ORIGINAL ARTICLE
(CC BY-SA)

UDC: 355/359:61]:[612.766.1:612.59
DOI: https://doi.org/10.2298/VSP211012099M

Relationship between heat storage and parameters of thermotolerance and fatigue in exertional heat stress

Povezanost između stepena akumulacije toplote u organizmu i pokazatelja termotolerancije i zamora kod toplotnog stresa usled fizičkog napora u uslovima povišene temperature spoljne sredine

Siniša T. Mašić*, Sonja S. Marjanović†, Jelena M. Stojićević*, Vanja M. Jovanović‡, Mirjana V. Joksimović§, Danijela Ilić‖

Military Medical Academy, *Institute of Hygiene, ‡Institute of Occupational Medicine, §Institute of Nuclear Medicine, Belgrade, Serbia; †University of Defence, Faculty of Medicine of the Military Medical Academy, Belgrade, Serbia; ‖University of Priština, Faculty of Medicine, Kosovska Mitrovica, Serbia

Abstract

Background/Aim. The risk assessment of heat illness and fatigue development is essential in military service. The aim of our study was to investigate the relationship between heat storage and various psychophysiological parameters of heat stress, as well as potential peripheral markers of fatigue in soldiers performing exertional heat stress tests. **Methods.** Fifteen young, healthy, and unacclimatized men underwent an exertional heat stress test (EHST) with the submaximal workload in warm conditions (WBGT 29 °C) in a climatic chamber. Every 10 min, the following parameters of thermotolerance were measured or calculated: core temperature (Tc), mean skin (Tsk) and body temperature (Tb), heart rate (HR), heat storage (HS), physiological strain index (PSI), as well as peripheral markers of fatigue [blood concentrations of ammonia, urea nitrogen (BUN), lactate dehydrogenase (LDH), cortisol and prolactin] and subjective parameters: thermal sensation (TS) and rate of perceived exertion (RPE). **Results**. Tolerance time varied from 45 to 75 min (mean 63 ± 7.7 min). Average values of Tc, Tb, and HR constantly increased during EHST, while Tsk reached the plateau after 10 min. Concentrations of all investigated peripheral markers of fatigue were significantly higher after EHST compared to baseline levels (31.47 ± 7.29 vs. 11.8 ± 1.11 μmol/L for ammonia; 5.92 ± 0.73 vs. 4.69 ± 0.74 mmol/L for BUN, 187.27 ±2 8.49 vs.152.7 3± 23.39 U/L for LDH, 743.43 ± 206.19 vs. 558.79 ± 113.34 mmol/L for cortisol, and 418.08 ± 157.14 vs. 138.79 ± 92.83 μIU/mL for prolactin). **Conclusions**. This study demonstrates the relationship between heat storage and Tc, HR, TS, and RPE, but also with PSI. Concentrations of cortisol and especially prolactin showed a significant correlation with parameters of thermotolerance.

Key words:
body temperature; heat stress disorders; hormones; military personnel; physical exertion.

Apstrakt

Uvod/Cilj. Procena rizika od nastanka zamora i nekog oblika toplotne bolesti je od velikog značaja za vojnu službu. Cilj ovog istraživanja bio je da se utvrdi povezanost između stepena akumulacije toplote i različitih psihofizioloških parametara toplotnog stresa, kao i mogućih perifernih markera zamora u populaciji vojnika izloženih toplotnom stresu kombinovanim sa fizičkim naporom. **Metode**. Petnaest mladih, zdravih, utreniranih i neaklimatizovanih muškaraca podvrgnuto je testu toplotnog stresa (TTS) tokom fizičke aktivnosti submaksimalnog opterećenja u uslovima povišene temperature spoljne sredine (29 °C) u klimatskoj komori. Na svakih 10 min registrovane su ili izračunavane vrednosti sledećih parametara termotolerancije: unutrašnje (timpanične) temperature (Tu), srednje temperature kože (Tsk), temperature tela (Tt), frekvence srčanog rada (FSR), akumulacije toplote (AT), indeksa fiziološkog napora (IFN), kao i perifernih markera zamora [koncentracije amonijaka, uree u krvi (BUN), laktat—dehidrogenaze (LDH) kortizola i prolaktina] i subjektivnih parametara – osećaja toplote (OT) i stepena napora (SN). **Rezultati**. Vreme tolerancije variralo je između 45 i 75 min (srednja vrednost 63 ± 7,7 min). Prosečne vrednosti Tu, Tt i FSR konstantno su rasle tokom TTS, dok je Tsk dostigla plato nakon prvih 10 min. Vrednosti svih ispitivanih perifernih markera zamora bile su značajno veće nakon TTS u odnosu na vrednosti pre testa (amonijak 31,47 ± 7,29 vs. 11,8 ± 1,11 μmol/L, BUN 5,92 ± 0,73 vs. 4,69 ± 0,74

Correspondence to: Sonja Marjanović, University of Defence, Faculty of Medicine of the Military Medical Academy, Crnotravska 17, 11 000 Belgrade, Serbia. E-mail: sonja.radakovic@vma.mod.gov.rs

mmol/L, LDH 187,27 ± 28,49 vs. 152,73 ± 23,39 U/L, kortizol 743,43 ± 206,19 vs. 558,79 ± 113,34 mmol/L i prolaktin 418,08 ± 157,14 vs. 138,79 ± 92,83 μIU/mL). **Zaključak**. Rezultati su ukazali na povezanost između stepena akumulacije toplote i Tu, FSR, OT i SN, ali takođe i IFN. Koncentracije kortizola i, naročito, prolaktina pokazale su značajnu povezanost sa parametrima termotolerancije.

Ključne reči:
telesna temperatura; stres uzrokovan toplotom, poremećaji; hormoni; kadar, vojni; napor, fizički.

Introduction

Fatigue is generally a useful mechanism in preventing harmful exertion and damage to the organism. On the other hand, the development of fatigue/exhaustion during strenuous physical work is of major importance for performance in the context of sports activities as well as in military service. There are several physiological and psychological factors related to the onset of fatigue: environmental conditions (especially high temperature and/or high humidity), duration and intensity of physical activity, supplementation, hydration status, motivation, and level of physical fitness. The feeling of fatigue is triggered by complex processes resulting from peripheral and central factors. Peripheral fatigue occurs within the muscle and is related to impairment in neuromuscular and muscular structures and functions [1], while central fatigue considers alterations in efferent neurons and impaired neurochemistry in the brain, such as the interplay between dopamine and serotonin, which affects mood and motivation [2]. Hence, some peripheral parameters in the blood may serve as markers of fatigue, such as lactate, ammonia, stress hormones, and pro-inflammatory interleukins [3].

The risk assessment of heat illness development is also essential in military service. There are numerous indices used in the prediction of excess heat strain during physical activity in hot conditions. The most commonly used are environmental parameters or their combination, such as Wet Bulb Globe Thermometer (WBGT) [4]. Furthermore, physiological parameters of thermotolerance are also used, such as core (tympanic) temperatures (Tc) and skin temperatures (Tsk) and heart rate (HR), with models developed to predict heat stress, such as physiological strain index (PSI). Estimating heat storage in the body is also used to evaluate both fatigue and the potential risk of overheating. Finally, some subjective parameters such as thermal sensation (TS) and rate of perceived exertion (RPE) may also serve in the prediction of the development of heat strain and fatigue [5].

Considering the importance of heat strain and fatigue in military personnel, the aim of our study was to investigate the relationship between heat storage and various psychophysiological parameters as well as potential peripheral markers of fatigue in soldiers performing an exertional heat stress test (EHST).

Methods

The study population consisted of 15 male soldiers aged 19–21, healthy, fit, and unacclimatized. The investigation was conducted at the Military Medical Academy (MMA) in Belgrade, Serbia designed as an experimental study. The study was conducted according to ethical principles for investigations in biomedical science, and signed informed consent was obtained from each participant. The subjects performed an EHST by walking on a treadmill with a submaximal workload in warm conditions [40 °C, WBGT 29 °C] in a climatic chamber (Weiss Technik, Germany). Tc and mean Tsk, as well as HR, were continuously measured every 10 min using a system for data acquisition MP 150 SKT100C (BIO PAC Systems Inc., USA) and Q4500 Exercise Test Monitor (Quinton Instruments, USA), respectively. Detailed descriptions of methods of temperature measurements were presented in our previous study [6]. The protocol of EHST and criteria for termination were also previously presented [7]. Before and immediately after EHST, venous blood samples were collected for analysis of peripheral markers of fatigue: concentrations of ammonia, blood urea nitrogen (BUN), lactate dehydrogenase (LDH), cortisol, and prolactin, and analyzed at the Institute of Medical Biochemistry, MMA. At the beginning of the EHST and every 10 min during the test, as well as at the moment when the subjects finished their tests, they assessed their subjective TS and RPE using a modified Gagge 8-point scale [8] with verbal descriptions between “cool” (ranking 5) and “unbearably hot” (ranking 13), and Borg 15-point scale of RPE [9] with verbal descriptions of physical workload between “very, very light” (ranking 6) and “very, very hard” (ranking 20), respectively.

Calculations

Body temperature (Tb) was calculated as:

$$K * Tc + (1 - K) * Tsk$$

In warm conditions, K has a constant value of 0.9 [10].

We used Tikuisis’ modification of Moran’s calculation for:

$$\mathrm{PSI} = 5 * \frac{\mathrm{Tc} - \mathrm{Tc}(0)}{39.5 - \mathrm{Tc}(0)} + 5 * \frac{\mathrm{HR} - \mathrm{HR}(0)}{180 - \mathrm{HR}\ (0)}$$

where Tc and HR represent current values of tympanic temperature and heart rate, while Tc (0) and HR (0) represent values of the same parameters at rest [5].

Heat storage (HS) was determined using Havenith’s calculation as follows:

$$\mathrm{HS} = ((0.8 * (\mathrm{Tc} - \mathrm{Tc}(0)) + (0.2 * (\mathrm{Tsk} - \mathrm{Tsk}(0))) * 3.49\ \mathrm{J/g}$$

where Tsk represents the current value of mean skin temperature, Tsk(0) represents the initial mean skin temperature, and 3.49 J/g is the specific heat of body tissues [11].

Since some subjects had shorter exposures than others, we introduced the rate of change (ROC) in investigated parameters with calculation as follows [12]:

$$\mathrm{ROC}\ (\mathrm{x}) = \frac{\mathrm{x}\ (\mathrm{end}) - \mathrm{x}\ (0)}{\mathrm{T}}$$

where x (end) is the investigated parameter (Tc, HR, PSI, HS, TS, RPE) at the end-point of EHST, x (0) is the value of the same parameter before the start, and T is the total exercise time.

Statistical analysis

The normality of data was tested by the Kolmogorov-Smirnov test. Data were presented as mean ± standard deviation (SD). The significance of differences between time points was tested using a *t*-test and Tukey's test for pairwise comparisons. The significance of relations was tested using the Pearson's correlation test. The statistical significance was accepted at $p < 0.05$. All statistical analyses were performed using SPSS 18 package (Chicago, USA).

Results

The baseline anthropometric and ergometric characteristics of the participants are presented in Table 1.

Tolerance time before termination of EHST (due to reaching the ethical barrier for Tc of 39.5 °C or unbearable subjective discomfort) varied between 45 and 75 min (the average time was 63 ± 7.70 min). Average values of core and body temperatures were very close and constantly increased during EHST, while mean skin temperature reached the plateau after the first 10 min, i.e., when sweating occurred (Figure 1). The average HR increased in the same manner (Figure 2).

Table 1

Anthropometric and ergometric characteristics of subjects

Characteristic	Mean ± SD	Range
Body weight (kg)	76.14 ± 7.12	65.86–88.32
Body mass index (kg/m^2)	22.9 ± 1.82	20.3–25.8
Body surface area (m^2)	1.97 ± 0.09	1.84–2.14
Body fat (%)	17.53 ± 3.33	13.8–23.1
LBM (kg)	62.77 ± 5.15	55.65–72.89
VO_{2max} (mL/kg LBM)	68.22 ± 12.16	52.13–89.98

LBM – lean body mass; VO_{2max} – maximal oxygen consumption; SD – standard deviation.

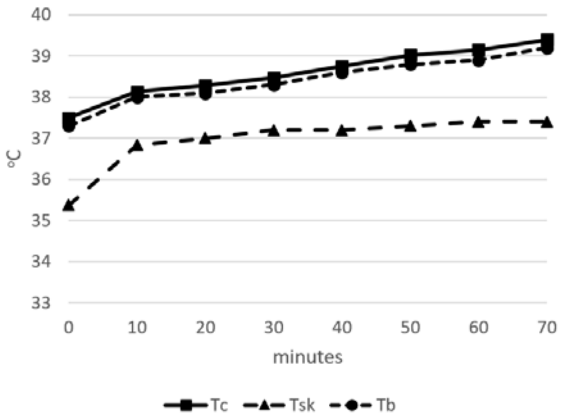

Fig. 1 – Average values of core, skin, and body temperatures during EHST.
EHST – exertional heat stress test; Tc – core (tympanic) temperature;
Tsk – mean skin temperature; Tb – body temperature.

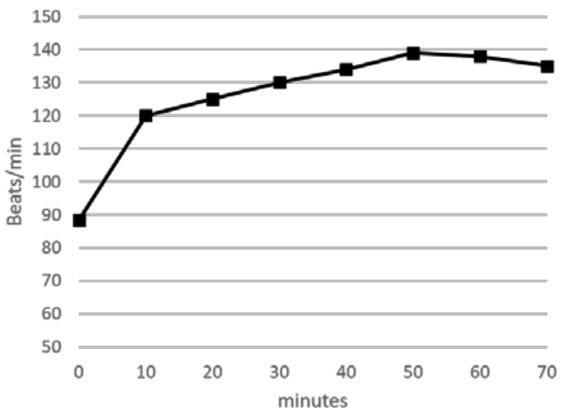

Fig. 2 – Average values of heart rate during EHST.
EHST – exertional heat stress test.

Values of all investigated peripheral parameters of fatigue were significantly higher after EHST compared to basal values (Table 2).

Average values of HS and levels of PSI constantly increased during EHST, following an almost identical pattern (Figure 3). Subjective measures of TS increased in the first 40 min, and after that, we recorded the plateau close to maximal values for the given scale, while RPE values continued to rise to the end of the test, approaching the maximal value (Figure 4).

Heat storage strongly correlated with average levels of Tc in time points between 10 and 60 min: r values varied between 0.6061 ($p < 0.05$) and 0.7894 ($p < 0.01$). HS also correlated with average HR from 20 to 60 min (r values varied between 0.54484 and 0.8498), and the strongest correlation was recorded with PSI in time points between 10 and 60 min (r values varied between 0.6778 and 0.8451). On the other hand, RPE showed a significant correlation to parameters of thermotolerance (Tc, HR, and PSI) only in the second half of the test, i.e., between 40 and 60 min (values of r coefficient varied between 0.5266 and 0.8498).

When analyzing the end-point values (the last measured values at the moment of exhaustion) of all the parameters of thermotolerance, TS, and peripheral markers of fatigue, only values of RPE and prolactin significantly correlated with HS [r = 0.59221 ($p < 0.05$) and r = 0.5516 ($p < 0.05$), respectively). There was also a significant correlation between end-point HS and VO_{2max} (r = 0.564983; $p < 0.05$), but not with

Table 2

Average concentrations of peripheral markers of fatigue before and after EHST

Marker	Before EHST	After EHST	*p*
Ammonia (μmol/L)	11.8 ± 1.11	31.47 ± 7.29	< 0.001
BUN (mmol/L)	4.69 ± 0.74	5.92 ± 0.73	< 0.001
LDH (U/L)	152.73 ± 23.39	187.27 ± 28.49	< 0.001
Cortisol (mmol/L)	558.78 ± 113.34	743.43 ± 206.19	= 0.001
Prolactin (μIU/mL)	138.79 ± 92.83	418.08 ± 157.14	< 0.001

EHST – exertional heat stress test; BUN – blood urea nitrogen; LDH – lactate dehydrogenase.

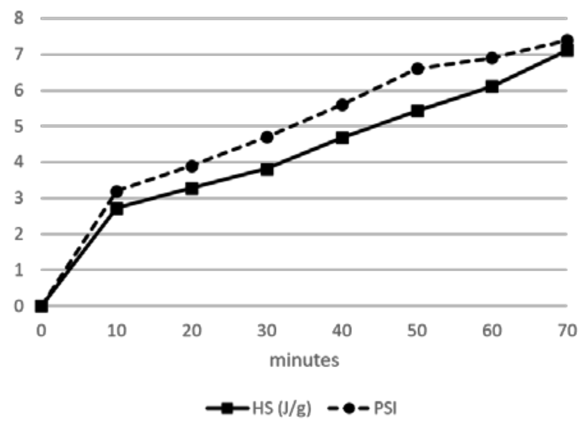

Fig. 3 – Average values of heat storage (HS) and physiological strain index (PSI) during EHST. EHST – exertional heat stress test.

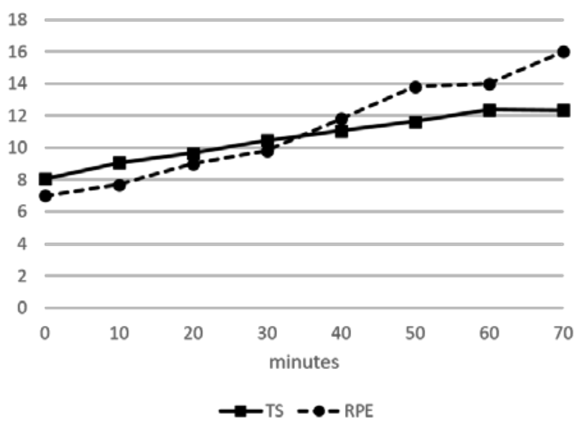

Fig. 4 – Average values of TS and RPE during EHST. TS – thermal sensation (modified Gagge's scale); RPE – rate of perceived exertion (Borg's scale); EHST – exertional heat stress test.

any anthropometric parameter whatsoever. The concentration of prolactin at the end of EHST significantly correlated with end-point values of thermotolerance: Tc, HR, and PSI (r = 0.5306; r = 0.5758; r = 0.6126, respectively; $p < 0.05$). The correlation was also highly significant between prolactin concentrations and RPE (r = 0.750084; $p < 0.001$) but not with TS.

In order to incorporate the tolerance time, we calculated rates of change in parameters of thermotolerance and fatigue between values at the very end of the EHST and the start values (Table 3).

Table 3

Rate of change (ROC) in parameters of thermotolerance and fatigue

ROC	Values
HS (J/g/min)	0.112 ± 0.016
Tc (°C/min)	0.032 ± 0.005
Tb (°C/min)	0.032 ± 0.004
HR (beat/min)	1.03 ± 0.30
PSI	0.135 ± 0.028
TS	0.064 ± 0.009
RPE	0.152 ± 0.040
Ammonia (µmol/L/min)	0.315 ± 0.142
BUN (mmol/L/min)	0.021 ± 0.008
LDH (U/L/min)	0.522 ± 0.203
Cortisol (mmol/L/min)	3.080 ± 2.255
Prolactin (µIU/mL)	4.44 ± 1.76

HS – heat storage; Tc – core temperature; Tb – body temperature; HR – heart rate; PSI – physiological strain index; TS – thermal sensation; RPE – rate of perceived exertion; BUN – blood urea nitrogen; LDH – lactate dehydrogenase.

When we introduced the ROC values, we found an even stronger correlation between HS and ROC RPE (r = 0.68311; $p < 0.01$), but the correlation between HS and ROC HR was also significant (r = 0.5915; $p = 0.05$).

We also analyzed the relationship between the rate of change in heat storage, i.e., the speed of increase in body heat, and end-point values of other investigated parameters. The ROC HS showed a statistically highly significant correlation with end-point values of HR and PSI (r = 0.636531; $p < 0.01$ and r = 0.570339; $p < 0.05$, respectively), as well as with concentration of prolactin after EHST (r = 0.51278; $p < 0.05$). The significance was borderline in the relation between ROC HS and values after EHST of two other peripheral markers of fatigue: concentrations of LDH and cortisol (r = 0.41812; $p = 0.054$ and r = 0.45442; $p = 0.051$, respectively).

Discussion

The high ambient temperature combined with physical activity plays an important role in physically demanding occupations such as military service [13]. Acclimatization is the most helpful method of alleviating physiological strain in hot conditions [14, 15]. Unacclimatized persons are prone to operational mean error rates when engaged in high-temperature surrounding conditions [16]. In this study, we investigated the physiological parameters of heat strain in a relatively homogenous population of young, fit male soldiers to establish a relationship between heat storage during heat stress tests and various markers of fatigue.

Finding suitable models of heat exchange between the human body and the environment has been an important issue for more than 70 years. The problem is especially pronounced when physical activity is involved. Besides classical parameters of thermotolerance such as Tc, Tsk, and HR, over 100 different heat stress indices have been explored [4]. The study conducted by Cuddy et al. [17] with 56 male participants performed EHST in conditions similar to our study and revealed several parameters which showed significant accuracy in assessing the risk of heat illness. The authors concluded that HR and Tsk, as well as PSI, may serve as predictors of heat risk. According to PSI values, subjects were divided into groups “at risk” (PSI > 7.5) and “not at risk” (PSI ≤ 7.5). Subjects in the “not at risk” group also showed significantly lower RPE, especially between 60 and 90 min of the test, which coincided with lower values of Tc and HR. In our study end-point, PSI was 8.35 ± 0.70. In the first 30 min, all subjects showed PSI under 7.5 (“no risk”). After 40 min, two subjects had PSI over 7.5, and at the end of the test, 12 of 15 had PSI over 7.5.

In a previously mentioned study [17], authors reported a significant relationship between subjective perception of heat strain and total exercise time, which is in disagreement with our results. We found no significant correlation between RPE and time before exhaustion. Our results rather support the theory of “critical Tc”, proposed by Gonzales-Alonso et al. [18]. They suggested that the absolute value of “critical Tc” triggers fatigue, regardless of the total exercise time. In accordance with their results, we found that exhaustion occurred at a similar Tc when all participants rated their RPE at the almost same level, close to the upper limit of the scale.

Several studies reported that the rate of heat storage is well correlated with acute fatigue during physical work in hot conditions. That was confirmed in an experiment conducted on animal model [19], but the results of the given study are in disagreement with the hypothesis of “critical Tc”. The rate of body heat storage is also related to body composition, i.e., the content of body fat [20], which is expected due to different specific heat of tissues. The cumulative value of heat storage in our investigation showed a constant increase, with a significant correlation with Tc, HR, and PSI from 10–60 min. That confirms the findings of other authors [19, 21].

Temperature sensation and thermal comfort may contribute to the self-regulation of exercise intensity. In addition, acceptability and comfort were found to be closely correlated. Zhang and Zhao [22] investigated local TS of different body parts, as well as overall TS in 30 subjects, and reported the positive correlation between these factors and thermal comfort. Other authors reported the linear correlation between the TS and ambient temperature and suggested using physiological parameters such as Tc, Tsk, and HR as predictors of thermal comfort [16]. However, the evaluation of TS is still a challenging issue [12]. Assessment of individual perception of the thermal state is commonly obtained using several standard scales, with a various number of points [23], which contributes to the difficulties in comparing the results. In our investigation, we used a modified Gagge 8-point scale [8] with verbal descriptions between "cool" (ranking 5) and "unbearably hot" (ranking 13). Gagge et al. [8] indicate that lower ambient temperature affects the subjective sensation of discomfort more than higher temperatures, and one may expect a rapid increase in discomfort with lowering Tsk. Nevertheless, values of subjective thermal comfort in our investigation showed a constant linear increase from the beginning to the end of EHST, with an average end-point value of 12.2 ± 0.6. At the end of the EHST, 12 out of 15 subjects showed values of 12, and the rest ranked their TS as "unbearably hot" (rank 13). This relatively high ranking of thermal discomfort is in agreement with the results of the previously mentioned study by Davey et al. [12], where the subjects reaching the thermal tolerance limit ranked their subjective TS with an average of 18.8 ± 1.3 using a 20-point scale. Considering the similar ambient temperature (WBGT 29 °C in our investigation and 28.79–31.85 in the given study), similar results of TS are expected.

RPE increase was faster between the 40th and 70th min compared to the first 30 min. After 30 min, it correlates with TC, HR, and PSI. Some authors suggest that participants who were allowed to self-select their exercise work by maintaining the RPE level, mobilize an anticipatory mechanism by adjusting the work rate regulating the degree of motor-unit recruitment in order to prevent a harmful increase in Tc and thus the onset of premature fatigue [21], which is confirmed by findings that RPE correlates with changes in electroencephalogram.

Finally, in our study, we wanted to investigate the potential importance of peripheral markers of fatigue and their relation to psychophysical parameters of thermotolerance. Concentrations of prolactin showed the most prominent role out of all the investigated markers. Prolactin is a stress hormone that may indicate the rate of central fatigue since its secretion is stimulated and inhibited by serotoninergic and dopaminergic neurons in the brainstem [2]. Fatigue may be considered an impairment of balance between brain secretion of serotonin and dopamine, which is reflected in prolactin concentration in blood. The increase in prolactin concentrations is expected in high-intensity and/or long-duration exercise in both cool and warm environments and passive thermal stress. Manfredelli et al. [24] found a correlation between the increase in prolactin and lactate levels during high-intensity exercise. However, prolactin response has been more pronounced during exercise in heat compared to cool conditions [25]. The investigation conducted on 21 young males exercising in the heat showed that concentrations of prolactin were more sensitive in indicating heat stress than cortisol, and the most important stimulus to prolactin secretion was an increase in Tc [26]. Nevertheless, other authors did not find any significant increase in cortisol and prolactin levels during exercise-heat stress. In their investigation, ten young and ten older men performed short-time (30 min) bouts of physical activity [3]. The acclimatization tends to alleviate the increase in prolactin during exercise in the heat [27].

Our results show the association between prolactin concentrations at the end of EHST and end-point values of Tc, HR, and PSI. Other authors also found a correlation between prolactin and parameters of thermotolerance. In their study, Wright et al. [2] investigated peripheral markers of central fatigue in a group of 23 healthy men, of which 12 were well-trained, with an average VO_{2max} of 70 ± 2 mL/kg of lean body mass (similar to our participants). They performed EHST under similar ambient conditions and similar workloads. Values of Tc, HR, and change in Tc at the moment of exhaustion were in agreement with our results. The same authors also reported a sudden decrease in circulating free tryptophan levels at Tc over 39.5 °C consistent with levels of thermal strain, which may be the consequence of increased permeability of the blood-brain barrier. However, the results of this study, as well as our findings, indicate that the increase in prolactin concentrations may serve as a peripheral marker of central fatigue, reflecting an increase in serotonin and a decrease in dopamine secretion in the brain.

Conclusion

Prevention of heat illness is one of the most important issues regarding physical activity in hot conditions. As expected, this study demonstrates the relationship between heat storage and physiological and psychological parameters of thermotolerance (Tc and HR, as well as TS and RPE). It also demonstrates the suitability of using PSI as a reliable index of thermal strain. The perception of heat strain agreed with physiological strain parameters. Concentrations of prolactin, and to some extent cortisol, showed the strongest correlation with these parameters and may thus be considered peripheral markers of fatigue.

Acknowledgement

This paper is part of the project MFVMA 1/20-22, funded by the University of Defence, Belgrade.

REFERENCES

1. *Cordeiro LMS, Rabelo PCR, Moraes MM, Teixeira-Coelho F, Combra CC, Waner SP,* et al. Physical exercise-induced fatigue: the role of serotonergic and dopaminergic systems. Braz J Med Biol Res 2017; 50(12): e6432.
2. *Wright HE, Selkirk GA, Rhind SG, McLellan TM.* Peripheral markers of central fatigue in trained and untrained during uncompensable heat stress. Eur J Appl Physiol 2012; 112(3): 1047–57.
3. *Kaltsatou A, Notley SR, Kenny GP.* Effects of exercise-heat stress on circulating stress hormones and interleukin-6. Temperature (Austin) 2020; 7(4): 389–93.
4. *Havenith G, Fiala D.* Thermal indices and thermophysiological modeling for heat stress. Compr Physiol 2016; 6(1): 255–302.
5. *Tikuisis P, McLellan TM, Selkirk G.* Perceptual versus physiological heat strain during exercise-heat stress. Med Sci Sport Exerc 2002; 34(9): 1454–61.

6. *Jovanovic DB, Karkalic RM, Tomic LjI, Velickovic ZM, Radakovic SS.* Efficacy of novel phase change material for microclimate body cooling. Thermal Sci 2014; 18(2):657-65.
7. *Radakovic SS, Maric J, Surbatovic M, Radjen S, Stefanova E, Stankovic N,* et al. Effects of acclimation on cognitive performance in soldiers during exertional heat stress. Mil Med 2007; 172(2): 133–6.
8. *Gagge AP, Stolwijk JA, Saltin B.* Comfort and thermal sensations and associated physiological responses during exercise at various ambient temperatures. Environ Res 1969; 2(3): 209–29.
9. *Borg GA.* Psychophysical bases of perceived exertion. Med Sci Sport Exerc 1982; 14(5): 377–81.
10. *Gagge AP, Gonzales RR.* Mechanisms of heat exchange. Biophysics and physiology. In: *Fregly MJ, Blatteis CM,* editors. Handbook of physiology. Environmental physiology. Section 4. New York: Oxford University Press; 1996. p. 45–84.
11. *Havenith G, Luttikholt VG, Vrijkotte TG.* The relative influence of body characteristics on humid heat stress response. Eur J Appl Physiol Occup Physiol 1995; 70(3): 270–9.
12. *Davey S, Downie V, Griggs K, Havenith G.* The physiological strain index does not reliably identify individuals at risk of reaching a thermal tolerance limit. Eur J Appl Physiol 2021; 121(6): 1701–13.
13. *Donnan K, Williams EL, Morris JL, Stanger N.* The effects of exercise at different temperatures on cognitive function: A systematic review. Psychol Sport Exerc 2021; 54: 101908.
14. *Racinais S, Alonso JM, Coutts AJ, Flouris AD, Girard O, Gonzalez-Alonso J,* et al. Consensus recommendations on training and competing in the heat. Scand J Med Sci Sports 2015; 25(Suppl 1): 6–19.
15. *Malgoyrea A, Siracusa J, Tardo-Dinoa PE, Garcia-Vicencioa S, Koulmanna N, Charlot K.* A basal heat stress test to detect military operational readiness after a 14-day operational (heat acclimatization period. Temperature (Austin) 2020; 7(3): 277–89.
16. *Zhou B, Ding L, Chen B, Shi H, Ao Y, Xu R*, et al. Physiological Characteristics and Operational Performance of Pilots in the High Temperature and Humidity Fighter Cockpit Environments. Sensors 2021; 21: 5798.
17. *Cuddy JS, Buller M, Hailes WS, Ruby BC.* Skin Temperature and Heart Rate Can Be Used to Estimate Physiological Strain During Exercise in the Heat in a Cohort of Fit and Unfit Males. Mil Med 2013; 178(7): e841–7.
18. *Gonzales-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B.* Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol (1985) 1999; 86(3): 1032–9.
19. *Rodrigues LOC, Oliveira A, Lima NRV, Machado-Moreira CA.* Heat storage and acute fatigue in rats. Braz J Med Biol Res 2003; 36(1): 131–5.
20. *Kakitsuba N, Mekjavic I.* Determining the rate of body heat storage by incorporating body composition. Aviat Space Environ Med 1987; 58(4): 301–7.
21. *Tucker R, Marle T, Lambert EV, Noakes TD.* The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. J Physiol 2006; 574(Pt 3): 905–15.
22. *Zhang Y, Zhao R.* Overall thermal sensation, acceptability and comfort. Buil Environ 2008; 43(1): 44–50.
23. *Schweiker M, Fuchs X, Becker S, Shukuya M, Dovjak M, Hawighorst M,* et al. Challenging the assumptions for thermal sensation scales. Build Res Inform 2017; 45(5): 572–89.
24. *Manferdelli G, Freitag N, Doma K, Hackney AC, Predel HG, Bloch W,* et al. Acute Hormonal Responses to High-Intensity Interval Training in Hyperoxia. J Hum Kinet 2020; 73: 125–34.
25. *Rojas Vega S, Hollmann W, Strüder HK.* Influences of exercise and training on the circulating concentration of prolactin in humans. J Neuroendocrinol 2012; 24(3): 395–402.
26. *Bridge MW, Weller AS, Rayson M, Jones DA.* Ambient temperature and the pituitary hormone response to exercise in humans. Exp Physio 2003; 88(5): 627–35.
27. *Burk A, Timpmann S, Kreegipuu K, Tamm M, Unt E, Oopik V.* Effects of heat acclimation on endurance capacity and prolactin response to exercise in the heat. Eur J Appl Physiol 2012; 112(12): 4091–101.

Received on October 12, 2021
Accepted on November 15, 2021
Online First November 2021