



Physiological tolerance to uncompensated heat stress in soldiers: effects of various types of body cooling systems

Uticaj sistema za hlađenje tela na toleranciju nekompenzovanog toplotnog stresa kod vojnika u uslovima nošenja nepropusne zaštitne odeće

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Abstract

Background/Aim. In military services, emergency situations when soldiers are exposed to a combination of nuclear, biological and chemical (NBC) contamination combined with heat stress, are frequent and complex. In these specific conditions, usage of personal body cooling systems may be effective in reducing heat stress. The present study was conducted in order to evaluate the efficiency of four various types of contemporary personal body cooling systems based on the “Phase Change Material” (PCM), and its effects on soldiers’ subjective comfort and physiological performance during exertional heat stress in hot environments. **Methods.** Ten male soldiers were voluntarily subjected to exertional heat stress tests (EHSTs) consisted of walking on a treadmill (5.5 km/h) in hot conditions (40°C) in climatic chamber, wearing NBC isolating impermeable protective suits. One of the tests was performed without any additional cooling solution (NOCOOL), and four tests were performed while using different types of cooling systems: three in a form of vests and one as underwear. Physiological strain was determined by the mean skin tem-

perature (T_{sk}), tympanic temperature (T_{ty}), and heart rate values (HR), while sweat rates (SwR) indicated changes in hydration status. **Results.** In all the cases EHST induced physiological response manifested through increasing T_{ty} , HR and SwR. Compared to NOCOOL tests, when using cooling vests, T_{ty} and T_{sk} were significantly lower (on 35th min, for 0.44 ± 0.03 and $0.49 \pm 0.05^\circ\text{C}$, respectively; $p < 0.05$), as well as the average SwR ($0.17 \pm 0.03 \text{ L/m}^2/\text{h}$). When using underwear, the values of given parameters were not significantly different compared to NOCOOL tests. **Conclusions.** Using a body cooling system based on PCM in the form of vest under NBC protective clothes during physical activity in hot conditions, reduces sweating and alleviates heat stress manifested by increased core and skin temperatures and heart rate values. These effects directly improve heat tolerance, hydration state, decrease in the risk of heat illness, and extends the duration of soldiers’ exposure to extreme conditions.

Key words:

heat stress disorders; protective clothing; physical exertion, military personnel.

Apstrakt

Uvod/Cilj. Izloženost vojnika toplotnom stresu pri vanrednim situacijama gde postoji kombinacija nuklearne, biološke ili hemijske (NBH) kontaminacije i visoke spoljašnje temperature, uz nošenje nepropusnog zaštitnog odela, predstavlja veoma složen problem. U takvim situacijama, primena individualnih sistema za hlađenje tela može biti efikasna za smanjenje toplotnog stresa korisnika. Ovaj rad iznosi rezultate istraživanja na polju efikasnosti nekoliko savremenih tipova sistema za hlađenje tela izrađenih na bazi „materijala koji menjaju fazno stanje“ i njihovog uticaja na fiziološku podobnost u uslovima izloženosti fizičkom naporu i ekstremno visokim temperaturama. **Metode.** Deset vojnika

muškog pola, odevenih u NBH zaštitnu odeću izolujućeg tipa od nepropusnog materijala, izlagano je visokoj temperaturi (40°C) uz istovremeni fizički napor submaksimalnog intenziteta (hodaње na pokretnoj traci, brzinom od 5.5 km/h). Jedan test je izveden bez ikakvog rashladnog sistema (NOCOOL), a naredna četiri uz upotrebu tri tipa rashladnih prsluka i jednog rashladnog pododela. Intenzitet fiziološkog opterećenja određivan je preko sledećih pokazatelja: srednje temperature kože (T_{sk}), timpanične temperature (T_{ty}) i frekvencije srčanog rada (HR), dok je vodeno-elektrolitski status određivan preko intenziteta znojenja (SwR). **Rezultati.** U svim slučajevima fizički napor u toploj sredini izazvao je fiziološki odgovor manifestovan kroz povećanje T_{ty} , HR i SwR. U varijantama primene tri tipa rashladnih prsluka

izmerene su značajno niže vrednosti T_{ty}, T_{sk} i SwR u odnosu na NOCOOL varijantu. Vrednosti prilikom nošenja pododela nisu se statistički značajno razlikovale u odnosu na NOCOOL varijantu. **Zaključak.** Primena ispitivanih sistema za hlađenje tela na bazi PCM, u formi prsluka koji se nose ispod nepropusne NBH zaštitne odeće, ublažava povišene unutrašnje temperature tela i srednje temperature kože, a takođe ublažava povećanje frekvencije srčanog rada i znoje-

nje, čime se poboljšava fiziološka podobnost zaštitne odeće, umanjuje rizik od toplotnog stresa i istovremeno produžava vreme boravka i rada vojnika u ekstremnim temperaturnim uslovima.

Ključne reči:
stres, toplotni, poremećaji; odeća, zaštitna; fizički napor; kadar, vojni.

Introduction

Accumulation of heat, reflecting peripheral and internal body temperatures, occurs during heavy physical exertion or exposure to warm and human environment. Long-term accumulation of heat in a quantity of about 0.5 W/kg during 2 h leads to increase in body temperature that some people cannot tolerate. Heat stress can occur in compensated and uncompensated forms. The ability to compensate heat load is primarily determined by biophysical factors (environmental conditions, clothing, the intensity of physical exertion), but also moderately under influence of biological factors such as acclimatization to heat and hydration status¹.

Physiological thermoregulation involves activation of mechanisms for disclosure of excessive heat and increase blood flow through the skin, which is achieved by enhancing stroke volume and heart rate and simultaneous increasing of sweating². During physical activity in hot conditions, sweating rate up to 1–1.5 L/h is not unusual, and may even reach 2 L/h under extreme efforts, providing a potential loss of excess heat by evaporation in the amount of 4500 kJ (14 W/kg, or 1 kW for a person weighted 70 kg). In the absence of proper rehydration, this process leads to the loss of body fluids from all body compartments. In prolonged periods of exposure to hot environment, the major heat dissipation mechanism is sweat evaporation, which is proportional to the effective (exposed) skin area, water vapour pressure gradient between the skin and the environment, and water vapour permeability of clothing. Hence, when protective military clothing is worn, sweat evaporation rates decrease and heat dissipation is reduced^{3,4}. The efficiency of physiological adaptation depends on the heat amount generated in active muscles, the intensity of the workload as well as the level of biophysical heat exchange with environment⁵. Extreme situations involving NBC contamination represent a considerable problem, due to the need for specific protection of engaged personnel. Very often, execution of various operations in contaminated area, such as determination of hazard type, detection, identification, rescue missions or decontamination, request engagement of personnel wearing protective equipment of different level. In practice, it is often necessary to achieve full NBC protection, covering the whole body and respiratory system. Specialized liquid-proof, contamination-resistant clothing covers most of the body's surface area⁶. As a result, the pathways for sweat evaporation and heat exchange by radiation and convection are disrupted, particularly in the torso area, with a number of layers providing insulation between the body and environment.

Considering these facts, various body cooling systems have been developed, with the main purpose to increase comfort, as well as to reduce thermal stress. In military services, the additional benefit is increased mission duration, decreased hydration needs, improved mental acuity and physical performance maintenance. Many systems are developed, yet they generally may be classified in five basic groups: evaporative cooling products, products based on phase change materials (PCM), compressed air systems, liquid circulation systems and thermoelectric systems⁷.

The aim of this study was to investigate the efficiency of cooling vest type system based on PCM. PCM is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and *vice versa*; thus, PCM are classified as latent heat storage units⁸.

This study investigated the efficiency of various types of body cooling systems in simulated conditions, similar to possible real extreme situations, using exertional heat stress test protocols previously developed in our laboratory^{9,10}. The main goal was to test the effects of cooling vests worn under NBC protective suit on subjective comfort and physiological strain during physical effort in hot environment. We hypothesized that cooling systems would alleviate soldiers physiological strain and extend previously limited duration of work while wearing isolating protective equipments in extremely hot conditions. It is reasonably assumed that it could increase the ability of military personnel to successfully complete any mission in conditions of possible chemical, biological, or nuclear threat.

Methods

The participants of this study were 10 male professional soldiers aged 25.8 ± 2.4 years, with similar anthropometric and ergometric characteristics. The subjects were briefed on the nature of the experiment, its purpose, conditions, safety measures, and potential risks. Each participant read and signed an informed consent form, in accordance to the standards of medical safety during examination in extreme hot or cold environment¹¹. The protocol for investigation was approved by competent Ethical Committee. The procedures performed in the present study corresponded to the standards or thermal strain evaluation by physiological measurements¹².

Exertional heat stress tests (EHSTs) were conducted in a climatic chamber in the Military Medical Academy, Bel-

grade, Institute of Hygiene, during May to September 2011. During EHSTs, participants wore individual isolating protective equipment used by specialized NBC military units of the Serbian Armed Forces. The equipment consists of a protective overall (made of polyester textile with both surfaces rubberized with butyl and caoutchouc-based compound), protective mask (model with phonic unit), double-layer gloves (rubber material, inside lined with cotton), and boots. The protective capacity of unused overall against drops of toxic agents is not less than 150 min, while after five alternative contaminations and decontaminations not less than 105 min. The material does not burn out under the effects of thermal impulse of at least 52 J/cm^2 , and sustains nuclear explosion of 30 kT for at least 10 s. In contact with drops of burning napalm compound, the overall does not burn out for at least 10 s.

Each of ten subjects performed five EHSTs in full protective equipment, without any cooling system (the NOCOOL) and with various cooling systems worn under the protective garment. Four different types of PCM cooling systems were tested: a model with crystal balls inside the vest which swell into biodegradable viscose gel by initial soaking in water (the model A); a model with cooling packs inserted into specially designed pockets inside the vest, with the ability to freeze at 18.3°C (the model T); a model with "phase core elements", i.e. salt mixture sealed inside an aluminium wrapper, in a form of 22 cartridges installed into special pockets, with activation point at 28°C (the model S); cooling underwear made of microcapsules from non-toxic paraffin placed in a durable membrane ($3.000.000 \text{ microcapsules/cm}^2$), obtained by polymerization of melamine-formaldehyde (the model O).

All EHSTs were performed under the same air temperature (40°C , relative humidity $30 \pm 3\%$) by walking on a motorized treadmill (speed 5.5 km/h). Skin temperatures (Tsk) were measured continuously using contact probes with transducers TSD202E and TSD202F (precision

monitored and recorded in real-time using a physiological data monitoring system (MP150 SKT100C, BIOPAC Systems Inc. USA). Heart rates (HR) were continuously telemetrically monitored (Q4500 Exercise Test Monitor, Quinton instruments, USA), and recorded every 5 min. Sweat loss was calculated as the difference between pre-test and post-test nude body weight. Sweat rates (SwR) were expressed per hour per square meter of body surface ($\text{L/m}^2/\text{h}$).

Considering given temperature conditions and physical exertion level, duration of the test was limited to maximally 45 min, while criteria for early termination were: achieving critical value of Tty (39.5°C), or HR (190 bpm), or subjecting feeling of unbearable strain^{13,14}.

The data are presented as mean \pm SD. The normal distribution was tested by the Shapiro-Wilk test. The significance of differences between the parameters obtained during tests without cooling systems (the NOCOOL group) and with cooling systems (the A, S, T, and O groups) at the end of EHST was tested by the Student's *t*-test, with significance level $p < 0.05$.

Results

None of the soldiers during or after EHSTs showed any symptom of heat stroke or severe heat exhaustion. Mean test durations without cooling systems and with cooling systems were 35 minutes and 45 minutes, respectively. In the NOCOOL group, 2 soldiers completed the test, in 7 cases the tests were terminated due to subjective intolerable strain, and in 1 case due to reaching Tty limit. Contrary, when cooling systems were used, in 85% of the cases the 45-minutes test was completed, and the Tty barrier was never reached. The average duration of the test when cooling was used was 10 minutes longer compared to that to the NOCOOL condition. The summary of the results for temperatures and heart rates are displayed in Table 1.

Table 1
Comparison of the means for temperatures and heart rates (HR) during exertional heat stress tests (EHST)

Parameters	NOCOOL, 35th min, 40°C	With cooling, 45th min, 40°C			
		A	S	T	O
Tty ($^\circ\text{C}$)	38.88 ± 0.12	38.6 ± 0.18	38.85 ± 0.14	38.97 ± 0.08	38.9 ± 0.09
Tsk ($^\circ\text{C}$)	38.22 ± 0.26	37.9 ± 0.22	38.20 ± 0.14	37.78 ± 0.18	38.37 ± 0.11
HR (bpm)	170 ± 14	162 ± 12	166 ± 15	160 ± 12	173 ± 10

Data given as $\bar{x} \pm \text{SD}$; Tty – tympanic temperature; Tsk – skin temperature; NOCOOL – no cooling system; A, S, T, O – models with cooling systems (for details see Methods)

$\pm 0.2^\circ\text{C}$, range $0\text{--}60^\circ\text{C}$, response time 0.9 s; BIOPAC Systems Inc. USA). The thermistors were set at 4 locations (neck, right scapula, left hand, and right shin). The mean Tsk was calculated every 5 minutes from the values obtained and weighted¹². Core (tympanic) temperatures (Tty) were continuously measured using contact probe TSD202A (precision $\pm 0.1^\circ\text{C}$, range $20\text{--}50^\circ\text{C}$, response time 0.6 s) with transducer introduced into the auditory canal and placed toward the eardrum. The temperatures were registered every 10 sec. All measurements were automatically

Comparable reviews of Tty values during EHST are displayed in Figure 1. The mean Tty in the NOCOOL increased from $36.30 \pm 0.15^\circ\text{C}$ at the start to $38.88 \pm 0.12^\circ\text{C}$ at the end of test (35th minute). With cooling systems, after 10th min Tty began to grow slower. Compared to the NOCOOL, in 35th min the mean Tty was lower for $0.59 \pm 0.04^\circ\text{C}$ (model A), $0.35 \pm 0.03^\circ\text{C}$ (S), and $0.38 \pm 0.02^\circ\text{C}$ (T). During entire duration of EHST, the mean values of Tty did not differ between the NOCOOL and the O group; $p > 0.05$.

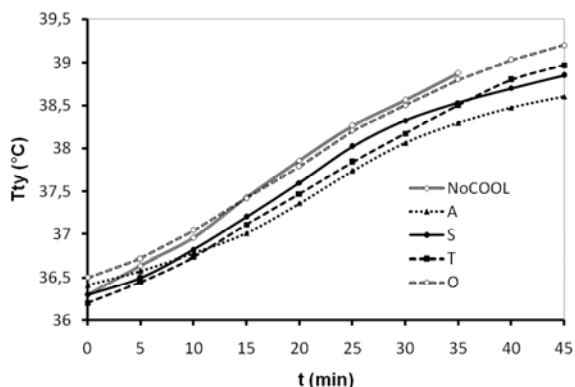


Fig. 1 – The mean tympanic temperatures (T_{ty}) during the exertional heat stress tests (EHSTs).

NOCOOL – no cooling system; A, S, T, O – models with cooling systems (for details see Methods).

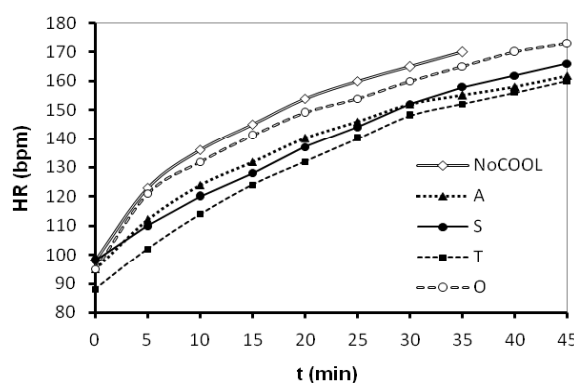


Fig. 3 – The mean heart rates (HR) during the exertional heat stress tests (EHSTs).

NOCOOL – no cooling system; A, S, T, O – models with cooling systems (for details see Methods).

Comparable reviews of T_{sk} values during EHST are displayed in Figure 2. Body skin temperatures increased in a similar pattern in all the groups, rapidly during the first 15 min (until sweating occurred), and then slowed towards the end of the test. When cooling systems were used, the mean T_{sk} values were significantly lower. The lowest values were recorded in the T group, with a significant difference as compared to both the S and the O groups (on 35th min: 37.45 ± 0.15°C (T) vs 38.07 ± 0.12°C (S); and 38.04 ± 0.09°C (O); *p* < 0.05). At the end of EHST, mean T_{sk} in the NOCOOL group (35th min) was 38.22 ± 0.26°C, and with cooling systems mean T_{sk} values at the end (45th min) were: 37.9 ± 0.22°C (A), 38.2 ± 0.14°C (S), 37.78 ± 0.18°C (T), and 38.37 ± 0.11°C (O), *p* < 0.05).

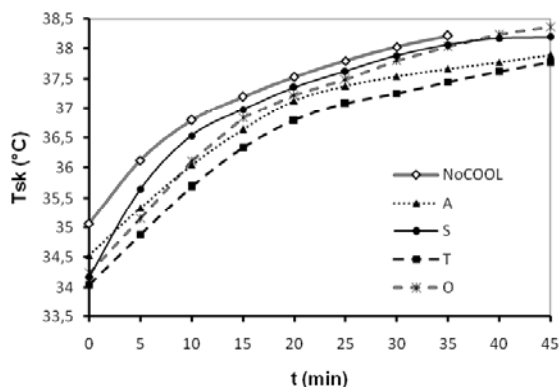


Fig. 2 – The mean skin temperatures (T_{sk}) during the exertional heat stress tests (EHSTs).

NOCOOL – no cooling system; A, S, T, O – models with cooling systems (for details see Methods).

The dynamics of the average heart rate values are displayed in Figure 3. During entire tests, there were no significant differences in HR values between the groups. Heart rates increased in similar manner in all the groups constantly toward the end of the tests, but the limit of 190 bpm was not reached during any single EHST. Maximum recorded HRs in subjects without cooling and with cooling systems were 179 and 166 bpm, respectively.

In order to minimize the differences regarding EHST durations, SwR was expressed per hour. The average rate of sweating, as expected, was the highest in the NOCOOL group (0.68 ± 0.04 L/m²/h). In the O group, the mean SwR was similar to the NOCOOL group (0.65 ± 0.08 L/m²/h). In the other three groups, the recorded values were similar with each other, and significantly lower compared to the NOCOOL and the O groups: 0.52 ± 0.12 L/m²/h (A), 0.54 ± 0.08 L/m²/h (S), 0.48 ± 0.14 L/m²/h (T), *p* < 0.01 (Figure 4).

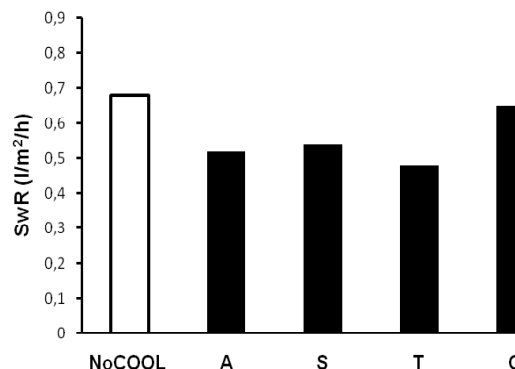


Fig. 4 – The mean sweat rates (SWR) during the exertional heat stress tests (EHSTs).

NOCOOL – no cooling system; A, S, T, O – models with cooling systems (for details see Methods).

Discussion

Impaired physical, cognitive, and working abilities is a well-known consequence of heat strain⁹. This is particularly important for military services. Core temperature (T_c) is considered as a relevant indicator of thermal strain², and tympanic thermometry is reliable method for monitoring changes in core temperature during physical activity¹⁵. While carrying our specific military tasks and missions, military training guidelines tolerate high level of body core temperature, even up to 40°C¹⁶. Sawka et al.¹⁷ reported similar T_c (39.4°C) at exhaustion. Study of Nag et al.¹⁴ with 11 male volunteers who did ergometric work at an intensity of 60% VO_{2max} suggests the tolerable limit of short duration

human exposure in heat (40–45 min) is at T_c 39°C. Considering the fact that these values of T_c are possible and common during NBC missions, they deserve to be investigated.

In our study a very small number of subjects even without cooling systems, terminated test before 45th min. This relatively good tolerance to heat may be attributed to high fitness level, considering their regular engagement in strenuous physical activity related to professional services. Fit individuals can tolerate higher values of T_c during heat stress before exhaustion (as much as 0.9°C) compared to unfit and untrained¹⁸.

Protective clothing worn by the participants was made of butyl rubber – a waterproof material, isolated type, which prevents disclosure of excessive heat through evaporation of sweat. Cooling vests covering only the torso area (A, S, and T) showed better results than O underwear. This is confirmed also by the soldiers subjective feeling, because from the total number of subjects who interrupted EHST, 72% were dressed in O. This is in agreement with the results reported by Montain et al.⁵. In their study seven acclimatized men attempted treadmill walks at 43°C wearing full of partial protective clothing. The authors determined that partial encapsulation results in physiological tolerance similar to that reported for unclothed persons. In situations when full encapsulation in protective clothing is necessary, cooling systems that enable heat dissipation from part of the body surface may be effective solution. Since the torso area has the greatest capacity for heat dissipation (both by evaporative cooling and heat conduction) of all the body surfaces, cooling strategies that put emphasis on the torso area promise the best results.

As the greatest benefit of all cooling systems the subjects cited easier breathing and less strain compared to tests without cooling. Alleviation of physical exertion is a result of less cardiovascular strain, as a consequence of slower increase of T_{ty} . This was reflected on lower values of heart rates while using cooling systems; mean HRs on 35th min in these groups were lower by 15 bpm (A), 12 bpm (S), and 18 bpm (T) compared to the NOCOOL group. The limit of 190 bpm was not reached during any single EHST. Maximum recorded HRs in the subjects without cooling and with cooling systems were 179 and 166 bpm, respectively. In despite of increased cardiovascular strain, the subjects maintained the given level of physical activity during the EHST. These results are in agreement with the suggestion of Ftaiti et al.¹⁹ who reported that, in trained subjects, exercise-induced hyperthermia had only minor effects on the neuromuscular performance. In their study, six trained males ran on a treadmill at 65% of their VO_{2max} while wearing impermeable suit. After 40 minutes, their physiological status was close to exhaustion, with average HR of 196 ± 8 bpm and T_{ty} $40 \pm 0.3^\circ\text{C}$, however, they managed to maintain the given intensity of physical work.

Evaporation of sweat as a mechanism for dissipation of excess heat has a special importance in heat stress caused by physical activity, when it occurs not only as a consequence of thermal factors (increasing of T_c and T_{sk}), but also non-thermal factors such as central activation, activation of mus-

cle-mechanoreceptors metabolism and activation of baroreflex due to physical activity. According to our test results, the rate of sweating is lower when using body cooling systems average for 0.13 L/m²/h (25%). This represents a significant percentage considering the impermeable material that behaves as heat transfer barrier. Our results indicate that the usage of cooling vests can spare a quarter of total sweat loss, which can contribute to prevention of dehydration during military missions while wearing NBC clothing.

Our results have confirmed that the cooling system based on PCM in the form of vest covering the torso show effectiveness in combination with protective clothing isolating type, while cooling underwear practically does not give significant results. According to our experience, cooling underwear tends to become soaked with sweat during testing. On one hand, wet underwear impairs evaporation of sweat, and on the other hand, it adds some weight and compromises body movements. Both facts mentioned above influence the thermal comfort of our subjects, making this variant of cooling less effective in given conditions.

Our results are consistent with the study of Hadid et al.⁴ who carried out investigation on effects of the cooling system based on air circulation on thermal stress caused by physical effort in soldiers. In their study, done by the similar methodology, the ballistic vests were used instead of protective clothing, while cooling was provided by using personal ambient ventilation system (blowing air from the environment using two small fans with batteries, with total supply of approximately 180 L/min of air). Twelve male volunteers were exposed to climatic conditions of 40°C/ 40% relative humidity, and 35°C/ 60% relative humidity, during two cycles of exercise/rest periods (total exercise time 100 min, total exposure with rest 180 min), while wearing a battle dress uniform and a ballistic vest, with cooling system and without it. Compared to the condition without cooling, mean skin temperatures while cooling were significantly lower in both exercise periods (by $0.9 \pm 0.4^\circ\text{C}$ in 40/40 condition, and by $0.6 \pm 0.5^\circ\text{C}$ in 35/60 condition) and dropped faster in rest periods. The mean values of heart rates and core temperatures (measured rectally), were lower with cooling systems, but a statistical difference was not reported except for several time points. In this study, the most evident influence of the cooling system was on sweat rate, which was by 21% and 25% lower, ($p < 0.05$); for 40/40 and 35/60 climate conditions, respectively. Considering a larger body surface covered with impermeable suit in our investigation, we assume that our results confirm the effectiveness of the used cooling systems on fluid balance maintenance during uncompensated heat stress.

Conclusion

Evaluation of various cooling system effectiveness led as to the two important conclusions: in case of cooling garment wearing in a form of vest covering the torso area (A, S, and T variants) body core temperature (measured through tympanic temperature) grow slower, and the mean body skin temperature is significantly lower. Moreover, heart rate val-

ues and subjective comfort point to a much expressed soldiers' physiological stability, which is a very important result from the aspect of confidence and efficiency in fulfilling the given military missions.

Finally, the conducted laboratory tests based on a specific methodology, confirm that the use of a PCM personal body cooling vest under the NBC protective impermeable equipment significantly improves physiological suitability of the equipment in soldiers who conduct tasks and missions in extreme situations including high outside temperature and

highly toxic contamination, and allow them to prolong mission duration.

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