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Effectiveness of a Light-Weight Ice-Vest for Body Cooling While Wearing Fire Fighter's Protective Clothing in the Heat

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The aim of the study was to examine the effects of wearing an ice-vest (ca 1 kg) on physiological and subjective responses in fire fighters. The experiments were carried out on a treadmill in a hot-dry environment. The physical cooling effect of the ice-vest was measured with a thermal manikin. The ice-vest effectively reduced skin temperatures under the vest. On average, heart rate was 10 beats/min lower, the amount of sweating was reduced by 13%, and subjective sensations of effort and warmth were lower during work with the ice-vest compared to work without it. Thermal manikin tests indicated that the useful energy available from the vest for body cooling was rather high (58%). In conclusion, the ice-vest reduces physiological and subjective strain responses during heavy work in the heat, and may promote efficient work time by 10%.

fire fighting smoke-diving thermal strain body cooling ice-vest

1. INTRODUCTION

Fire fighters' work, especially smoke-diving, often involves exposure to heavy physical work and heat stress. This combination of stress factors reduces efficient work time and productivity and may increase the risk of heat-related illnesses.

Several different auxiliary personal body cooling devices have been developed for the industry [1, 2, 3, 4, 5, 6]. They are, however, often of limited value for fire fighters because of their greater weight or connection to additional equipment. An ideal body cooling device for fire fighters should be rather light-weight,

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should not interfere with the job performance, and it should be feasible and easy to use during fire alarms.

The Swedish Rescue Board has been developing a light-weight (ca 1 kg) ice-vest (water) for fire fighters. In their preliminary wear trials, they confirmed two aspects: (a) wearing the ice-vest did not reduce the safety of working in a hot environment, and (b) the instructors and fire fighters felt that the use of ice-vest reduced heat strain and improved job performance during and after working in the heat.

The aim of the present study was to examine the effects of wearing the ice-vest on physiological and subjective responses during treadmill walking in the heat. In addition, the physical cooling effect of the ice-vest was measured with a thermal manikin.

2. MATERIALS AND METHODS

Four experienced fire fighters participated in the experiments. They were healthy, moderately physically active, and all had a normal blood pressure. Their mean age, height, and weight were 36 years (32–39), 186 cm (182–188), and 87 kg (78–98), respectively.

In all tests, the subjects wore standard clothing for fire fighters (RB90, Swedish Rescue Services, Sweden) with self-contained breathing apparatus (AGA Divator, Interspiro, Sweden). During the tests, the face mask was not used because oxygen consumption was measured. The total extra weight carried was 21–23 kg.

RB90 is a complete fire fighter ensemble, including underwear used by Swedish Rescue Services and it corresponds to the EN 469:1995 [7] requirements. The outer garment of RB90 consists of an outer layer (woven 77% meta-aramid, 23% para-aramid, Delta T), a barrier (Teflon®, Gore-tex®), tricot fabric Rachel (100% meta-aramid, Conex®), and a lining (wowen 100% para-aramid, Nomex®). Knee and shoulder areas are reinforced from the outside with Kevlar® (100% para-aramid). Underwear consists of double-stitched tricot fabric of 55% cotton (mainly outer side), and 45% polypropylen (mainly inner side).

The ice-vest (Flexi ICE Cold Vest®, Interspiro, Sweden) was made of cotton. The inside consisted of two flat plastic holders, which had several small pockets for water. Five different vests were used in the tests, and their weight varied slightly (1.0–1.1 kg). In two of the vests, the inside was covered with a net, whereas the other three vests had cotton cloth. No lining effect was noticed during the tests due to negligible insulation of any lining type compared to the total insulation of the garment package and high temperature gradients from ice towards both body and the environment. The ice-vest covered most of the trunk area, and it was worn over the underwear. The vests were kept in a freezer at –20 °C overnight before experiments.

Experiments were carried out in a climatic chamber (air temperature 45 °C, relative humidity 30%). In the tests, the subjects walked on a treadmill for 30 min twice at moderate exercise intensity (4 km/hr, 0º), and twice at heavy exercise intensity (4 km/hr, inclination 4º). At each work intensity, one test was done without and one with the ice-vest. A 5-min rest period preceded each test. For each subject, only one test was done in one day. The order of testing was randomized.

During the tests, rectal temperature was measured with a thermistor probe (TinyTalk, Orion Components Ltd., UK) inserted 10 cm beyond the anal sphincter. Skin temperatures were measured with small thermistors (StowAway XTI, Onset Computer Corporation, USA) taped to the skin. The sites for skin temperature measurements were forearm, upper arm, chest, back, thigh, and calf. The thermistors were pre-programmed and they recorded temperatures once per minute.

In all tests, heart rate was measured once a minute with the telemetric SportTester system (PolarElectro, Kempele, Finland). Oxygen consumption was measured with a portable gas analysing system (Metamax, Cortex, Germany) twice during each test (10–15 min and 25–30 min). For that purpose the subjects wore a half-face mask during the tests instead of the full-face mask of AGA Divator (Interspiro, Sweden).

Changes in nude body weight during the tests were used to estimate the amount of sweating (KC 240, Metler-Toledo, Switzerland, accuracy ±2 g).

During the tests, the subjects rated their perceived exertion (RPE), and thermal sensation with standard scales (Table 1).

TABLE 1. Scales for Subjective Evaluation of Exposure

Perceived Exertion Scale	Thermal Sensation Scale
6	–4 *very, very cold*
7 *very, very easy*	–3 *very cold*
8	–2 *cold*
9 *very easy*	0 *neither cold nor warm*
10	+1 *slightly warm*
11 *quite easy*	+2 *warm*
12	+3 *very warm*
13 *slightly strenuous*	+4 *very, very warm*
14	
15 *strenuous*	
16	
17 *very strenuous*	
18	
19 *very, very strenuous*	
20	

The total insulation[1] (1 clo = 0.155 K m^2 W^{-1}) of the fire fighter clothing including the non-frozen ice-vest was calculated from the heat losses measured according to ENV 342:1998 [8] on a thermal manikin. Heat loss related to the ice-vest only was measured in a condition where ambient temperature was set to be equal to the manikin surface temperature (34 °C). Two additional temperature sensors were inserted into the ice-vest. These were used to record the temperatures of inner and outer surface of the ice layer.

No tests of statistical significance were considered feasible because of the small number of subjects. The results are expressed either as means or as an average with the range of values in parentheses or as a mode.

3. RESULTS

3.1. Oxygen Consumption, Heart Rate, and Sweating

Oxygen consumption was, on average, very similar between the tests without and with the ice-vest at both work levels (Table 2).

TABLE 2. Oxygen Consumption (L/min) During Tests Without and With the Ice-Vest at Moderate and Heavy Work Levels. The Values are the Means (Range) for 4 Subjects

Work Level	Without Ice-Vest	With Ice-Vest
Moderate	1.18 (1.10–1.25)	1.17 (0.96–1.34)
Heavy	2.25 (2.04–2.72)	2.23 (1.88–2.68)

During the first 15 min of walking at the moderate work level, average heart rate was similar between the tests without and with the ice-vest (Figure 1). However, during the last 15 min of walking, heart rate was at a lower level with the ice-vest than without it. At the heavy work level average heart rate increased continuously, but remained constantly lower with the ice-vest compared to the no-vest condition (Figure 1). At the end of walking at both work levels mean heart rate was 10 beats/min lower with the ice-vest than without the vest (Table 3).

At both work levels the average amount of sweating was lower with the ice-vest compared to tests without it (Table 4). At the moderate work level the reduction in sweating was 17%, and at the heavy work level 9% (average reduction 13%). The results on heart rate and sweating were otherwise systematic, but in one subject at the

[1] clo-value

heavy work level no effect of the ice-vest was observed (sweating 497 vs. 505 g, heart rate 180 vs. 181 beats/min), though a clear effect was seen at the moderate work level. The reason for this was unclear.

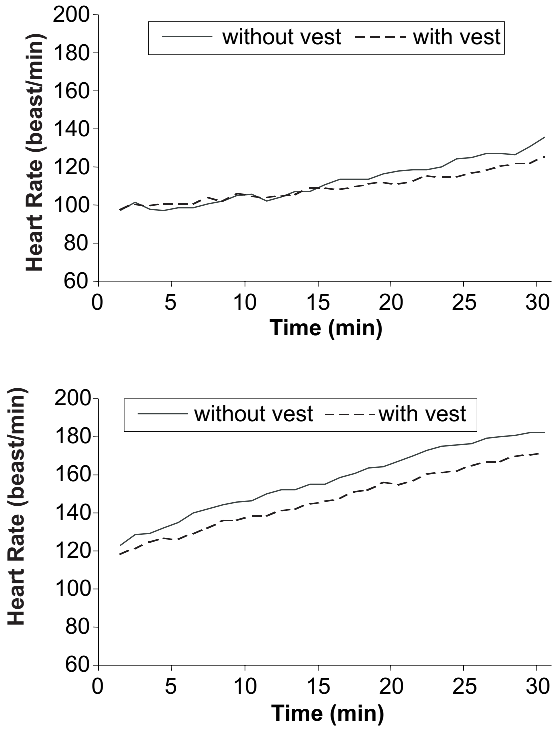

Figure 1. Average heart rate during walking in the heat at moderate (upper panel) and heavy (lower panel) work levels with and without the ice-vest.

3.2. Body Temperatures

At both work levels, rectal temperature increased continuously during tests reaching higher values at the heavy work level (Figure 2). During both tests, the resting level of average rectal temperature was slightly lower with the ice-vest. However, the increase in rectal temperature was similar between tests with and without the ice-vest.

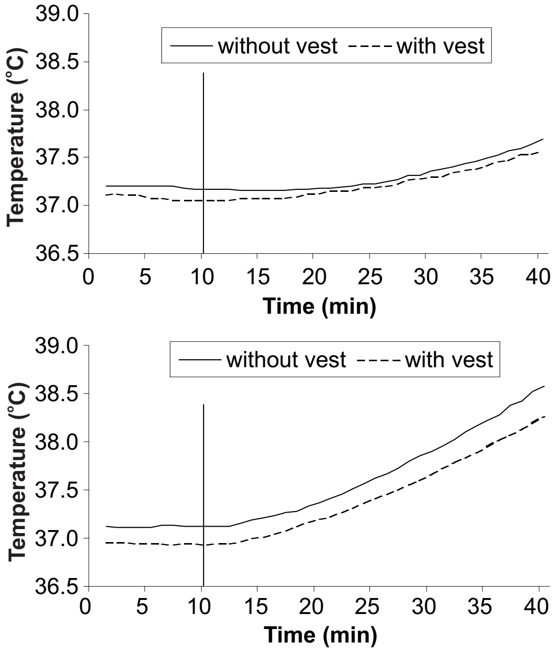

Figure 2. Average rectal temperature during walking in the heat at moderate (upper panel) and heavy (lower panel) work levels with and without the ice-vest. The walking started at minute 10.

TABLE 3. Heart Rate (beats/min) at Rest and at the End of Exercise at 2 Work Levels Without and With the Ice-Vest. The Values are the Means (Range) for 4 Subjects.

	Rest		End of Walking	
Work Level	**Without Vest**	**With Vest**	**Without Vest**	**With Vest**
Moderate	60 (55–72)	58 (46–78)	136 (131–147)	126 (117–130)
Heavy	62 (56–73)	61 (50–74)	182 (180–185)	172 (162–181)

TABLE 4. Amount of Sweating (g) During the Tests at Moderate and Heavy Work Levels Without and With the Ice-Vest. The Values are the Means (Range) for 4 Subjects

Work Level	Without Ice-Vest	With Ice-Vest
Moderate	443 (338–485)	369 (250–447)
Heavy	608 (497–693)	555 (505–598)

The skin temperatures during the laboratory tests are shown in Figure 3. During tests with the ice-vest, back skin temperature decreased during the first 10–15 min over 10 ºC compared to tests without the vest. Then it gradually started to increase. The decrease in chest skin temperature with the ice-vest

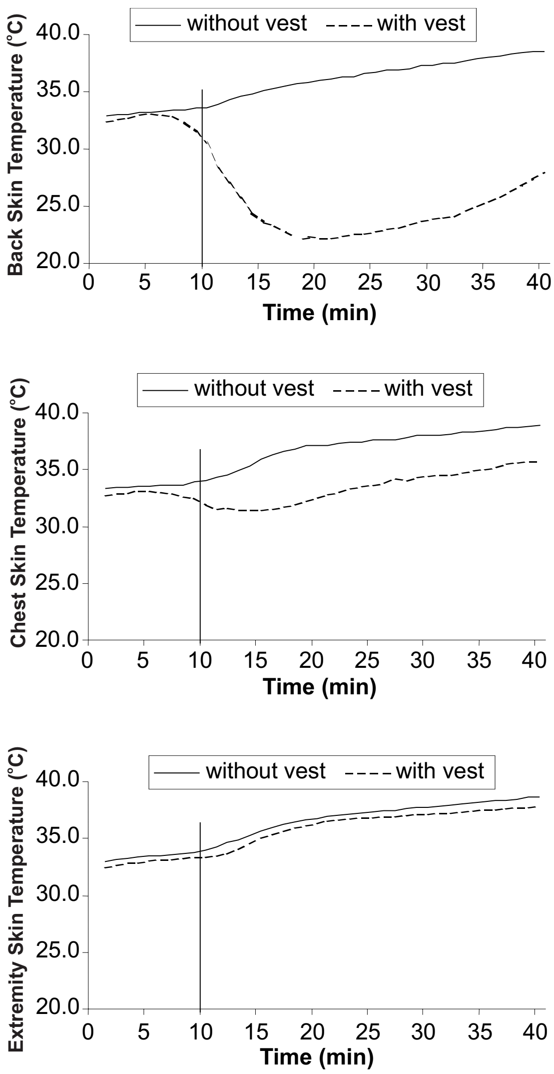

Figure 3. Average back (top), chest (middle), and extremity (bottom) skin temperature during walking in the heat at the heavy work load with and without the ice-vest. The walking started at minute 10.

was much lower than in the back. In other skin areas the temperature differences were small.

3.3. Perceptual Responses

At the moderate work level the RPE was similar between tests with and without the ice-vest (Table 5). At the heavy work level, RPE was during the first 10 min very similar between the two test conditions, but at 20 and 30 min of walking the RPE was ca 1 unit lower with the ice-vest.

At both work levels, the subjects felt cooler in the whole body when wearing the ice-vest (Table 6). Naturally, the cooler sensations were felt under the ice-vest on chest and back. Also, thermal sensations were slightly lower in other areas with the ice-vest, especially at the heavy work level.

TABLE 5. Rating of Perceived Exertion During Tests With and Without the Ice-Vest at Moderate and Heavy Work Levels at Minutes 10, 20, and 30. The Values are the Means (Range) for 4 Subjects

Work Level	Time	Without Ice-Vest	With Ice-Vest
Moderate	10	9.5 (7–11)	10.0 (7–13)
	20	11.5 (7–15)	11.3 (7–15)
	30	12.5 (7–15)	12.8 (9–16)
Heavy	10	13.0 (12–14)	12.8 (11–15)
	20	15.3 (14–16)	14.5 (13–16)
	30	17.3 (16–18)	16.0 (15–17)

TABLE 6. Thermal Sensation in the Whole Body (General) and in Different Body Parts During Tests at 2 Work Levels at the End of 30-min Exposure With And Without the Ice-Vest. The Values are the Modes

Work Level	Skin Area	Without Ice-Vest	With Ice-Vest
Moderate	Chest	+2	0
	Back	+2	0
	Face	+2	+2
	Hands	+2	+2
	Feet	+2	+2
	General	+2	+1
Heavy	Chest	+3	+1
	Back	+3	0
	Face	+3	+2
	Hands	+3	+3
	Feet	+3	+2
	General	+3	+2

3.4. Thermal Manikin Tests

The thermal insulation of the fire fighter clothing with the non-frozen ice-vest was 2.15 clo. With the frozen ice-vest the heat losses were higher than with non-frozen ice-vest, and they changed over the time according to the melting process and temperature change in vest. The heat losses related only to the frozen ice-vest were determined at 34 °C (Figure 4). The values for the beginning of the test that were uncertain due to the initial computer regulation were extrapolated with the help of polynomial regression. According to the data the mean heat losses from the whole body at particular environmental conditions due to the ice-vest were 26 W/m^2 (Table 7). However, for the torso they were 74 W/m^2. Power in watts showed that the rest of the body stood for less than 11% of heat losses.

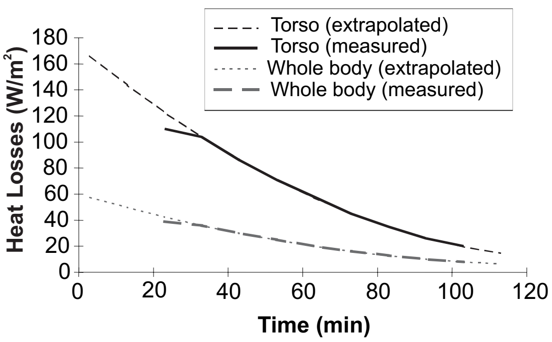

Figure 4. Change in heat losses measured on the thermal manikin with the ice-vest at an air temperature of 34 °C for the whole manikin body surface and for the torso only.

TABLE 7. Mean Power and Total Energy to the Whole Manikin Body and to the Torso Only, Based on Extrapolated Measurements With the Ice-Vest at 34 °C

Parameter	Torso	Whole Body
Mean power (W/m^2)	74	26
Mean power (W)	42	47
Energy (kJ)	272	301

The heated manikin test identified clearly the three phases of cooling provided by the ice-vest. The theoretical amount of heat required for the three phases are calculated and presented in Table 8. The warming of 1 kg of solid ice from –20 to 0 °C takes about 5 min and requires 38.4 kJ corresponding to an average power consumption of 128 W. The melting of the ice takes about 40–45 min and requires about 334 kJ. The subsequent warming of the water to 34 °C takes an hour or more with much less energy consumption 142 kJ. Not all of this power is useful for body cooling since heat is taken up from surrounding air as well. It may be said that areas under functions in Figure 4 correspond to total useful energy per area for torso (0.70 m^2), and whole body (1.77 m^2) cooling, respectively. The useful energy available for body cooling was calculated from the average measured and interpolated heat loss over whole test period. It was 58% of the total theoretical energy need for turning ice at –20 ºC into water at 34 ºC (301/514 kJ).

TABLE 8. Calculation of the Theoretical Energy Yield Associated With the Heating and Phase Change of the Ice in the Vest

Phase	Time (min)	kJ	%	Power (W)
1 kg of ice, –20–0 °C	5	38	7	128
1 kg of ice, melted	40–45	334	65	139
1 kg of water, 0–34 °C	>60	142	28	40

4. DISCUSSION

The present series of studies examined the effectiveness of a 1-kg ice-vest for body cooling in fire fighters' work. The laboratory study was done in a controlled way so that the only changing variable was exposure to the cold ice-vest on the torso, which was compared with tests without the ice-vest. The results showed that the vest did not increase the metabolic rate, and did not affect skin temperatures outside the vest. Also, rectal temperature was not influenced by the ice-vest during the tests. Probably, in such tests of relatively short duration the metabolic rate dominated strongly the rectal temperature response.

The main findings were that heart rate was 10 beats/min lower, sweating was 13% lower, and subjective sensations of physical effort and warmth were lower when the work was done with the ice-vest. Especially, the effects were seen more clearly at the heavy work level, which was close to the real demands of smoke-diving tasks in terms of energy expenditure and heat stress [9].

Kamon et al. [2] have shown that the cooling effect of frozen water-garments is a linear function of the amount of ice. In their study, they used a 3.8-kg ice-vest, and found that sweating was reduced by about 50%, which compares rather well to our findings (3.8 × 13%). Also, they observed very clear reductions in body temperatures and heart rate, and large increases in tolerance times. According to their calculations, a 1-kg ice-vest would give about 10% improvement in performance time during work in the heat. Based on the heart rate data, we can also see that reaching the same heart rate (e.g., 160 beats/min) with the ice-vest as without it takes about 5 min more, which in a 30-min work period comes close to a 10% increase in possible tolerance time. Even though the amount of ice was not big in our study, the added benefit in work time may be of crucial value in extremely demanding smoke-diving tasks of short duration.

It can be concluded that the light-weight ice vest reduces circulatory, thermal, and subjective strain during heavy work in the heat. The added benefit is ca 10%. Additional benefits may include improved visibility due to lesser sweating on the face, and a reduced need for fluid replacement with repeated work bouts.

Slightly more than 50% of the energy was available for body cooling according to the manikin test. This figure is dependent on the type, construction and arrangement of the layers on both sides of the vest. The figure may be increased by reducing insulation layers between skin and ice-vest, and/or adding an insulative or reflective layer outside the vest, or by more ice. Such arrangements, however, need to consider possible effects on thermal sensation, restriction of movements and weight.

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