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Physiological Evaluation of Chemical Protective Suit Systems (CPSS) in Hot Conditions

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This job-related experiment investigated physiological strain in subjects wearing impermeable chemical protective suit systems (CPSSs) weighing about 28 kg. Two types of CPSSs were studied: the self-contained breathing apparatus was carried either inside or outside the suit. Eight healthy and physically fit male firefighter instructors aged 32 to 45 years volunteered for the study. The test drill, performed at a dry, windless t_a *of 40 °C, was divided into 2 consecutive work sessions of 14.5 min (a 20-min rest between) including typical operational work tasks. Considerable thermal and maximal cardiovascular strain and intense subjective discomfort measured in the firefighters emphasize the need to limit working time in hot conditions to only 10–12 min while wearing CPSSs. The present results indicate that the exceptionally heavy physical load and psychological stress during operations in chemical emergencies must be considered in the assessment of the cardiovascular capacity of ageing firefighters using CPSSs.*

chemical protective suit   hot conditions   physiological strain

1. INTRODUCTION AND STUDY AIMS

In many rescue operations in which the use of a self-contained breathing apparatus (SCBA) is necessary, the main limiting factor for task duration is the air containers running out of air. Heat-related diseases, even a lethal heat stroke, are additional risks in firefighting and rescue work in the heat [1, 2, 3, 4, 5]. The risk is especially high when a water vapour impermeable protective clothing system is used [6, 7, 8]. Operations during chemical accidents are considered physically and mentally extremely demanding tasks even for highly trained professionals who are prepared to face the worst possible situations involving dangerous gases, or chemical and nuclear agents.

The increased use and transportation of toxic chemicals in conjunction with stricter safety limits for hazardous exposures increase the need to wear impermeable clothing in order to prevent contamination. The possibility of biological warfare and terror activity has aroused increasing interest in the ergonomic and physiological studies on NBC-suit systems (nuclear, biological and chemical protective clothing) [6, 7, 8, 9].

The present standards—ISO 7243:1982 [10] for heat stress and ISO/CD 7933:2001 [11] for heat strain—are not applicable when assessing safe duration of work in rescue operations in

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accident situations in which impermeable protective clothing is worn. One of the main questions raised in connection with extreme heat stress pertains to tolerable physiological limits in regard to the health of exposed workers. The general consensus is that at least conditions of thermal equilibrium are permissible. However, under extreme conditions, excessive heat accumulation is reflected by a continuously increasing body temperature and an acceleration of heart rate [1, 2, 3, 5, 7, 12]. Most importantly, there is an urgent need to extend our knowledge of physiological strain in actual rescue operations in order to improve the safety of rescue workers while wearing impermeable protective clothing, which decreases the rate of heat exchange. Information for safe exposure times for military purposes is available [9] but similar information for firefighting and rescue work is insufficient.

This study is part of a comprehensive project, which investigated physiological strain in firefighters under various climatic conditions wearing a chemical protective suit (CPS) with an SCBA either inside or outside the suit. The instructors of the Finnish Emergency Services College inspired the initiative for this job-related experiment, the main purpose of which was to improve the students' safety in their chemical accident response training. The field experiments were conducted in cold winter (–11 to –20 °C) and moderate warm sunny summer conditions (+13 to +20 °C) at an outdoor processing plant [13].

The detailed goals of this sub-study were to (a) find the degree of physiological strain in firefighters wearing two different types of impermeable CPSs in hot and dry conditions during a job-related drill simulating typical work tasks in a chemical accident, (b) examine the effects of CPS systems on work performance and wear comfort.

2. METHODS

2.1. Subjects

The voluntary subjects were 8 healthy experienced male firefighting instructors of the Finnish Emergency Services College with an average age of 38.6 (31–44) years, height 183.5 (178–190) cm, weight 88.3 (72–110) kg, body fat 14.6% (9.2–18.9), body area 2.1 (1.9–2.3) m^2, BMI 26.2 (22.6–31.9). Before the experiments the subjects had a medical check-up including a clinical exercise test and routine examinations of blood and urine. Maximal oxygen consumption (V_{O2max}) was then determined under neutral conditions. Physical working capacity (V_{O2max} 51.6 (46–60) $ml \cdot kg^{-1} \cdot min^{-1}$) of this selected group of instructors was categorized as average to excellent in their age group.

2.2. Chemical Protective Suit System (CPSS)

The CPSS consisted of standard test clothing (pants, cotton underwear with long sleeves and legs, a polyester fleece sweat shirt and trousers, a wool underhood, wool socks, cotton undergloves) with a thermal insulation of about 1.5 clo, a helmet and an impermeable CPS. Two types of CPSs were studied: the SCBA (Dräger PA 90/6 L, approximately 16 kg; Dräger Sicherheitstechnik GmbH, Germany) was carried either outside SuitA or inside SuitB. The material of both CPSs was butyl rubber. SuitA weighted 5.5 kg and SuitB 7.8 kg. Correspondingly, the air flow rates of the air supply to the CPSs were 4 L/min and 2 L/min. The total mass of the CPSS averaged 25.5 kg for the SuitA system and 27 kg for the SuitB system.

2.3. Experimental Design

The test protocol (Figure 1) was developed to simulate work tasks encountered in an actual

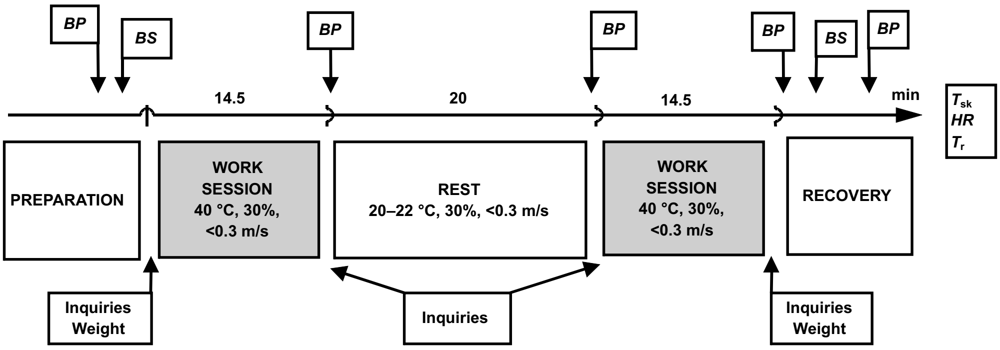

Figure 1. Experimental design of a job-related test drill in hot conditions while wearing impermeable chemical protective suit with a self-contained breathing apparatus. *Notes.* *BP*—blood pressure, *BS*—blood samples, T_{sk}—skin temperature, T_r—rectal temperature, *HR*—heart rate.

chemical accident. The 14.5-min duration of a work session (work tasks with transit periods) was the same as in the test drill developed by Louhevaara and co-workers [14] for the assessment of the physical work capacity of firefighters. The drill, performed in a climatic chamber controlled at a t_a of 40 °C, an RH of 30%, and a v_a of <0.3 m/s, was divided into two consecutive work sessions. There was a 20-min passive rest period at t_a of 20–22 °C in between each session for drinking ad libitum, and body cooling (partly doffing the CPS for ventilation of underclothing), and changing the air container. The selected work tasks modified from the European standard EN 943–1:2002 [15] for chemical protective suits for emergency teams are shown in Figures 2 A-E. Three of the subjects performed the drill with both CPSSs. The suits for the drills were randomly assigned and the total number of experiments for SuitA was 5 and for SuitB 6, respectively.

The test protocol was approved by the Institutional Ethics Committee and the written informed consent of the subjects was obtained before the experimental sessions. The test drill was terminated if one of the following criteria was met: (a) emptying of the air container; (b) $T_{re} \geq 39.5$°C with subjective signs of severe discomfort or fatigue, chest pain or intense muscle pain; and (c) objective signs of exhaustion and exertion dyspnoea or dizziness.

2.3.1. Physiological measurements

Heart rate (*HR*) was recorded once a minute (Polar Sport tester PM 3000, Finland). Rectal temperature (T_{re}) was continuously measured with a flexible thermistor probe (YSI 401, Yellow Springs Instrument Co., USA) at a depth of 10 cm and, correspondingly, skin temperatures (T_{sk}) were measured at the neck, scapula, hand, and shin (YSI 427), and registered once a minute (Grant Squirrel Meter/Logger 1200, Grant Instrument [Cambridge] Ltd., UK). Mean skin temperature ($\overline{T}_{sk}$) was calculated using weighting coefficients of ISO 9886:1992 [16] and, correspondingly, mean body temperature ($\overline{T}_b$) using the weighting coefficients 0.9 for T_{re} and 0.1 for $\overline{T}_{sk}$. The change in heat storage for exposure time was calculated from changes in $\overline{T}_b$ using 0.97 W·hr/kg·°C for specific heat of the body. Sweat loss was determined with the weight change in a clothed subject before and after the exercise (Sauter EC 240, Type 1200 ± 5g, Type 1200; August Sauter GmbH, Germany) and corrected with water intake and the sweat absorbed into the test clothing. Brachial blood pressure was measured (sphygmomanometer) in a neutral climate in a supine position prior to and within 2 min after each work session.

2.3.2. Subjective evaluations

Ratings of perceived exertion (RPE) using the Borg scale [17] from 6 (*very, very light*) to 20 (*very, very hard*), thermal comfort and thermal sensation modified from ISO 10551:1995 [18], as well as skin wettedness using the scale from 1 (*dry*) to 5 (*watery wet*) were requested at the start and at the end of each work session. The subjects also filled out a questionnaire on CPSS wear comfort and function at work.

A. 5 min of walking on a treadmill, 5 km/hr, 1° grade

B. 2 min of ascending and descending stairs (height of footstep 27 cm) at one's own speed

C. 2 min of carrying a 35-kg can on a treadmill, 3.5 km/hr, 1° grade

D.

E.

2 min of scooping sand to a height of 1.5 m, at one's own speed

Figure 2A–E. Work tasks of a job-related drill in hot conditions while wearing an impermeable chemical protective suit with a self-contained breathing apparatus inside or outside the suit.

2.4. Statistics

Means ± *SD*, ranges and medians were used for describing of the data. The distributions of the variables were not normal and Wilcoxon test was used to compare differences between test conditions. The <.05 level of probability was accepted as significant.

3. RESULTS AND DISCUSSION

The previous results of a simulated chemical accident at an outdoor processing plant while wearing the same CPSSs [13] indicate both in winter and in summer significantly greater thermal and cardiovascular strain in firefighters while working in the fully encapsulating impermeable SuitB compared to the suit SuitA (SCBA carried outside the suit). On the contrary, this laboratory drill in hot conditions showed no significant difference in physiological responses between SuitA and SuitB, and the results given in this paper are the mean values for both CPSSs. Some of the present results are compared with the results found during drills conducted outdoors at an outdoor processing plant.

3.1. Work Performance

The subjects completed all the drills. However, four of them had symptoms (headache, dizziness, cessation of sweating) reflecting thermoregulatory failure. During the second work session the work tasks that were performed at one's own speed (ascending and descending stairs and scooping sand, Figures 2 B, D and E) decreased in performance, 13% (4–43) on average: stepping speed slowed down and the number of scoops decreased.

3.2. Physiological Responses

3.2.1. Pulmonary ventilation

The average pulmonary ventilation rate for work sessions was 77.9 ± 15 L/min corresponding to an average ventilation rate measured in the field during typical firefighting and rescue operations. However, the individual variation in the ventilation rate was great (58–112 L/min). For most subjects the ventilation rate for the second work session was higher than for the first work session. The air container of three subjects was empty at the end of both work sessions. This means that in a real accident, the instructors would not have had any chance of returning from the hazard area. According to the Finnish legislation for rescue operations 100 bar of reserve air is necessary in order to ensure a safe return from the scene of an accident.

3.2.2. Cardiovascular strain

During the first minutes of each work sessions *HR* increased rapidly near individual HR_{max} and fluctuated at that level during the work. After the first work session ceased, the *HR* dropped slowly and remained during 20-min rest period at levels of 95 to 135 b·min^{-1}. After the entire drill, the mean *HR* was still on a considerably higher level after the half-hour recovery than before dressing in a CPSS.

The end-exercise *HR*s for each work task, and for the first and the second work sessions are presented in Table 1. The average end-exercise *HR* was higher for each work task at the end of the second work session. This also applies to individual *HR*s with the exception of subject No. 1, who had the same *HR* for walking and for stepping at the end of the first and the second work session. The highest *HR*s were measured during the carrying of a 35-kg can on the treadmill and most of the subjects reached their previously measured maximal

TABLE 1. The End-Exercise Heart Rates for Each Work Task, and for the 1st and the 2nd Work Sessions 1 and 2 (WS1 and WS2) While Wearing Impermeable a Chemical Protective Suit With a Self-Contained Breathing Apparatus in Hot Conditions

Subject No.	End-Exercise Heart Rate ($b \cdot min^{-1}$)							
	Walking		Stair Climbing		Carrying a Can		Scooping Sand	
	WS 1	WS 2	WS 1	WS 2	WS 1	WS 2	WS 1	WS 2
1	126	126	145	145	150	161	138	149
2	114	125	131	142	154	158	128	135
3	109	134	133	158	145	174	133	159
4	152	179	174	193	182	200	179	198
5	120	153	151	176	162	184	149	182
6	137	155	147	163	163	179	152	162
7	128	141	145	157	154	170	135	149
8	152	165	173	182	181	187	173	179
M	**130**	**147**	**150**	**165**	**161**	**177**	**148**	**164**

HR levels in V_{O2max} test. The average peak *HR* (175 ± 13.0 min^{-1}) was considerably higher for the hot work sessions than for the field tests [13] in summer (166 ± 15 min^{-1}) or in winter (157 ± 13 min^{-1}).

Circulatory load was expressed as a time fraction of *HR* >75% of the individual measured maximal *HR* ($HR_{>75\%}$). On average, it was 23% of the total duration of work. However, significant individual differences between subjects were observed in $HR_{>75\%}$, being between 9 and 46%.

Myocardial oxygen demand, assessed by the rate-pressure double-product (RPDP), remained considerably higher after hot exposure than after the drills conducted outdoors in winter and in summer [13]. The cardiac oxygen demand reverted nearly to the resting level after 5 min of recovery both in winter and in summer and the mean increase was only about 1.1-fold compared to the resting level. Five minutes after the end of first hot work session the RPDP was 1.8-fold (±0.4) compared to the initial resting level. At the end of the second hot work session circulatory strain was more pronounced and after 5-min recovery cardiac oxygen demand was still 2-fold (±0.5) in contrast to the rest. In an ageing firefighter, that high cardiovascular load may increase the risk for cardiac events even during a short hot work session. According to the most recent statistics (cf. [5]), heart attacks represent the most frequent cause of line-of-duty deaths for firefighters in the USA.

3.2.3. Thermal responses

3.2.3.1. Rectal temperature. The mean increase in T_{re} during the drill was 1.2°C, ranging from 0.9 to 1.6 °C (Figure 3). The passive rest period in a neutral climate between the work sessions had no or a minimal positive cooling effect on T_{re}. The rate of change in T_{re} for each work session, calculated as the final T_{re} minus the initial T_{re}, was 2.0 ± 0.6 ºC/hr for the first work session and 2.3 ± 0.7 ºC/hr for the second work session. The greatest individual change for the first work session was 3.1 ºC/hr and the smallest 1.2 ºC/hr. Respectively, the changes for the second work session were 3.7 and 1.2 ºC/hr.

3.2.3.2. Skin temperature. During the drill, the average mean skin temperature (T_{sk}) fluctuated at about the same level as or higher levels than the T_{re}. The highest mean T_{sk} values of about 38 °C and the highest individual T_{sk} values of over 39 °C were measured at the shin.

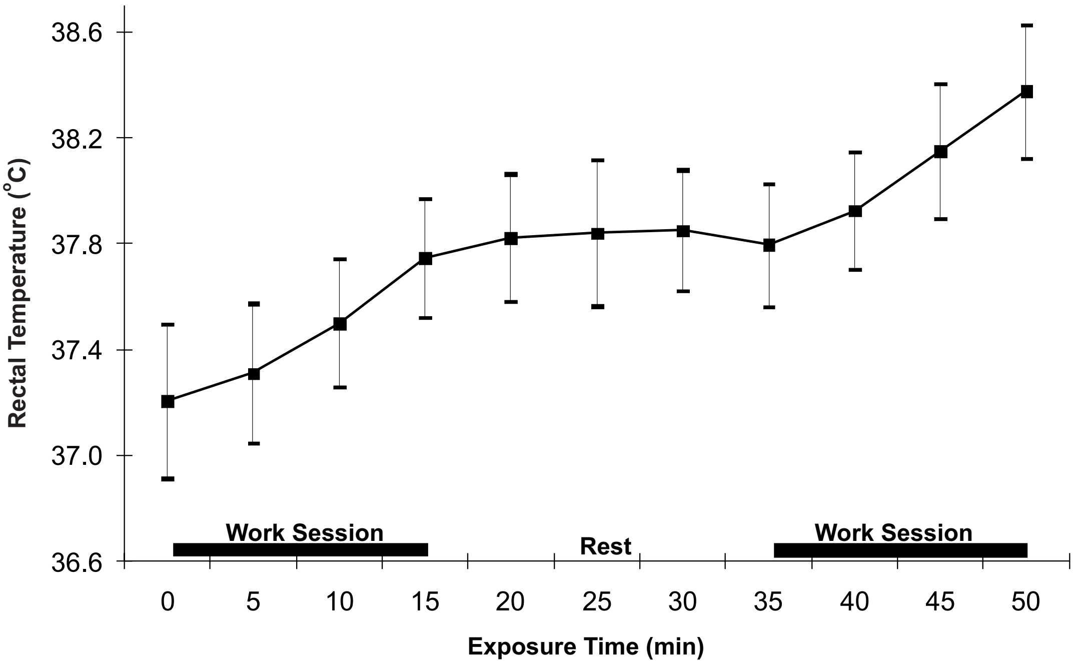

Figure 3. Time course for rectal temperature during a job-related drill in hot conditions while wearing impermeable chemical protective suits with a self-contained breathing. The values are means (*N* = 10) and *SD*.

These temperatures hardly decreased during the passive rest period under neutral conditions, because the limited time allowed doffing the suits only partially (Figure 4).

3.2.3.3. Heat storage. The individual rates of change in heat storage varied from about 26 to 53 W/m^2, being about 40 W/m^2 on average. Heat accumulation was significantly greater

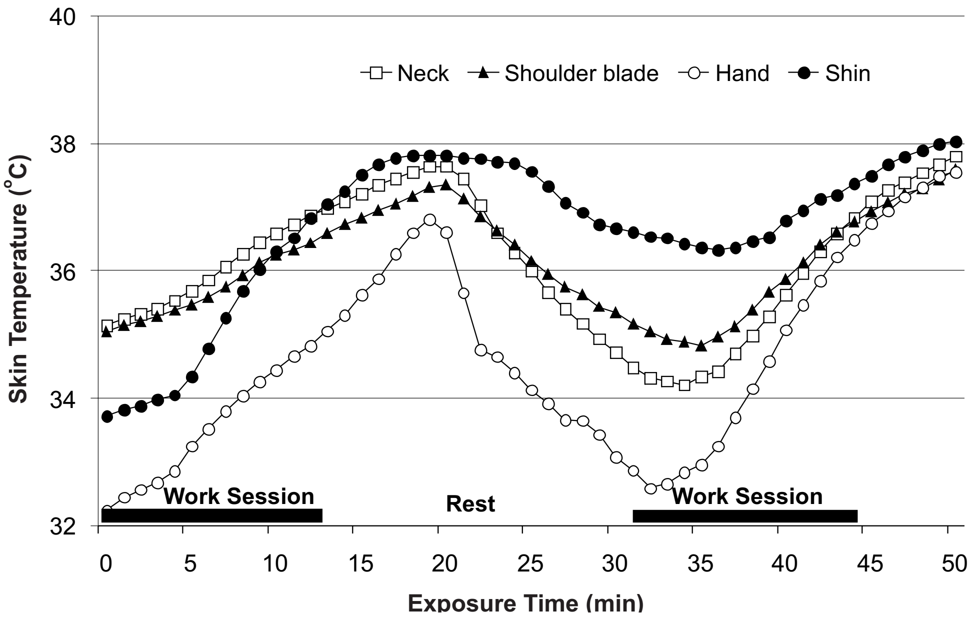

Figure 4. Time courses for skin temperatures during a job-related drill in hot conditions while wearing impermeable chemical protective suits with a self-contained breathing apparatus. The values are means (*N* = 10 for neck, shoulder blade, hand, and *7* for shin).

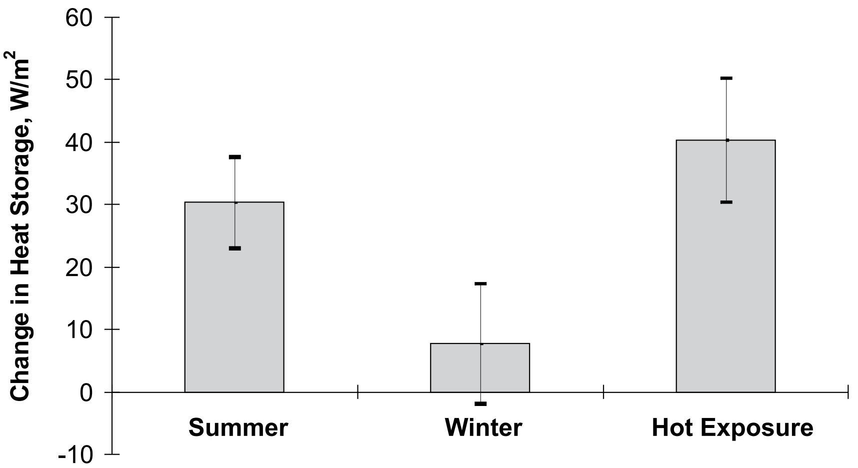

Figure 5. Average (±*SD*) change in heat storage during job-related drills in hot conditions (40 °C, *N* = 11) and in moderate warm summer (13 to 20 °C, *N* = 12) and in cold winter (–11 to –20 °C, *N* = 12) conditions at an outdoor processing plant while wearing impermeable chemical protective suits with a self-contained breathing apparatus.

than measured in the field studies [11] wearing the same CPSSs in summer and in winter (Figure 5).

3.2.4. Body fluid balance

Sweat rate varied greatly between individuals. On average, the sweat rate was about 1 kg/hr·m^{-2} and significantly higher than the rates measured during the drills in the field wearing (Figure 6) the same CPSSs [13]. However, the water replacement of highly trained professionals was adequate in most cases, and the average water deficit was only about 0.4%. No significant changes in the serum electrolytes or muscle enzyme creatine kinase analysed from blood samples before and after the exercise were detected during this short hot work.

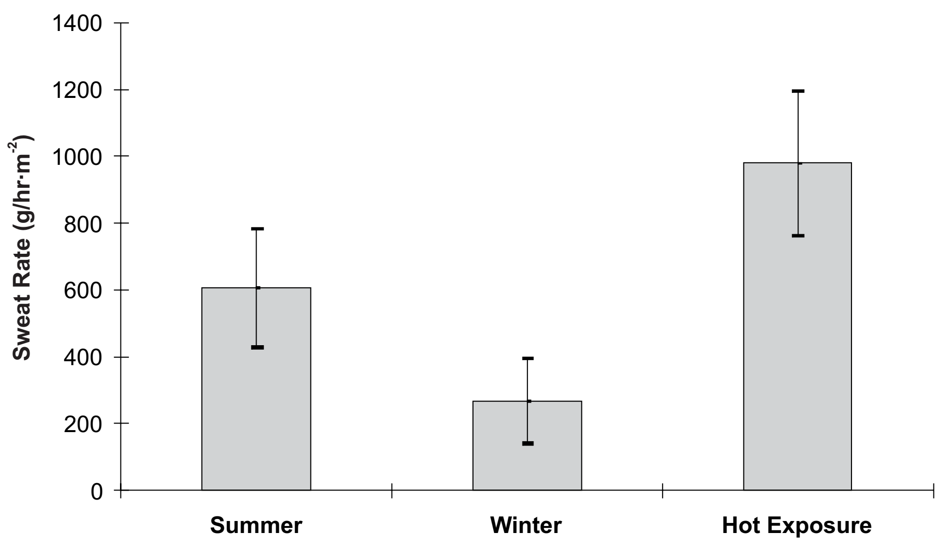

Figure 6. Mean (±*SD*) sweat rates during job-related drills in hot conditions (40 °C, *N* = 11), and in moderate warm summer (13 to 20 °C, *N* = 12) and in cold winter (–11 to –20 °C, *N* = 12) conditions at an outdoor processing plant while wearing impermeable chemical protective suits with a self-contained breathing apparatus.

3.3. Subjective Evaluations

On average, the work was perceived as being *hard* at the end of the first work session (Figure 7). The 20-min rest was too short for recovery, and the second work session was, on average, perceived as being *very hard.* Some subjects even reported *very, very hard.* Four subjects exhibited symptoms predicting heat exhaustion (goose bumps, shivering, headache and nausea). For these four, the average T_{re} increase was over 1 °C, and for two of them it was as high as 1.6°C, and heat accumulation varied from 43 to 52 W/m^2. The average time fraction of the $HR_{>75\%}$ was 38% for subjects with symptoms compared to the average of 17% for the rest of the study group.

At the end of the first work session the subjects reported their condition as *warm* (Figure 8) and *uncomfortable* on average, and the skin was felt to be *clammy*. At the end of the

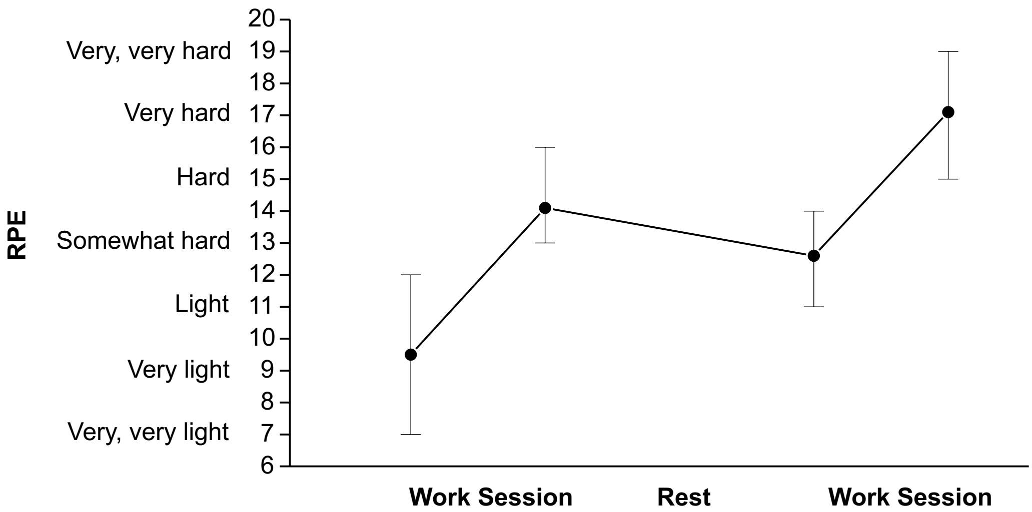

Figure 7. Ratings of perceived exertion (RPE) during a job-related drill in hot conditions while wearing impermeable chemical protective suits with a self-contained breathing apparatus. The values are means and the ranges (*N* = 11).

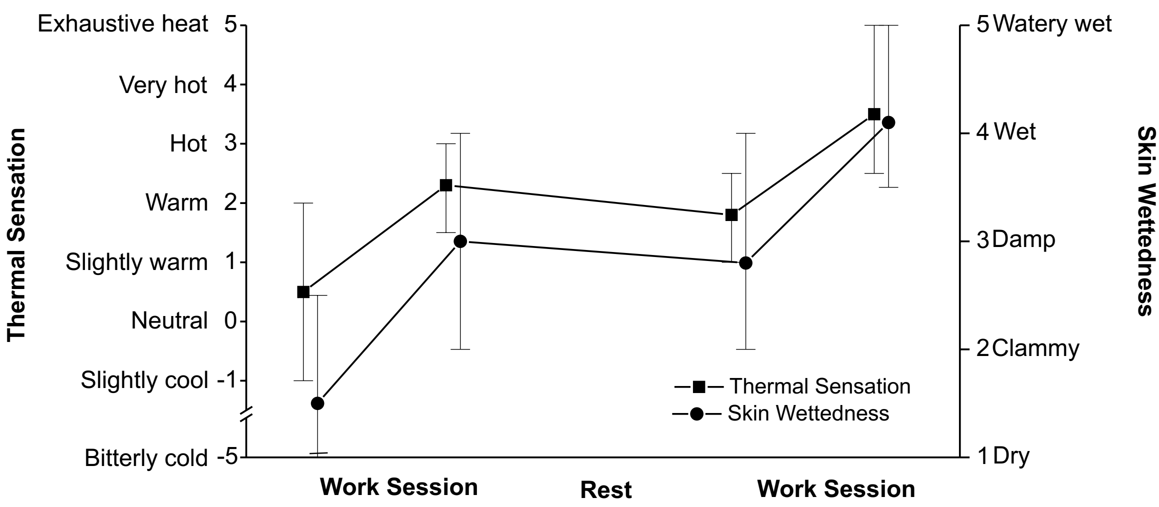

Figure 8. Ratings of thermal sensation and skin wettedness during a job-related drill in hot conditions while wearing impermeable chemical protective suits with a self-contained breathing apparatus. The values are means and the ranges (*N* = 11).

second work session the corresponding reports were *hot*, *very uncomfortable* and *wet.* Some subjects even reported *exhaustive heat, almost intolerable* and *watery wet.*

3.4. Suit Functionality

There were clear differences in suit functionality. Donning and doffing an encapsulated CPS without additional help was impossible for experienced firefighting instructors contrary to the suit with an SCBA outside the suit. Restricted movement and especially the loss of vision due to misting of the visor (Figure 9) caused additional stress to the wearer of the encapsulated suit. In the field experiments even three near-accidents were registered.

Figure 9. Misting of the visor was a problem while wearing an encapsulating chemical protective suits system.

4. CONCLUSIONS

The present finding indicates maximal thermal and cardiovascular strain and intense subjective discomfort in experienced healthy and physically fit firefighting instructors during two sessions of 14.5 min of job-related heat exposure while wearing an impermeable CPS with an SBCA either inside or outside the suit. Physiological strain in studied hot conditions was significantly greater than previously measured in the same subjects in prolonged job-related drills while wearing the same CPSSs in moderate warm summer and also in firefighting drills wearing a European type multilayer turnout suit [1]. Twenty minutes of passive recovery in a neutral climate was not enough for body cooling and repeated work sessions caused cumulative cardiovascular and thermal strain in all subjects. Furthermore, in some instructors, signs and symptoms of heat exhaustion were found.

The results emphasize the need to limit the duration of work in hot conditions to only 10–12 min while wearing an impermeable CPSS with an SCBA. When the actual rescue tasks involve repeated exposures with a CPSS in hot conditions the risk of exhaustion is increased even after two work sessions. Therefore a prolonged recovery period in a cool environment and preferably some form of active cooling is necessary to prevent intolerable heat strain and exhaustion.

The exceptionally heavy physical load and psychological stress during the operations in chemical emergencies must be considered in the training of firefighters, and also in the assessment of the cardiovascular capacity of ageing firefighters.

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