THE INFLUENCE OF AN ACTIVE MICROCLIMATE LIQUID-COOLED VEST ON HEAT STRAIN ALLEVIATION

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Abstract: *This research was performed to test the effectiveness of the microclimate body cooling system which belongs to the group of active systems with liquid-cooled technology. The liquid cooling vest efficiency was observed concerning the physiological fitness of the standard protective set used in specific environmental conditions which imply increased thermal strain of the test subjects. Experimental results from the research are based on the examinations carried out in a thermo-physiological laboratory.*
Ten healthy male volunteers - test subjects aged (23.4 ± 2.4 years, weight 74 ± 7 kg, and height 184 ± 9 cm) were exposed to thermal strain testing (40 °C temperature, 40±3% relative humidity, without wind) and simultaneously to physical effort caused by walking on the treadmill at a speed of 5 km/h, during 45 minutes. Tests were performed in two variants - without any cooling system (NC) and with the KewlFlow Circulatory Cooling Vest with Cooler Kit (LC). Throughout heat exposure, the subject's body core temperature (tympanic temperature - Tty), mean skin temperature (Tsk) and heart rate (HR) were measured. Furthermore, sweat rate (SwR) was calculated in order to determine all changes in the water and electrolyte status.
Experimental results confirm that the results of this study have recognized the benefits of a liquid-cooled vest in lowering the thermal strain.

Key words: *heat stress, cooling vest, liquid cooling, physiology, thermal strain indicators.*

1. INTRODUCTION

There is a wide variety of normal body core temperature. When resting, human body temperature (normothermia) is normally considered to be 37.0 ± 0.5 °C. When exercising or when it is exposed to heat, body core temperature can increase up to 3 °C [1]. When body temperature gets to 41.5 °C this condition can be defined as a heat exhaustion [2]. A heat stroke is considered to be life-threatening and occurs when the temperature keeps rising and is followed by some neurological signs [3,4]. Thus, a thermal balance is extremely significant for athletes, firefighters and military combat personnel, as they are the ones who need to keep up their agility during performance.

In order to control the temperature from rising beyond limits, the body perspires and disperses thermal energy by evaporative cooling. If it happens that, during a certain physical activity, the thermal insulation of a clothing is diminished using various physical processes, then the generated heat can partially be removed by transmission. In this case, the body does not need to perspire excessively.

The total quality of insulation a garment possesses highly depends on the thickness and density of the component fabrics. Insulation is improved if the garment is thick and not so dense and if it has air

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gaps between layers. In addition, the external temperature plays a significant role in the efficacy of insulation, which is not so powerful if the temperature becomes extreme. It means that a garment, which will be able to protect human body against either heat or cold, has to be chosen based on climate.

The process of heat accumulation happens during different excessive physical exertion or specific exposure within warm and humid environmental conditions. In that case, accumulation of heat at a rate of 0.5 W/kg during 1 to 2 h results in an increase in body temperature [5]. Accumulation of heat in the body will always result in an increase in body temperature, regardless of the rate.

Because of that, heat stress in a compensated form which can develop under many different working conditions/activities. That means that there is a balance between heat loss and heat production. During a specific physical task, it can lead to an equilibrium core temperature (steady state). Generally, when demands for sweat evaporation go beyond the evaporative capacity of the environment, uncompensated heat stress occurs.

According to some authors [6], during compensable heat stress a decreasing cardiovascular and thermoregulatory strain occurs with increasing fitness before acclimation. Thus, only cardiovascular benefits with fitness are achieved. Other studies [7] show, a lower HR, body core temperature and Tsk, along with increased tolerance time, reported during compensable heat stress in very fit subjects compared with subjects of average fitness.

There are many biophysical factors (e.g. clothing, environmental conditions, physical exertion level) that influence the compensation of heat stress [8].

Evaporation by sweating can be the main means for dissipating heat during long stays in hot environment over a long period of time. Hence, when specific protective overgarment is worn, heat dissipation is reduced constantly with sweat evaporation rates decreasing. The productiveness of physiological adaptation is influenced by the amount of heat generated in the muscles as well as the intensity of the external work and the rate of body heat exchange [9].

Contemporary needs of first responders and other people who needs personal protective equipment request the highest physiological suitability and comfort of people during specific activities, missions and tasks in different areas/conditions. For that purpose, reducing physiological strain can be accomplished by the use of modern garments that provide greater physiological suitability, based on ventilation and sweat evaporation. With this in mind, different systems for body cooling have been developed, with the main purpose to increase comfort as well to reduce thermal strain. [10,11]. From the other side, brain temperature is also a critical factor affecting motor activity during different exercises in hot conditions. [12]

Although many systems exist today, they can generally be classified in five basic groups: evaporative cooling products, products based on PCM-based products (Phase Change Materials) compressed air systems, liquid circulation systems and thermoelectric systems [13,14].

The purpose of this study is to evaluate the efficiency of the microclimate cooling vest based on the liquid circulation tube system, combined with the standard protective set, on humans' physiological suitability during bodily efforts in a hot environment. We assumed that cooling vest application reduce humans' physiological strain and expand the capacity to carry out any task successfully in extremely hot conditions.

2. METHODS

2.1. Subjects

Ten male test subjects (23.4 ± 2.4 years), with similar anthropometric parameters (weight 74 ± 7 kg, height 184 ± 9 cm) participated in the study.

Before the beginning of the exercise a medical examination is obligatory and the subjects are informed about all the experimental details (nature, purpose, conditions) and the risks and discomforts that they imply. Furthermore, each participant read and signed a specific consent form, in accordance with the standards of medical safety during examination in adverse weather conditions [15]. A competent Ethical committee approved the investigation protocol. The performed procedures correlated with the standards of thermal strain evaluation by psychological measurements [16]. The outcome reflects heat stress tests carried out in the standard climatic chamber, which meets all requirements to meet relevant standards [15,16].

2.2. Clothing

During exercises, the participants were dressed in standard protective set produced by company YUMCO (Republic of Serbia). Set consists of standard leather boots, regular trousers (50% cotton and 50% polyester) and a shirt (67% cotton and 33% polyester fabric of 150 g/m^2 surface mass (± 5%)). All clothing components are waterproof, designed to protect the user in specific temperature range (-30 °C to +50 °C). It is important to note that no specific undergarment was used during examination, only standard underwear.

2.3. Cooling System

The cooling system tested in this study was the KewlFlow Circulatory Cooling Vest with Cooler Kit (TechNiche International). This cooling system uses pumped ice water through special tubes integrated into the vest [17]. The result is continuous flow of cool water around the upper body, keeping the user cool and comfortable. The specific design of ice cooler or backpack enables that ice and water can be easily refilled for extended constant supply.

Figure 1. KewlFlow Circulatory Cooling Vest

The water flow process is provided by a micro-pump (7.4 A, 7.5 L/min) with a power source (Li-ion battery 7.4 V/30000 mAh) and a charger (110-240 V AC).

The vest is made of 100% Polyester Mesh fabric, with integrated circulatory tubing produced from clear thermoplastic polyurethane - TPU (approx. 12 m of tubes, 5 mm diameter, 0.8 mm thickness, 10 mm spacing). The shoulder pack consists of the 100% nylon carrying case with spill-proof inner cooler made of silver waterproof material. The working time is from 1.5 hrs (intensive physical effort) up to 3 hrs (without much physical effort).

2.4. Experimental design

During six months of testing, each subject performed a heat-stress test (HST), which consisted of walking on a motorized treadmill in a hot environment (40 °C, 40±3% relative humidity (RH), wind speed 0.1 m/s), while wearing the protective set. Each subject performed two times the same tests: in standard protective set without any cooling system (variant NC) and with the KewlFlow Circulatory Cooling Vest (variant LC).

Before each test was conducted, it was necessary to prepare and setup the climatic chamber and experimental equipment (setting the climatic chamber - temperature and humidity by testing equipment, validation of treadmill, measurement devices and other monitoring tools).

Before subjects entered the chamber, their weight without any equipment was recorded (just in the underwear). Subsequently, their skin and tympanic temperature thermistor monitoring cables were connected to a computerized BIOPAC data acquisition system. Then the subjects entered the chamber and began to exercise.

Considering the given environmental conditions and thermal strain level, duration of the test was initially limited to a maximum of 45 min, while criteria for early termination were: achieving a critical value of Tty (39.5 °C), or HR (190 bpm), or subject's feeling of unbearable strain.

2.5. Instrumental setup and protocol

A certified physiological data monitoring system (Biopac Systems, USA) was used for all measurements of the temperature of the subject's every time they were exposed to it and automatically monitored and recorded in real time [18,19]. The contemporary system includes: MP150 unit for acquisition, universal interface module (UIM100C) and five skin temperature amplifier modules (SKT 100C).

The UIM100C Universal Interface Module serves as an interface between the MP150/100 and external devices. SKT100C has been created to measure general temperature, to define a respiration rate, to investigate psycho-physiological characteristics and for sleep studies. It is a skin temperature amplifier module, specifically created to observe skin and core temperature and respiration rate.

Heart rate (HR) over a time interval t (min) is defined as HR = n/t, where n is the number of heartbeats observed during this time interval. It is expressed in beats per min (bpm). During this tests only the increase in heart rate connected with the thermal strain experienced by the subject was examined. Heart rate was measured and recorded continually and automatically using a Quinton® Q4500 Exercise Test Monitor (Quinton Instruments Company, USA). It was done using monitors that received readings from the heart rate straps fastened to each subject (on the chest and the bottom of the spine). During the experiments, the treadmill which was used was controlled and handled by the same device (the speed and grade parameters).

Method used in this study aims to measuring the temperature of the tympanic membrane (Tty) whose vascularisation is provided in part by the internal carotid artery, which also supplies the hypothalamus. As the thermal inertia of the eardrum is very low, due to its low mass and high vascularity, its temperature reflects the variations in arterial blood temperature, which influence the centers of thermoregulations. Tympanic temperature was measured by conducting thermo-element TSD202A into the aural channel and investing as close as possible to the eardrum. This measurement was continually, with recording data every 10 s. Having been placed to the eardrum precisely, this measurement was continual with data recorded every 10 seconds.

Skin temperature (Tsk) varies widely over the surface of the body, especially during extreme ambient conditions. Skin temperature is influenced by: the thermal exchanges by conduction, convection, radiation and evaporation at the surface of the skin, and - the variations of skin blood flow and of the temperature of the arterial blood reaching the particular part of the body. In warm and hot environment, except in the presence of the high asymmetrical radiation, local skin temperatures tend to be homogeneous, so few measuring points can be used with accuracy. The mean body skin temperature was determined continually, measuring of local body temperatures on four points, using transducers types TSD202E and TS202F[2]:

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[2]In warm and hot environments, except in the presence of high asymmetrical radiation, local skin temperatures tend to be homogeneous, so a few measuring points can be used with accuracy.

$$Tsk = 0{,}28Tsk_1 + 0{,}28Tsk_2 + 0{,}16Tsk_3 + 0{,}28Tsk_4 \quad (1)$$

where:

Tsk_1 - skin temperature measured in the middle of the neck root,
Tsk_2 - skin temperature measured in the middle of the right scapula,
Tsk_3 - skin temperature measured in the middle of the upper palm side,
Tsk_4 - skin temperature measured in the middle of right shin.

Assessment of thermal strain was also performed based on a heart rate (HR), expressed in beats per minute (bpm).

A person's body-mass loss (Δmg) during an interval of time represents the sum of a few different components (eq. 2.):

$$\Delta mg = \Delta msw + \Delta mres + \Delta m0 + \Delta mwat + \Delta msol + \Delta mclo \quad (2)$$

To sum up, the total mass loss is dependent on different factors such as sweat loss (Δmsw), the difference between carbon dioxide and oxygen (Δm0), the evaporation of the respiratory tract (Δmres), the intake (food) and excretions (stools) of solids (Δmsol), the intake and excretions (urine) of water (Δmwat), and the sweat accumulation in the clothing (Δmclo). The sweat loss component (ΔmSW) is the most relevant factor when the rate of sweating (SwR) is taken into account. According to the given standards, it was mandatory to measure the differences in the body weight (pre-test and the post-test nude body weights, by a digital scale Chyo MW-100K). Given the same standards, sweat rates (SwR) were expressed per hour per square meter of body surface ($L/m^2/h$).

Furthermore, this procedure requires the measurement of the subjective assessment of the level of comfort. For the purpose of which it was rated by each subject using the scale of perceived exertion (RPE). This scale values range from 1 to 7, where 1 denotes "comfortable" and 7 denotes "extremely intolerable hot": 1) Comfortable; 2) Warm but fairly comfortable; 3) Uncomfortably warm; 4) Hot; 5) Very hot; 6) Almost as hot as I can stand; 7) So hot I am sick and nauseated. The subjects were asked to point on the scale their subjective assessment every 5 min during the exposure [20].

2.6. Statistics

The obtained data are shown as mean values and standard deviations (±SD). The Shapiro-Vilk's test was used for this purpose. The differences between the NC and the LC groups performing the HST were tested by Student's test. The SPSS 17.0 software to process statistical material and the 0.05 level of significance were used in the experiment.

3. RESULTS AND DISCUSSION

The anthropometric characteristics of the subjects are shown in Table 1.

Table 1. The anthropometric characteristics of the 10 subjects

Age (yrs)	Height (cm)	Weight (kg)	Body mass (kg)	Body fat content (%)	Surface area (m^2)
23.4 ± 2.4	184 ± 9	74 ± 7	23.7 ± 2.4	26.3 ± 1.9	2.04 ± 0.84

After the anthropometric measurements have been realized, examinations in thermo-physiological laboratory started. The summary of the results for the main thermal strain indicators (temperature and heart rate), obtained in the final minute of the exercise, is displayed in Table 2.

Table 2. Comparison of the mean values (±SD) from 10 subjects of tympanic temperature (Tty), mean skin temperature (Tsk) and heart rate (HR) with the cooling system (LC) and without it (NC) at the 45th min of HST

Parameters	NC		LC	
	t_{45}	t_{45}-t_0	t_{45}	t_{45}-t_0
Tty	37.96 ± 0.21	1.18 ± 0.34	37.47 ± 0.19	0.73 ± 0.28
Tsk	36.11 ± 0.18	0.91 ± 0.86	35.37 ± 0.15	0.4 ± 0.75
HR	138 ± 18	74 ± 12	125 ± 16	53 ± 9

The value of t_{45} represents the characteristic shown in the 45th minute of the experiment, and the value of t_{45}-t_0 is the established difference between 45th minute and the beginning of the experiment.

Tympanic temperature

The dynamics of the average Tty with and without the personal cooling system (NC and LC, respectively) are displayed in Fig. 2.

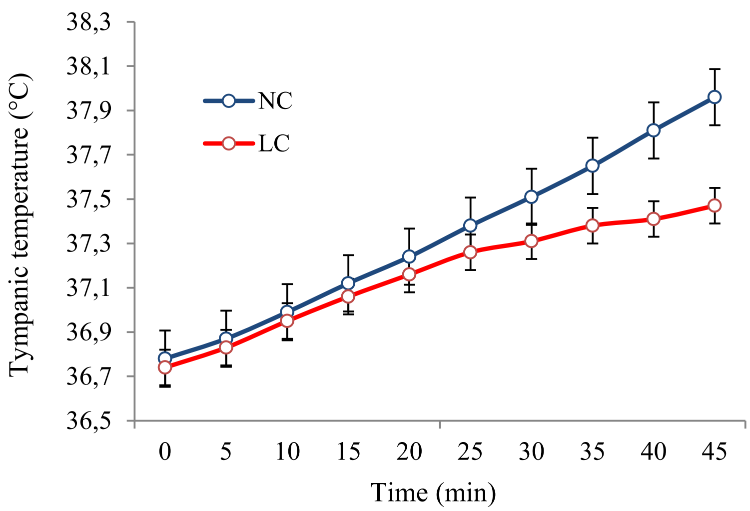

Figure 2. The mean tympanic temperature (Tty) of test subjects, with the cooling (LC) and without it (NC)

The baseline values of Tty were 36.78 °C and 36.74 °C for LC and NL, respectively. In the case with cooling, around the 25th minute the temperature began to grow noticeably slower, so in 35th minute the average Tty was 0.27 ± 0.13 °C lower for LC as compared to NC ($p<0.05$). The maximum difference of 0.49 ± 0.09 °C was recorded at the end of the HST ($p < 0.05$). Furthermore, the total temperature rises ΔTty (t_{45}-t_0) was lower in the case of cooling (0.73 ± 0.28, Table 2).

3.1. Body skin temperature

The dynamics of the average Tsk through the 45-minute long heat-stress exposures, with the cooling system and without it, are displayed in Fig. 3.

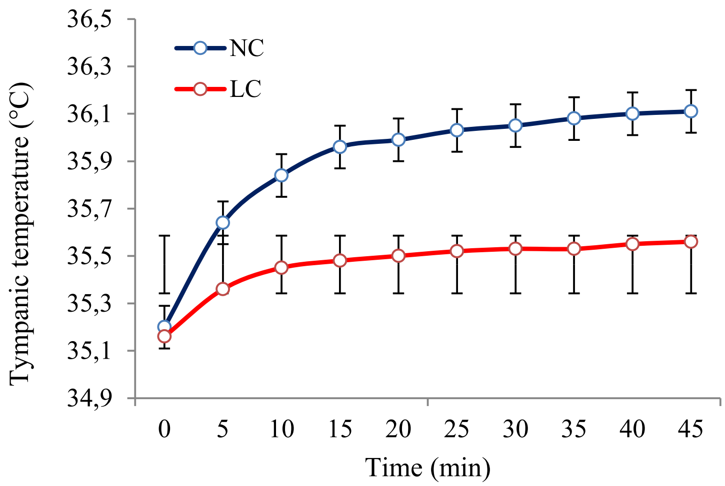

Figure 3. The mean body skin temperature (Tsk) of test subjects, with the cooling (LC) and without it (NC)

In both variants the body skin temperature was raised, in the first 15 minutes much faster than later. The highest value of Tsk was attained in the case NC in 45th minute (36.11±0.19 °C), while with the cooling vest the temperature was 35.56 ± 0.18 °C.

In the torso area (neck and scapula), significantly lower values of the skin temperature were observed with the option LC (an average of 0.75 ± 0.08 °C), as a direct consequence of the cooling vests effects, whereas, at the other two points (a leg and an arm), the measured values did not change much, as expected ($p > 0.05$).

3.2. Heart rate

Fig. 4. shows the dynamics of the average heart rates in both cases. During the experiments, there were no notable differences in the values of the heart rate. That is to say, the heart rate raised correspondingly in both cases without getting to the limit of 190 bpm in neither type of exercise.

The maximum recorded heart rate reached the value of 138 bpm, without cooling vest, in 45th minute. During the HST, in the LC case, the heart rate was lower for about 8 bpm (the maximum difference of 13 bpm was noted at the end of the HST).

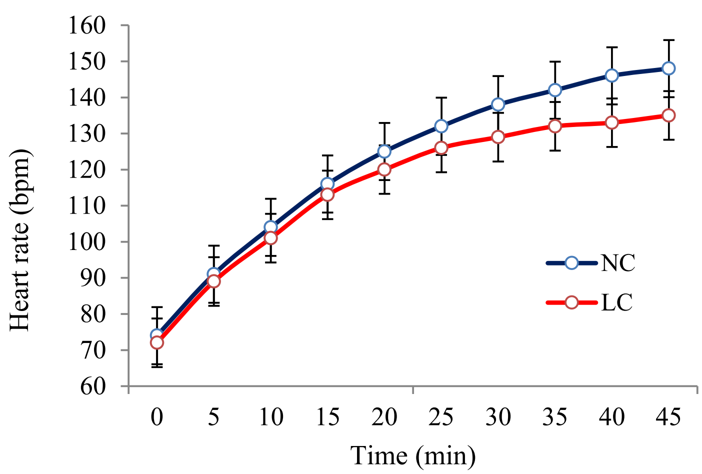

Figure 4. The mean heart rate (HR) of test subjects with the cooling (LC) and without it (NC)

3.3. Sweat rate

Sweating, as a mechanism for disclosure of excess heat, has a special importance in the thermal stress caused by physical activity, when it occurs not only as a consequence of thermal factors (increasing of body core and skin temperature), but also non-thermal factors such as central activation, activation of muscle-mechanic receptors metabolism and activation of baroreflex due to physical activity.

According to the many different definitions, sweat rate is the amount of fluids that subject lose through sweat during a workout session. In this case, the average rate of sweating, as expected, achieved a higher value in the NC variant (0.44± 0.12 $L/m^2/h$). On the other hand, the rate was significantly lower (0.31 ± 0.09 $L/m^2/h$; $p < 0.05$) when the liquid-cooled vest was applied - 45 min HST under specific environmental conditions of 40 C, 40% RH, displayed in Fig. 5.

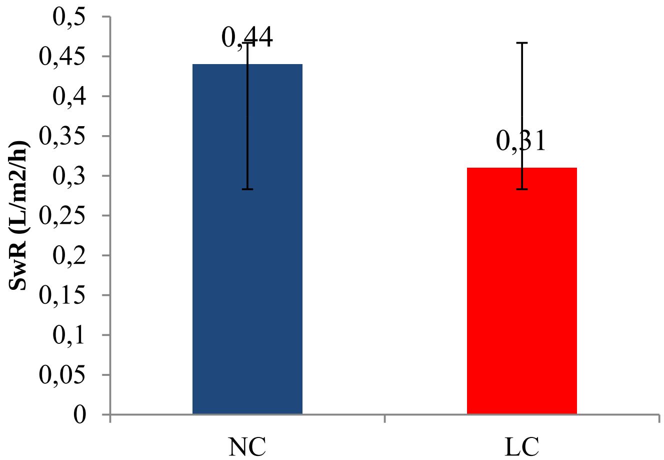

Figure 5. Comparison of the sweat rates of test subjects under specific environmental conditions

3.4. Subjective assessment of comfort

From 5th to 45th minute, the participants felt more comfortable while wearing the cooling vest than without it. The subjective assessments of the level of comfort during the exercise, with the cooling vest and without it, are shown in Fig. 6.

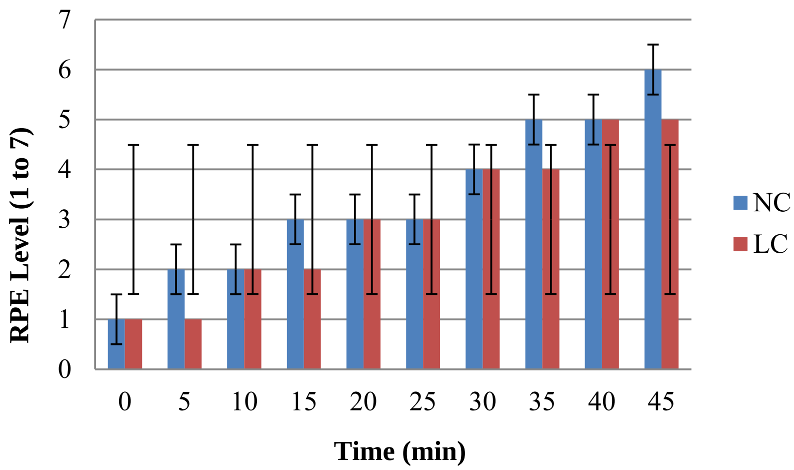

Figure 6. Comparison of the subjective assessment of test subjects with the cooling (LC) and without it (NC)

4. DISCUSSION

The obtained results are compatible with the study of A. Hadid&R.Yanovich [1], in which they tested the efficiency of the air circulation cooling system, in relation to the thermal stress that comes after physical effort. In this study, using the same methodology, cooling was provided by a personal ambient ventilation system under the ballistic vest. During the experiment, twelve male volunteers were exposed to the extreme climatic conditions of 40 °C and 35 °C during a 115 min exercise routine. A 70 min resting recovery followed when they wore a battle dress uniform and a ballistic vest, with or without cooling system.

Generally, in both climates, the use of the cooling system reduced the physiological strain caused by physical exertion, with significant benefits in nearly all of the physiological parameters tested. In contrast, during resting recovery at the same climate conditions, no differences were obtained between the exposure with the cooling and without it. In the 40 °C climate conditions, the average rate was 21% lower for the exposure when the cooling vest was worn ($p < 0.005$). In the 35/60 climate conditions, it was 25% lower ($p < 0.001$).

Somewhat similar results were shown in the work of some other authors [21], who also researched the effectiveness of an air-cooling vest to decrease thermal strain for light armour vehicle personnel. In this experiment conducted by MCLellan TM [22], seven males were subject to either hot, dry (HD, 49 °C, 10% relative humidity) or warm, humid (WH, 35 °C, 70% relative humidity) conditions and they were either given (C) or they were not given (NC) cooling through an air-vest. They all underwent 3 hours of heat-stress exposure at all times, but the rise in rectal temperature approached 2 °C during HD with NC. The data clearly show the advantage of providing microclimate cooling to lower the thermal strain of LAV (Light Armour Vehicle) crew.

Although subjects felt uncomfortable (because of a wet skin) they were able to dissipate sufficient amounts of heat through the evaporation of sweat to minimise the increase in body temperature after 3 hours of heat-stress exposure. However, as mentioned above, if the rate of heat production or activity level were increased and/or the duration of heat-stress exposure were increased, then the level of thermal strain could easily approach the values noted during the HD exposure without cooling. When cooling was applied during the warm and humid condition Tre (rectal temperature) actually decreased towards the end of the heat-stress exposure. In other words, the amount of cooling provided was greater than that required to maintain thermal equilibrium and a marginal heat debt was incurred.

One option that could be considered for the instrumentation of the micro-climate cooling system is to allow the soldier to self-regulate the cooling power based on their own subjective symptoms of thermal comfort. Not all of the environmental conditions would necessitate the use of full cooling power to reduce thermal strain and, as such, a self-regulating system would seem desirable. One issue that would need to be considered with the use of a cooling-vest is the added thermal resistance of the vest worn under conditions where cooling was not applied.

Furthermore, it has been made obvious that sweating as one of the mechanisms for removing excess heat plays an important role in thermal stress as a result of physical activity. It does not matter whether it is a result of thermal factors (increasing of body core and skin temperature), or non-thermal factors such as central activation, activation of muscle-mechanoreceptors metabolism and activation of baroreflex due to physical activity.

During the similar experiments, to appraise the design of specific liquid cooling garments, the thermal manikin wearing liquid cooling garments and heat insulation garment was put in the temperature cabin, then the inlet and outlet temperature of cooling liquid in the liquid cooling garments were measured and the heat removed was calculated [23].

5. CONCLUSION

Internal body temperatures during trainings can quite often be raised up to 40 °C. Given that fact, they are valuable and they should be researched in detail. The persons who were tested pointed out that the most beneficial factors when using the cooling systems were easier breathing and less strain.

The carried research has been based on the methods containing the relevant standards, which in this scientific field are related to thermal strain evaluation by physiological measurements (ISO 9886 and ISO 12894). For this purpose, ten healthy males have been engaged as test subjects. They have been selected out of larger group of volunteers and they've all possessed similar anthropometric characteristics. In order to gather all the necessary data a contemporary measurement device has been used (Biopac, Quinton®). It enabled the acquisition of measured, monitored and recorded physiological parameters in real-time.

After the research had been carried out using the above-mentioned body cooling system, we can conclude the following: when the cooling vest is used, the body temperature measured through the tympanic temperature grows more slowly, and the main body skin temperature is significantly lower. Besides that, the heart rate values and the subjective assessment of comfort levels point out that test subject's physiological stability represents a relevant factor from the aspect of confidence and efficiency in fulfilling different tasks.

The results undoubtedly confirm the advantages of the liquid cooling vest in reducing thermal strain of the volunteers. The tympanic temperature and the heart rate are significantly decreased when cooling is provided during exposure to hot environment. That means that cooling vests have considerable effect on reducing heat strain. As protective gears they will be used in critical chemical, biological, radiological and nuclear situations. As previous study demonstrated that a cooling vest improved performance in hot ambient conditions, future research should focus on the magnitude of cooling necessary to enhance performance of different durations and under different conditions.

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