Their ages were 20-39 years old (mean=25, SD=8), heights 1.78-1.84 m (mean=1.81, SD=0.03), weights 67.2-76.3 kg (mean=72.6, SD=4.2). Each subject came to the lab and performed each of four tests (4 clothing conditions) during the same period of the day with the intervals of at least one day in between the experiments

Prior to heat exposure the subjects passed a type of max-test in order to define exercise level for heat exposure. Their maximum heart rates were between 188-202 b/min (mean=195, SD=6) and oxygen consumption 3.97-4.63 l/min (mean=4.16, SD=0.29).

Clothing

Four types of clothing were used by the subjects in the tests and are shown in the following table.

Table 1. Specification of garment components for the different ensembles.

Code	Ensemble (weight, kg)	Garment components	Equipment	Insulation value clo, (m ² C/W)
UW	underwear (RB90) (2.76)	T-shirt, briefs, RB-90 underwear (long shirt and long trousers), socks, sports shoes	Full face mask, pulse belt and watch	1.43 (0.222)
RB90	RB90 system (20.7)	T-shirt, briefs, <u>RB90 underwear</u> (shirt and trousers), outer garment (<u>RB90 jacket and trousers</u>), balaclava, RB90 gloves, socks, <u>firefighting boots</u>	Helmet, full face mask, compressed air cylinder, pulse belt and watch	2.78 0.431
ARY	New firefighting clothes, Norway ARY (19,8)	T-shirt, briefs, <u>new outer garment (jacket and trousers)</u> , balaclava, RB90 gloves, socks, firefighting boots	Helmet, full face mask, compressed air cylinder, pulse belt and watch	2.77 0.430
ARY+	ARY with added middle layer (21.2)	T-shirt, briefs, <u>training overall (jacket and trousers)</u> , <u>new outer garment (jacket and trousers)</u> , balaclava, RB90 gloves, socks, firefighting boots	Helmet, full face mask, compressed air cylinder, pulse belt and watch	3.03 0.470

Experimental procedure

During preparation, all clothing, equipment (i.e., compressed air supply container, mask, helmet, etc.), and subject (nude and with all clothing and equipment) were weighed. The rectal temperature and skin temperature (8 locations) were measured with a Labview program (National Instruments, USA) every 15 seconds.

After preparation, the subjects cycled on a bicycle ergometer at 50 W with all clothing except for compressed air container and gloves for 20 minutes in order to simulate preparation work before smoke diving. Oxygen uptake was measured by MetaMax for 6 minutes after 5 minutes of cycling. Heart rate was monitored by Polar heart rate monitor (Sport Tester, Polar Electro Oy, Finland).

The subjects were weighed again after 20 min of cycling, put on the air bottles, entered the climatic chamber on 23rd minute and started to walk on a treadmill at 5 km/h. The chamber temperature was controlled at 55 °C, relative humidity at 30%, wind speed at 0.4 m/s. Oxygen uptake was measured after 5 min of walking, heart rate, rectal and skin temperatures were recorded continuously. The termination of walking and exposure was based on one of the following three criteria: 1) subjects felt conditions intolerable and unable to continue, 2) rectal temperature reached 39.0 °C, 3) subjects walked 30 min on the treadmill.

After cessation of exposure subjects were weighed again immediately. Each piece of clothing was weighed separately immediately after the subjects removed it. Right after the subjects were undressed and the measuring equipment was removed, the subjects were weighed just wearing the briefs and the rectal sensor.

3. RESULTS

The individual values for certain parameters at the time of withdrawal were recorded and the average values are given in Tables 2 and 3.

Table 2. Working time at 55 °C, metabolism, heart rate and perceived exertion (RPE). Mean and 1 SD of 5 subjects. Values are taken at the time of cessation of exposure.

	Time, min,sec		Metabolism, W/m ² bicycle		Metabolism, W/m ² walking		Heart rate, bpm		RPE	
UW	29.30	1.26	189	5	198	16	161	22	16	2
RB	22.15	2.52	204	12	273	11	174	9	17	1
N	24.12	2.02	201	15	267	12	173	11	17	0
NM	23.27	1.59	204	13	276	16	177	12	18	1

Table 3. Thermal responses. Mean and 1 SD of 5 subjects. Values are taken at the time of cessation of exposure

	Tsk, °C		T _{re} , °C		Total sweat prod, g		Evaporated sweat, g		Thermal sensation	
UW	39.5	0.6	38.9	0.3	869	154	161	22	3.1	0.5
RB	39.8	0.4	38.9	0.3	1049	261	174	9	4.0	0.7
N	39.8	0.3	39.1	0.0	987	222	173	11	4.1	0.7
NM	39.9	0.2	39.1	0.0	1013	374	177	12	3.9	0.5

The metabolic rate during bicycling was around 200 W/m² for all conditions. During walking and heat exposure it was 198 W/m² for UW and about 270 W/m² for the other ensembles (Table 2).

Heart rate increased only marginally during the bicycle exercise and measured between 100 and 120 beats per min. Under heat exposure heart rate increases sharply for all conditions and reaches values between 160 (UW) and 170-180 beats per min for the other conditions (Table 2 and Figure 1).

All subjects completed 28-30 minutes in UW, but quitted after 20-27 minutes in the other three ensembles (Table 2). The reason for quitting was that T_{re} reached the break criterion of 39.0 °C. In few cases only the subject voluntarily stopped the exposure before this criterion was reached. The exposure time is significantly longer only for UW versus the three suits, not between suits.

The evolution of rectal temperature responses are shown in Figures 2 as mean values of five subjects for the four ensembles. At the end of the 20 min bicycle exercise skin temperature levels off after a 1-2 °C initial increase. Rectal temperature increases only marginally.

Under heat exposure all temperatures increase and there is no levelling off in any conditions. The lines for the turnout gears stop at the time when the first subject drops out. The slope and shape of these three lines are almost identical. The evolution of skin and rectal temperature for the UW conditions are significantly different. The initial rise in T_{sk} is somewhat quicker for UW due to lesser protection (insulation) against the environmental heat. This initial rise, however, slows down and the rate of increase becomes much slower already after 3-4 minutes. The main reason is that evaporative cooling is higher and the metabolic rate is lower with this two layer clothing compared with the turnout gears.

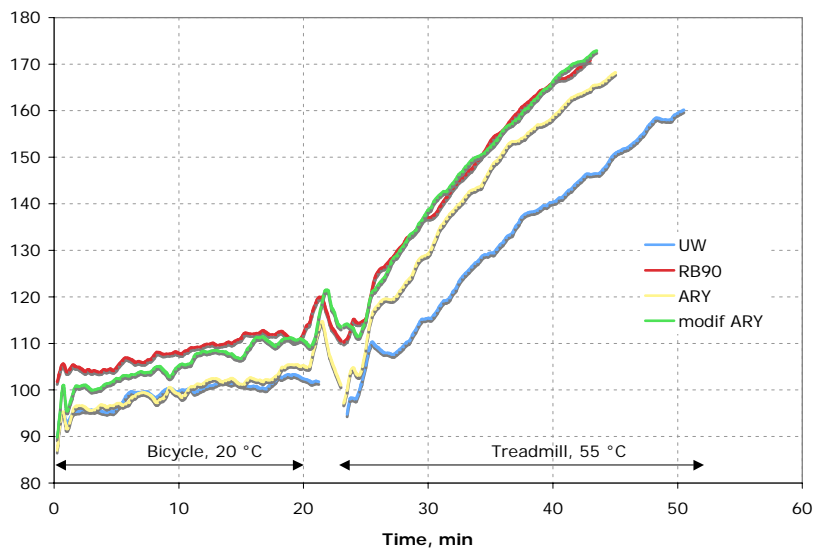


Figure 1. Mean heart rates for five subjects during the exposure.

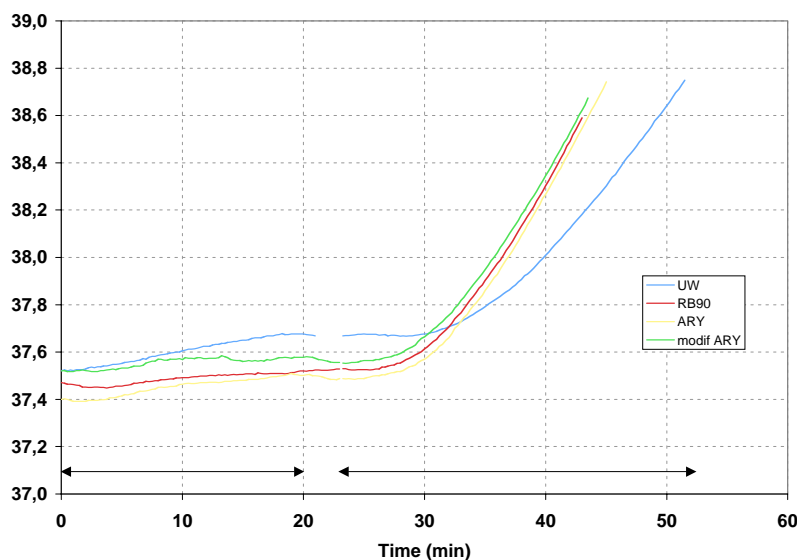


Figure 2. Time course of rectal temperature during the exposure. Mean values for five subjects. Curves stop when the first of five subjects stops.

The final values of skin temperature at cessation of exposure are almost the same for all ensembles or close to 40 °C. Similarly the rectal temperature at cessation is around 39 °C (Table 3). The values in Figure 2 are slightly lower as they show the values at the time when the first subject drops out.

Total sweat amount was 869 g for UW and around 1000 g for the turnout gears. The individual variation was considerable. The evaporated amount of sweat was similar or around 170 g for all ensembles.

4. DISCUSSION

Thick, multi-layer clothing is required to protect firefighters against environmental hazards of thermal origin, such as hot air, radiant heat, flames, hot surfaces and splashes of burning or melting materials (1). However, thick clothing also prevents the escape of metabolic heat released with physical work. The final balance is determined by temperature and water vapour pressure gradients and thermal properties of the clothing.

The only means of heat dissipation to the environment under the experimental conditions is by evaporation. This, however, is severely hampered by the thick, multi-layer clothing. Nevertheless, approximately 70 g evaporated during the bicycle part and 105 g during the heat exposure.

The stored heat for the same period calculated from mean body temperature increase was about 150 Wh (5 °C in T_{sk} and 1.5 °C in T_{re}).

Two of the clothing ensembles had almost the same thermal insulation value; 0.43 m²°C/W. The insulation of the third ensemble was 10 % higher or 0.47 m²°C/W. This difference, however, had little or no effect on heat balance and physiological strain. In fact, with the above assumption regarding resultant insulation this would correspond to a difference in heat exchange by less than 5 W/m².

McLellan and Selkirk studied the effect of shorts or long pants under a firefighter ensemble on heat stress at various combinations of workrate and work time in 35 °C and 50 % relative humidity (12). They concluded that the reduction in clothing (and thermal insulation) did not influence heat stress during heavy or moderate exercise with exposure times less than 1 hour.

A 10 % reduction in metabolic rate (20-30 W/m²) can easily be achieved by the individual by adjusting his or her pace of work. Although not investigated in this study it can be speculated that such a reduction in metabolic rate would reduce total heat stress. From an operational point of view it seems that much is to be won by trying to establish an intelligent balance between physical loads and efforts and external stress factors. The results from the UW experiments show a significantly reduced thermal stress, resulting from the combined effect of lower metabolic heat production and better heat transfer to the environment, mainly by evaporative heat loss. The beneficial effect however is strongly dependent on environmental conditions.

In summary it can be concluded that light to moderate work at temperatures of 55 °C and higher implies extremely high levels of heat stress, in particular when exposure is combined with carrying protective clothing and compressed air respirators. Small variations in thermal properties of protective clothing have little or no effect on heat exchange and do not affect the resulting thermal strain.

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