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Test of Firefighter's Turnout Gear in Hot and Humid Air Exposure

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Five students of a rescue training school cycled at 50 W for 20 min at 20 °C before walking at 5 km/hr up to 30 min in a climatic chamber at 55 °C and 30% relative humidity. 4 different types of clothing ensembles differing in terms of thickness and thermal insulation value were tested on separate days. All subjects completed 28–30 min in light clothing, but quit after 20–27 min in 3 firefighter ensembles due to a rectal temperature of 39 °C or subjective fatigue. No difference in the evolution of mean skin or rectal temperature was seen for the 3 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 heat physiological strain for the given experimental conditions.

body temperature heat stress physiological strain protective clothing

1. INTRODUCTION

Firefighters are exposed to many hazards associated with their work. Apart from many toxic substances in the ambient air, high radiant heat intensities and hot flames are common risks in fire extinguishing work [1]. Firefighters' turnout equipment is designed to protect against environmental hazards. Clothing 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 firefighters. The basic mechanisms of heat transfer in dry air are by convection and radiation through clothing. Heat is transferred from the body if skin temperature is higher than ambient temperatures. In hot air and in highly radiant conditions heat may flow from the ambience to the skin surface. The protective clothing, however, reduces or even completely prevents the body's normal heat exchange with the environment. If it is a hot, dry environment, some body cooling may take place by sweat evaporation. This process, however, is also restricted by the thick, multilayer clothing. In hot, humid air moisture may actually condense in clothing or, in the worst case, on the skin surface. The actual transfer of water vapour depends on the direction and magnitude of the pressure gradient and the vapour resistance of the intermediate layers. 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, 4, 5, 6, 7, 8].

Respirators provide clean air in contaminated atmospheres. The self-contained compressed

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air breathing apparatus (SCBA) often weighs in excess of 10 kg. All together, the protective equipment worn by the firefighter can weigh more than 20 kg, imposing a considerable extra physical load. This load adds to the metabolic cost, in particular when the firefighter is moving [9, 10, 11]. High metabolic rates have been reported for various tasks associated with firefighting [12, 13, 14].

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, Sweden, approved the study. A medical doctor and a study leader with first-aid education were present at all tests.

2.1. 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 (M = 25, SD = 8), height 1.78–1.84 m (M = 1.81, SD = 0.03), weight 67.2–76.3 kg (M = 72.6, SD = 4.2). The subjects were informed that they should not smoke and drink coffee or tea 2 hrs before the experiment. They should not do strong physical activities at least 1 hr before the experiment. Each subject came to the lab and performed each of the four tests (four 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 heat rates were 188–202 beats/min (M = 195, SD = 6), and oxygen consumption was 3.97–4.63 L/min (M = 4.16, SD = 0.29).

2.2. Clothing

Four types of clothing systems were used by the subjects. The composition of the different systems and the acronyms are described in Table 1.

2.3. Experimental Procedure

During preparation, all clothing, equipment (i.e., compressed air supply container, mask, helmet, etc.), and the subject (nude and with all clothing and equipment) were weighed. The rectal temperature sensor (YSI-401 Yellow Springs Instrument, USA, accuracy ±0.15 °C) was inserted by the subjects at a depth of 10 cm inside the anal sphincter. Skin temperature sensors (NTC-resistant

TABLE 1. Specification Garment Components for the Different Ensembles

Code	Ensemble (weight, kg)	Garment Components	Equipment	Insulation Value in clo (m^2 °C/W)
UW	RB90 underwear (2.76)	T-shirt, briefs, RB90 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, RB90 underwear (shirt and trousers), outer garment (RB90 jacket and trousers), balaclava, RB90 gloves, socks, firefighting boots	Helmet, full face mask, compressed air cylinder, pulse belt and watch	2.78 (0.431)
ARY	New ARY firefighting clothes (19.8)	T-shirt, briefs, new outer garment (jacket and trousers), balaclava, RB90 gloves, socks, firefighting boots	Helmet, full face mask, compressed air cylinder, pulse belt and watch	2.77 (0.430)
ARY mod	ARY with added middle layer (21.2)	T-shirt, briefs, training overalls (jacket and trousers), new outer garment (jacket and trousers), balaclava, RB90 gloves, socks, firefighting boots	Helmet, full face mask, compressed air cylinder, pulse belt and watch	3.03 (0.470)

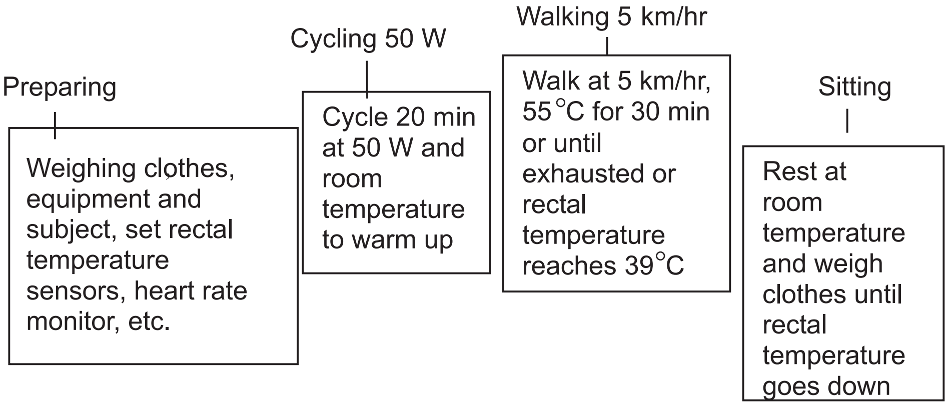

Figure 1. Scheme of activities during exposure.

temperature matched thermistors ACC-001, Rhopoint Components Ltd, UK, accuracy ±0.2 °C, time constant 10 s) were taped on the left side of the body in eight places, i.e., chest, scapula, forehead, upper arm, forearm, head, thigh and calf.

After preparation, the subjects cycled on a bicycle ergometer at 50 W with all clothing except for the compressed air container and gloves for 20 min in order to simulate preparation work before smoke diving. Core and skin temperatures were recorded with a Labview program (National Instruments, USA) with an interval of 15 s when the subject started cycling. Oxygen uptake was measured with MetaMax (Cortex, Germany) for 6 min after 5 min of cycling. Heart rate was monitored with a Polar heart rate monitor (Sport Tester, Polar Electro Oy, Finland). Subjective ratings of physical exertion (Borg rating scale) and whole-body thermal sensation were asked and recorded at the beginning of cycling and thereafter every 10 min throughout the experiments.

The subjects were weighed again after 20 min of cycling, took on air bottles, and then entered the climatic chamber in the 23rd minute. The chamber temperature was controlled at 55 °C, relative humidity at 30%, wind speed at 0.4 m/s. The subjects walked on a treadmill at the speed of 5 km/hr. Oxygen uptake was measured after 5 min of walking, heart rate, rectal (T_{re}) and skin (T_{sk}) temperatures were recorded continuously. The termination of walking and exposure was based on one of the following three criteria: (a) subjects felt the conditions were intolerable and were unable to continue, (b) T_{re} reached 39 °C or (c) subjects walked 30 min on the treadmill.

The subjects then came out and were weighed again immediately. The subjects sat and rested until T_{re} started to decrease. During that process they were allowed to take off equipment and the jacket and to open up underwear. 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 briefs and the rectal sensor. Figure 1 is a schematic diagram of the procedure.

2.4. Variables and Measuring Equipment

The climatic chamber temperature (55 °C), relative humidity (30%), wind speed (0.4 m/s) and walking speed (5 km/hr) were kept constant throughout the experiment. Results were analysed with one-way ANOVA with SUITS as factor. Statistical differences are denoted for $p < .05$.

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.

The metabolic rate during cycling was around 200 W/m^2 for all conditions and not significantly different between suits. During walking and heat

TABLE 2. Working Time, Metabolism, Heart Rate (HR) and Perceived Exertion (RPE). *M* and 1 *SD* of 5 subjects. Values Were Taken at the Time of Cessation of Exposure for Each Subject

			Metabolism (W/m^2)							
	Time (min)		Bicycle		Treadmill		HR (bpm)		RPE (—)	
Code	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
UW	29.30*	1.26	189	5	198*	16	161	22	16	2
RB90	22.15	2.52	204	12	273	11	174	9	17	1
ARY	24.12	2.02	201	15	267	12	173	11	17	0
ARYmod	23.27	1.59	204	13	276	16	177	12	18	1

Notes. *—a significant difference between UW and the three suits.

TABLE 3. Thermal Responses. Values are *M* and 1 *SD* of 5 Subjects and Are Taken at the Time of Cessation of Exposure for Each Subject

	T_{sk} (°C)		T_{re} (°C)		Total Sweat Production (g)		Evaporated Sweat (g)		Thermal Sensation	
Code	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
UW	39.5	0.6	38.9	0.3	869	154	330*	47	3.1	0.5
RB90	39.8	0.4	38.9	0.3	1049	261	162	37	4.0	0.7
ARY	39.8	0.3	39.1	0.0	987	222	178	19	4.1	0.7
ARYmod	39.9	0.2	39.1	0.0	1013	374	174	14	3.9	0.5

Notes. *—a significant difference between UW and the three suits. T_{sk}—skin temperature, T_{re}—rectal temperature.

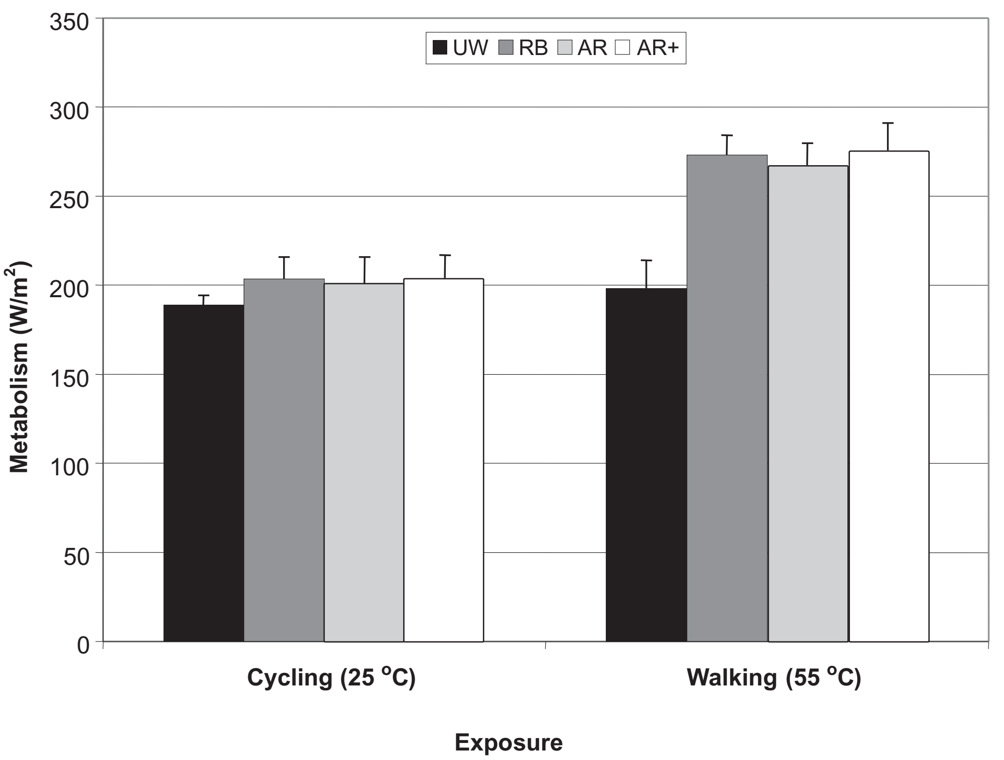

Figure 2. Metabolic rate during exposure. Values are *M* and 1 *SD* for 5 subjects.

exposure it was significantly lower (198 W/m^2) for UW than for the other ensembles: about 270 W/m^2 (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 increased sharply for all conditions and reached values between 160 (UW) and 170–180 beats per min for the other conditions (Table 2 and Figure 3).

All subjects completed 28–30 min in UW, but quit after 20–27 min in the other three ensembles (Table 2). The reason for quitting was that T_{re} reached the break criterion of 39 °C. In few cases only did the subject voluntarily stop the exposure before this criterion was reached. Exposure time was significantly longer only for UW versus the three turnout gears, not between turnout gears.

The evolution of T_{re} and T_{sk} responses is shown in Figures 4 and 5 as mean values of 5 subjects for the four ensembles. At the end of the 20-min bicycle exercise skin temperature levelled off after a 1–2 °C initial increase. T_{re} increased only marginally.

Under heat exposure all temperatures increased and there was no levelling off in any conditions. The lines for the turnout gears stopped when the first subject dropped out. The slope and shape of these three lines were almost identical. The evolution of T_{sk} and T_{re} for the UW conditions were significantly different. The initial rise in T_{sk} was somewhat quicker for UW due to lesser protection (insulation) against environmental heat. This initial rise, however, slowed down and the rate of increase became much slower already after 3–4 min. The main reason was that evaporative cooling was higher and the metabolic rate was lower with this two-layer clothing compared with the turnout gears.

The rate of change in T_{re} was calculated for each individual for the last 10 min of each exposure. This value averaged 0.051 ± 0.01 for UW, 0.089 ± 0.01 for RB90, 0.088 ± 0.006 for ARY and 0.086 ± 0.004 °C/min for ARYmod. The value for UW is significantly lower than for the other suits.

The final values at cessation of exposure were almost the same for all ensembles or close to

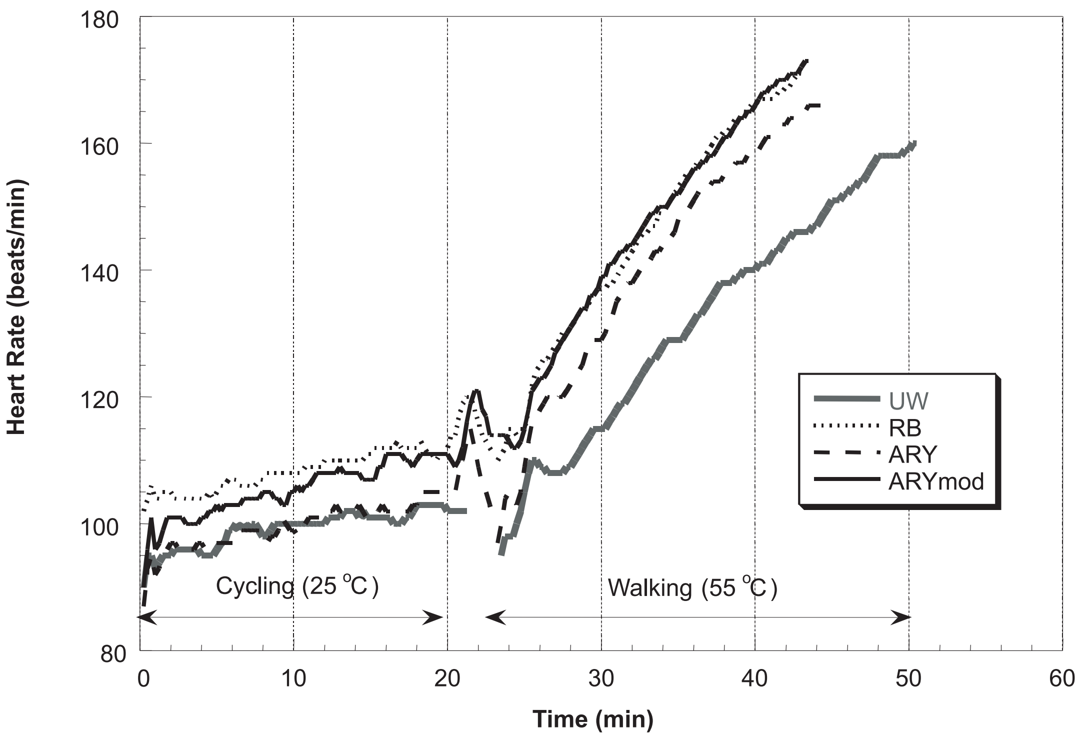

Figure 3. Mean heart rate for 5 subjects during exposure.

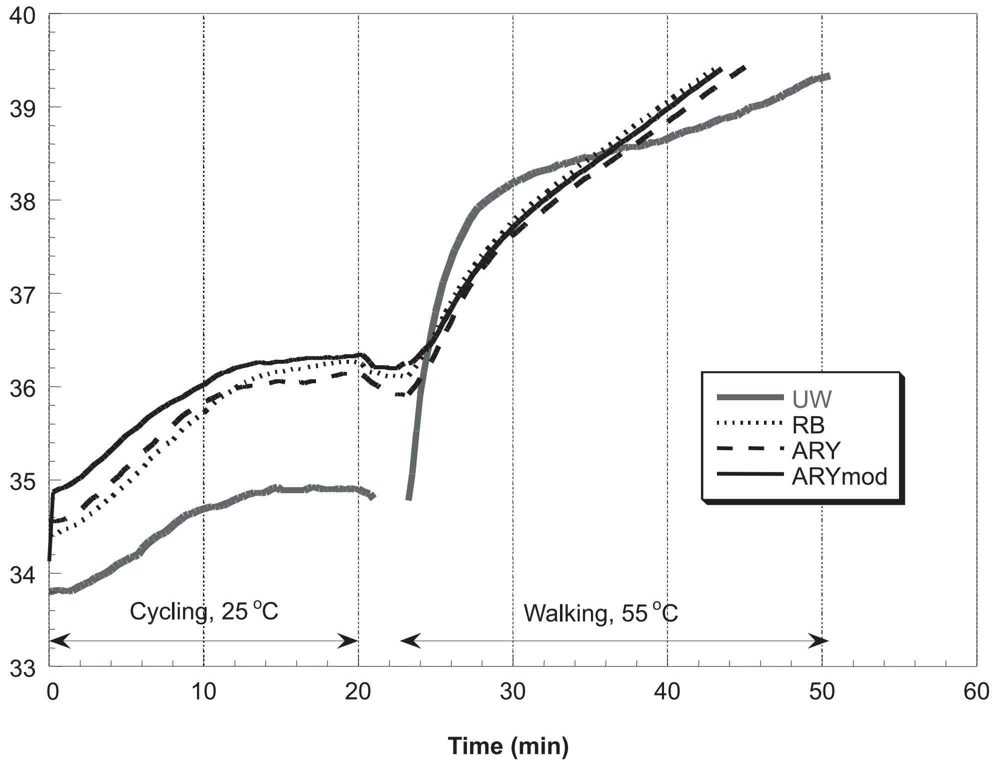

Figure 4. Time course of skin temperature during exposure. Mean values for 5 subjects. Curves stop when the first of 5 subjects stops.

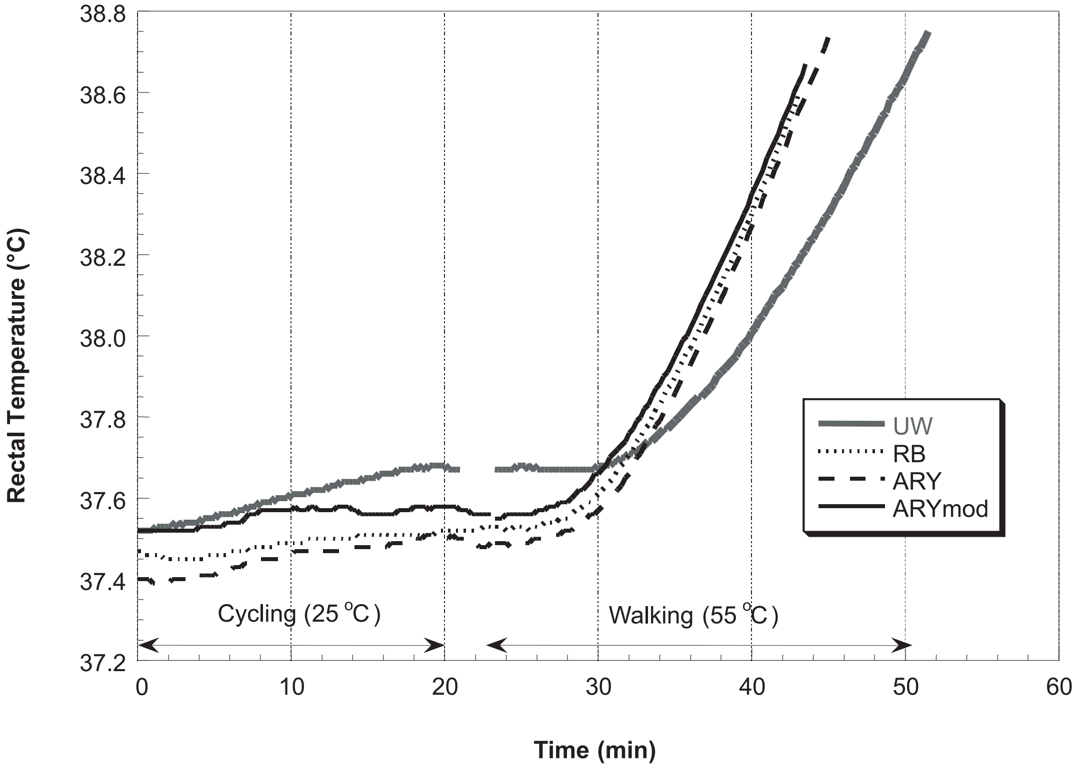

Figure 5. Time course of rectal temperature during exposure. Mean values for 5 subjects. Curves stop when the first of 5 subjects stops.

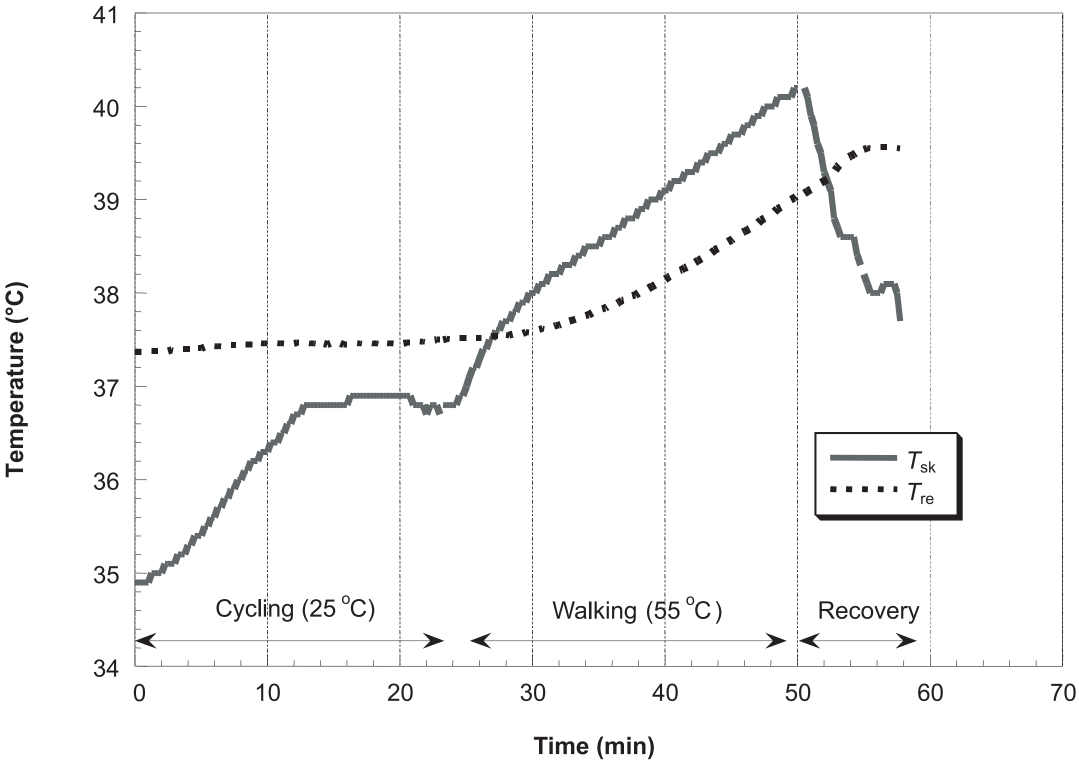

Figure 6. Time course of rectal (T_{re}) and skin temperature (T_{sk}) response in 1 subject during exposure and recovery.

40 °C. Similarly, T_{re} cessation was around 39 °C (Table 3). The values in Figures 4 and 5 were slightly lower as they showed the values at the time when the first subject dropped out.

T_{sk} dropped immediately after cessation of exposure when the subject left the climatic chamber. T_{re}, however, continued to rise for several minutes (Figure 6).

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.

The subjective perception of the warmth of the environment was 3.1 (*hot*) for the UW and close to 4 (*very hot*) for the other 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.

Protective equipment (clothing and respirator) also adds to the physical work due to its weight [11]. In this experiment metabolic energy production averaged 275 W/m^2 during walking in turnout gears at 5 km/hr in the heat. This is 37% more than for underwear alone and can be ascribed to the increased weight to be carried; 2.7 kg for UW versus about 20 kg for the ensembles. During cycling metabolic rate increased by 7%, mainly due to increased friction during leg movements with multi-layer clothing.

The physiological strain was considerable due to the combination of physical work and heat stress. Heart rate reached levels close to the maximal level of the individual. Also the subjects rated the conditions as very exhausting. The high level of strain resulted in fatigue and exhaustion in all subjects. In all experiments with turnout gear except two, exposure was interrupted before the 30 min were over. Subjects reached the break criterion of 39 °C in T_{re} or stopped voluntarily due to exhaustion. Only in four conditions did the subjects decide to quit before T_{re} reached this level.

The ambient temperature was about 15 °C higher than T_{sk}. A rough estimate of the environmental heat gain by convection and radiation provides a figure of about 50 W/m^2, assuming a resultant insulation of clothing during work at about 0.3 m^2 °C/W. The static value averaged 0.4 m^2 °C/W measured with a thermal manikin. This figure becomes about 100 W/m^2 for the UW conditions due to much lesser clothing insulation. Despite high ambient temperature, metabolic heat as a result of physical work is by far the most important thermal stress factor.

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 three ensembles only allowed approximately a 50% increase in evaporation during the severe heat stress. The corresponding values for the UW were 76 and 254 g, respectively; an increase by 330%. If to assume the evaporative cooling efficiency to be 100, then the heat dissipation for the ensembles in the heat amounts to about 110 W/m^2. The figure for the UW conditions becomes about 210 W/m^2. In both cases this is far from sufficient to balance the heat production during work.

A rough estimate of the heat balance shows a net heat gain of about 155 W·hr for the average exposure period of 23 min. The stored heat for the same period calculated from mean body temperature increase was about 154 W·hr (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 m^2 °C/W. The insulation of the third ensemble was about 10% higher or 0.47 m^2 °C/W. This difference, however, had little or no effect on heat balance and physiological strain. In fact, with the assumption regarding resultant insulation this would correspond to a difference in heat exchange by less than 5 W/m^2.

McLellan and Selkirk studied the effect of shorts or long pants under a firefighter ensemble on heat stress at various combinations of work rate and work time in 35 °C and 50% relative humidity [15]. They concluded that the reduction in clothing (and thermal insulation) did not influence heat stress during heavy or moderate exercise with exposure times shorter than 1 hr.

In our experiment the much lighter clothing (UW) resulted in a significantly lower metabolic rate, better evaporative cooling, slower heat storage rate and longer exposure time (30 min). However, the final physiological and thermal strain was almost the same as for the shorter exposures with the other suits due to the longer exposure time of 30 min (Tables 2 and 3). When responses were compared at the stop time for the other suits, the strain in UW were clearly lower (Figures 3–5).

A 10% reduction in metabolic rate (20–30 W/m^2) can easily be achieved by individuals by adjusting their 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 load and effort 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. This should be the subject of future studies.

5. CONCLUSIONS

1. 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 wearing protective clothing and carrying compressed air respirators.

2. Small variations in thermal properties of protective clothing have little or no effect on heat exchange and do not affect the resulting thermal strain.
3. The most determinant factor for the resulting heat stress under the given conditions is the metabolic heat production. Hence a reduction in work rate has a larger effect on the final heat stress than small variations in heat transfer properties of the protective clothing.
4. The high rates of body heat storage after 5–10 min of heat exposure result in a rapid build-up of body heat content that accelerate core temperature increase. This process continues after cessation of exposure and maximal core temperature appears to be reached 5–10 min after cessation.
5. The large amount of heat absorbed by the body tissues requires careful measures for recovery, with implications for and times of cooling.

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